

**DEVELOPMENT AND ENGINEERING PROPERTIES OF
CONSTRUCTION MATERIALS MADE USING MELTED PLASTICS
WASTES AS THE ONLY BINDING PHASE**

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Abstract

Modernization has brought about steady increase in the consumption of goods and services by human societies across the globe, which mostly driven by both population growth and the change of individual living standards. This, of course, leads to an ever-increasing waste production that ends up in landfills and very often as a source of pollution on natural ecosystems, especially in the low and middle-income countries where waste management is almost inexistent.

The management of waste streams is a huge challenge for developed countries as well, where societal and environmental impacts are visible despite massive investments in waste management. One of the most problematic waste materials is plastic, which can remain in nature for over 100 years without degradation, leading to serious environmental concerns. As one of the most significant innovations of the 20th century, plastic is a widely used and cost-effective material for many applications. After their useful lifetimes, their management is problematic. Thus, robust and innovative approaches of managing such waste material are needed in order to mitigate the problem.

One of the innovative approaches of tackling the menace cause by plastic waste is through its incorporation into the construction materials. This thesis seeks to address this problem by exploring the use of melted plastic wastes (High Density Poly Ethylene, HDPE and Low Density Poly Ethylene, LDPE) as binder in developing new construction materials (mortar with melted plastic as the only binder, MPB and Plastic Waste Crete, PWC) as an alternative to partially replace traditional concrete and mortar, or finding other engineering uses for this type of waste.

Worldwide, about 190 m³ of concrete is poured every second, which translates to 6 billion m³ per year and making it, one of the most widely used manufactured materials. However, the production of concrete requires water and cement. Cement is expensive, and its production contributes to the emission of environmentally polluting gases. Replacing this binding element with recycled plastic derivatives would have significant economic and environmental benefits. In addition to the elimination of cement cost, this will result in water savings, which is especially important for areas without fresh water scarcity.

Some researchers have used plastics in concrete and mortars as additives and/or replacement for fine and coarse aggregates. In addition, different types of plastics have been used in bitumen as an additive to reduce construction cost and improve sustainability by adding value to wastes materials. However, there is paucity of technical information about the use of the melted HDPE and LDPE plastic wastes as the only binding phase in concrete- or mortar-like materials. Moreover, many parameters such as preparation conditions, field variables, constituent elements, and final applications have impacts on the performance of construction materials

Thus, the key objective of this PhD research is to develop the mortar with plastic binder (MPB) and PlasticWasteCrete (PWC) by using molten HDPE and LDPE plastic wastes as the only binder as well as to investigate the engineering properties of these new types of construction materials.

The plastic contents of 45%, 50%, 60% and 65% and HDPE to LDPE ratios of 40/60, 50/50, and 60/40 were selected for the experimental tests. Clean river sand was used as the only aggregate for the MPB, while both sand and gravel were used for the PWC. Various tests were then performed on prepared MPB and PWC samples at different curing times from early to advanced ages to assess their engineering properties. These tests were conducted in accordance with the ASTM standards to evaluate the mechanical properties (compressive strength and splitting tensile strength), permeability and density of the MPB and PWC materials. Additional tests were carried out to analyze the products at the microstructural level (optical microscope, SEM, MIP and thermogravimetric analysis) to gain an insight into the microstructural properties of the developed materials and how that affect their engineering properties.

The compressive strength tests revealed the optimal plastic content for the MPB and PWC with the best strength performance. The average compressive strength values for various optimal formulations after 28 days were found to be in the range of 9 to 18 MPa. The splitting tensile strength for the new materials from 1 to 28 days of curing time, were found to be between 1 and 5 MPa. The average hardened density of the MPB and PWC is about 2 g/cm³, which makes them lightweight material according to RILEM classification. In addition, various absorption tests (capillary and immersion) were performed on different MPB and PWC samples, and the obtained results showed that they are porous materials having lower rate of absorption than the traditional cementitious materials (mortar, concrete). This observation was supported by the results from both MIP and SEM analyses. Finally, thermogravimetric analysis provided interesting details on the thermal decomposition of the new materials, with significant changes or mass loss for these products being observed only at temperatures higher than 300°C.

The findings from this study suggest MPB and PWC made with melted plastic waste as the only binder have a promising potentials for use in construction. The research conducted in this PhD study offers a good understanding of the engineering properties of the materials as well as the optimal formulations that yield best performance in terms of strength and durability. In summary, it provides useful technical information and tools on the MPB and PWC that will contribute in setting guidelines on the optimal applications of these products in the field of construction in order to have safe, durable and cost-effective structures.

Résumé

Avec la modernisation de nos sociétés, les habitudes ont considérablement changé, ainsi, on observe une forte consommation des biens et services, due à l'augmentation de la population et l'amélioration de leurs conditions de vie. Ce qui conduit à une augmentation considérable des quantités des déchets qui terminent leurs cycles au niveau des décharges ou dans les océans/fleuves devenant ainsi une source de pollution des écosystèmes naturels, surtout dans les pays à revenu faible et intermédiaire avec des systèmes défaillants ou moins performants de gestion des déchets. La gestion des flux de déchets est aussi un défi pour certains pays développés, où les impacts sociaux et environnementaux sont visibles en dépit des investissements massifs dans ce secteur.

Parmi ces déchets, nous avons les plastiques, l'une des innovations du 20^e siècle avec des qualités versatiles et coût faible, se trouve partout dans nos vies quotidiennes. Après leur utilisation, les plastiques deviennent des déchets qui peuvent rester dans la nature plus de 100 ans sans aucune dégradation, avec des conséquences néfastes sur l'Homme et l'environnement. Ainsi, une approche robuste et innovante de gestion de ces déchets est nécessaire afin d'atténuer leurs impacts. L'une des approches innovantes pour réduire l'impact causé par les déchets plastiques consiste à les incorporer dans les matériaux de construction.

Ainsi, le problème est abordé dans cette thèse en développant des technologies permettant de recycler les plastiques fondus comme liant dans les nouveaux matériaux de construction (MPB et PWC), afin d'offrir une alternative pour remplacer partiellement le béton / mortier traditionnel.

Le béton est l'un des matériaux les plus utilisés au monde, avec environ 190 m³ coulés chaque seconde, correspondant à 6 milliards de m³ par an. Cependant, la production de béton nécessite de l'eau et du ciment. Le ciment coûte cher et sa production contribue à l'émission de gaz polluants l'environnement. Le remplacement d'une partie du béton traditionnel par un matériau à base des déchets plastique aura des avantages économiques, sociaux et environnementaux importants.

Allant dans ce sens, certains chercheurs ont utilisé les plastiques dans le béton et le mortier comme additifs et / ou substituts des matériaux granulaires tels que le sable et le gravier. Aussi, différents types de plastiques ont été utilisés dans le bitume comme additif pour réduire les coûts de construction et améliorer la durabilité, ainsi contribuer à donner de la valeur aux déchets. Cependant, jusqu'à présent, il existe peu d'informations techniques sur l'utilisation de déchets plastiques (HDPE et LDPE) fondus comme seuls liants pour développer de nouveaux types de matériaux de construction. En plus, plusieurs facteurs (les conditions de préparation, les éléments constitutifs, les applications finales, etc.) ont un impact sur les caractéristiques des matériaux de construction.

Ainsi, l'objectif de cette recherche doctorale est de développer des nouveaux matériaux de construction (MPB et PWC) en utilisant les déchets plastiques fondus (HDPE et LDPE) comme seul liant, puis déterminer les propriétés caractéristiques de ces matériaux afin de trouver la formulation optimale conduisant à la meilleure résistance. En plus de l'élimination du coût du ciment, cette technologie permet aussi de faire des économies d'eau, bénéfique surtout pour les

zones avec des difficultés d'accès à l'eau potable. Cela contribuera à la réduction des coûts de la construction en utilisant les produits innovants comme alternative au béton / mortier conventionnel.

Un vaste programme expérimental, comprenant des tests à petite et grande échelle, a été développé afin d'atteindre les objectifs de cette étude de doctorat. La campagne expérimentale a comporté différentes étapes comprenant la sélection des matériaux, la détermination de la formulation optimale et les conditions appropriées pour la préparation des matériaux susmentionnés. Par la suite, pour une meilleure compréhension du comportement technique et des propriétés du produit final, divers tests ont été effectués sur les matériaux préparés à différents temps de durcissement. Ces tests ont été menés conformément aux normes ASTM pour évaluer les propriétés mécaniques (résistance à la compression et à la traction), la perméabilité et la densité des nouveaux matériaux. Les expériences ont été approfondies en analysant les produits au niveau microstructural (microscope optique, SEM, MIP et analyse thermique) pour avoir un aperçu des propriétés microstructurales des matériaux développés et essayer de comprendre les relations avec leur comportement mécanique.

Les essais de compression ont permis de trouver la teneur en plastique optimale pour les matériaux (MPB et PWC) avec les meilleures valeurs de résistance. Les résistances moyennes à la compression à 28 jours pour diverses formulations étaient comprises entre 9 et 18 MPa. La résistance à la traction par fendage des nouveaux matériaux entre 1 et 28 jours se situait entre 1 et 5 MPa. La densité moyenne du béton et mortier écologique est proche de 2 g / cm^3 , ils peuvent donc être considérés comme des matériaux légers selon la classification RILEM. De plus, divers tests d'absorption (capillaire et par immersion) ont été réalisés sur différents échantillons de MPB et PWC, les résultats obtenus ont montré qu'il s'agit de matériaux poreux ayant un taux d'absorption plus faible que les matériaux traditionnels contenant du ciment. Plusieurs analyses microstructurales ont été réalisées sur différents échantillons des nouveaux produits (MPB et PWC) et les matériaux cimentaires traditionnels ont été utilisés pour renforcer notre compréhension. Enfin, l'analyse thermique a fourni des détails intéressants sur la décomposition thermique de ces nouveaux matériaux ; des changements significatifs avec une perte de masse considérable ont été observés seulement pour des températures supérieures à 300°C .

Les résultats de ces essais permettent d'acquérir une bonne compréhension des propriétés techniques des nouveaux matériaux (MPB et PWC) ainsi que de déterminer les teneurs optimales en plastique conduisant aux meilleures performances en termes de résistance et de durabilité. Ainsi, les recherches menées dans cette étude de doctorat fournissent des informations techniques et des outils utiles sur le MPB et le PWC; et contribueront à installer des bases pour guider les applications optimales de ces nouveaux produits dans le domaine de la construction afin d'avoir des structures sûres, durables et rentables.

Dedication

“Homage to Allah, Almighty God, for all his graces”.

This thesis is dedicated to:

- My late mother and best friend Djoncounda Daffé, torn from our lives in October 2019. Dearest **Nanna**, brave woman, who was forced to stop studying few months before her graduation for a marriage of which I am the fruit, you were a mother, a friend, a confidante, and guide, but above all a protector for me with your noble advice. Receive here my deepest respect and affectionate tribute as the fruit of your labor in a polygamous household with complex realities and its share of sacrifices. Thanks to the foundation you laid mom, the best is yet to come, mom, albeit without your physical presence. May God grant you Jannatul Firdaws as a reward for all your efforts. I am grateful for the education and all the love you gave me, nothing and no one can ever give me what you did.
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List of Symbols and Abbreviations

ABS Acrylonitrile Butadiene Styrene

ASTM American Society for Testing and Materials - Standards

bfs blast furnace slag

°C Degree Celsius

CAAA Clean Air Act Amendments

CCMCP Cementitious construction materials containing plastics wastes

E Elongation at rupture

EC Ecological concrete

EM Ecological mortar

EPS Expanded polystyrene

EPS-E Extruded expanded polystyrene

EPS-M Molded expanded polystyrene

°F Degree Fahrenheit

FME Flexural modulus of elasticity

GPa Gigapascal

HDPE High density polyethylene

HIPS High-impact polystyrene

IWMC Integrated waste management concept

ISO International Organization for Standardization

LC Lightweight concrete

LDPE Low density polyethylene

MPB Mortar with plastic binder

MEPS heat-treated expanded polystyrene foam

MF Aminoplast

MSW Municipal Solid Waste

NA Natural aggregates

NPC Normal Portland cement
 SPI Society of the Plastics Industry
 PA Polyamides
 PA 6.6 Nylon.
 PC Polycarbonate
 P-C Polymer concrete
 PE Polyethylene
 PEHD Polyethylene high-density
 PEN Polyethylene naphthalate
 PET Polyesters and Polyethylene terephthalate
 PETW PET waste aggregate
 PF Phenoplasts
 PMMA Methyl polymethacrylate in the amorphous state
 POM Polyacetal or polyoxymethylene or polyformaldehyde
 POMC Polyacetal Copolymer form
 POMh Polyacetal Homopolymer
 POPs Persistent organic pollutants
 PP Polypropylene or Polypropene
 PS Polystyrene
 PS "crystal" Polystyrene "crystal"
 PS "shock" Polystyrene "shock"
 PUR Polyurethanes
 PVC polyvinyl chloride
 PWC PlasticWasteCrete
 R Tensile strength
 RILEM International Union of Laboratories and Experts in Construction Materials, Systems and Structures
 R_(IZOD) Shock resistance (IZOD)
 SPI Society of the Plastics Industry

T_c Content of a continuous heat

T_{flc} Deflection Temperature under load (1.8 N/mm²)

Compressive strength (Unconfined Compressive Strength)

USA United States of America

W/C or W/C_m Water cement ratio

WPLA Polyethylene terephthalate bottles lightweight aggregates

WPLAC Waste PET bottles lightweight aggregate concrete

Chapter 1. General introduction

1.1 Introduction

Plastics, one of the most significant innovations of 20th century are everywhere in today's lifestyle; they have become an inseparable and integral part of our lives. They are used for packaging, protecting, serving, and even disposing of all kinds of consumer goods. With the industrial revolution, mass production of goods started and plastic seemed to be a cheaper and effective raw material. The amount of plastics consumed annually has been growing steadily, the world's annual consumption of plastic materials has increased from around 5 million tons in the 1950s to nearly 100 million tons in 2001 (Siddique et al., 2008). Its low density, strength, user friendly designs, fabrication capabilities, long life, light weight, and low cost are the factors behind such phenomenal growth. Nowadays, every vital sector of the economy starting from agriculture to automobile, health, telecommunications, transportation, food, building construction, communication or InfoTech has been virtually revolutionized by the applications of plastics (Brydson, 1999; Hopewell et al, 2009); this material is not biodegradable and can stay unchanged for more than hundred years (Siddique et al., 2008). The use of this product is growing rapidly and the problem is what to do with plastic-wastes. As shown in the Figure 1-1, in the year 2000, plastics amount was about 7% of municipal solid wastes (MSW), by weight, in England (Nabajyoti and Jorge, 2012). In USA, polyethylene was found to be the major component of the plastics waste followed by the polypropylene as shown in the Tableau 1-1 (Subramanian, 2000). These statistics are more significant for developing areas where governments are struggling to solve wastes related problems (e.g., Figure 1.2) and sometime do not have environment protection in their priorities.

Table 1-1: Types and quantities of municipal solid waste in USA (adapted from Subramanian, 2000)

Type of plastic	Quantity (1000 tons)
High density polyethylene (HDPE)	4120
Low density polyethylene (LDPE)	5010
Polyethylene terephthalate (PET)	1700
Polypropylene (PP)	2580
Polystyrene (PS)	1990
Other	3130

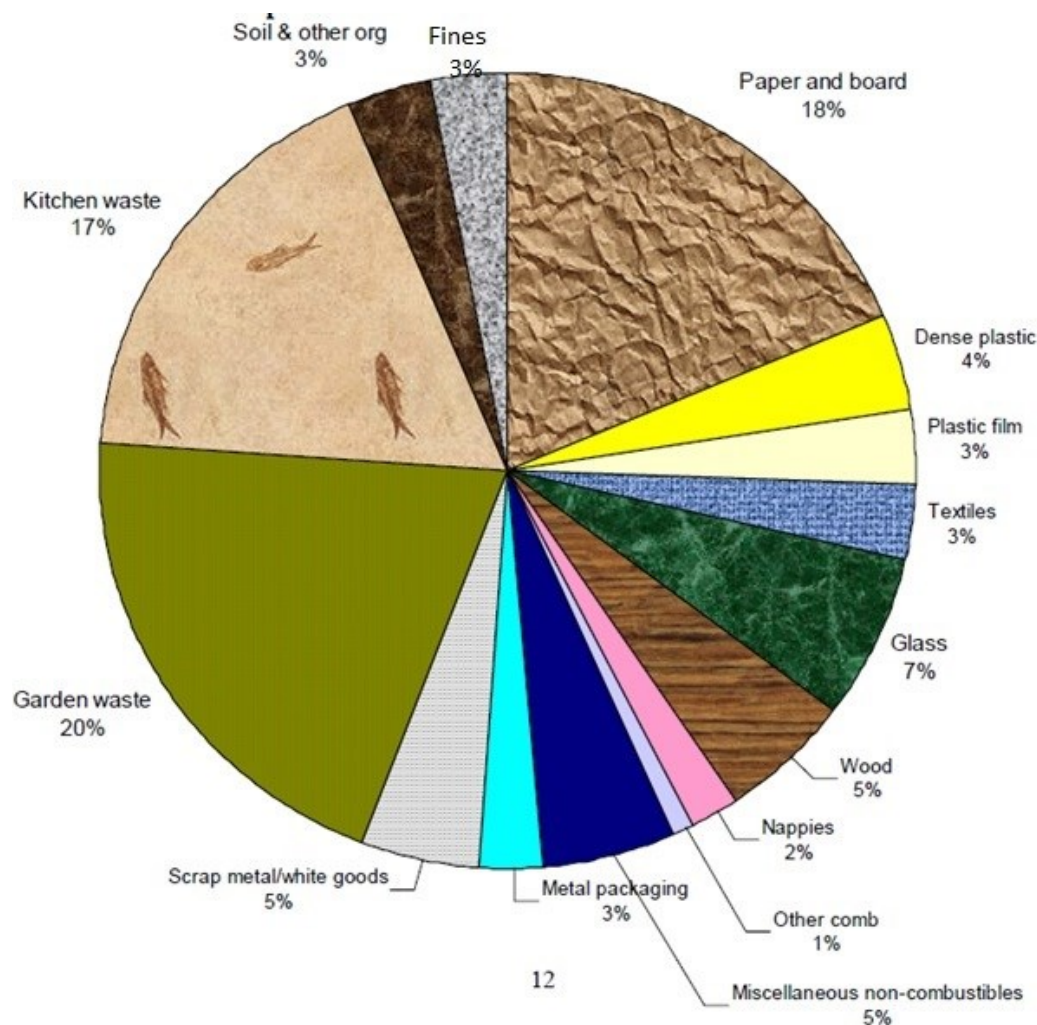


Figure 1-1: Total household waste composition in England, year 2000 (Nabajyoti and Jorge, 2012)

Composed of several toxic chemicals (dioxins, cadmium, lead, etc.), plastic wastes are a serious environmental threat for modern civilization, therefore, contribute to pollute soil, air and water. Studies (Bale 2011; Lynn et al. 2016; Marques-Pinto and Carvalho, 2013; Meeker et al. 2009) have linked the improper disposal of plastic to problems such as breast cancer, reproductive problems in humans and animals, genital abnormalities and even a decline in human sperm count and quality. Plastic garbage can reduce the rate of rainwater percolating and deteriorate the soil fertility if mixed with soil elements. Since plastic is a non-biodegradable material, landfill accepting/using plastic would mean preserving the harmful material forever due to its slow degradation rate and bulky nature. The hazards caused by plastics are numerous; they may block the drainage system of a city and contribute to ocean's pollutions. The blocked drains provide excellent breeding grounds for disease-causing mosquitoes and water borne diseases besides causing flooding. Some countries such as Kenya Mali, Rwanda and Senegal have restricted the

use of plastic bags and many are in the process of doing so. However, the reality for developing areas is different; it is very difficult to master and/or control the supply chain of plastic materials with rigorous application of the law for sellers and their clients.

Considering the importance given to the protection of environment and its preservation for future generations, deciders gave an important attention to this sector. Thus, researchers and industries focused some of their energy on finding alternatives for recycling plastic wastes related materials and many works have been done on the use of plastic wastes in civil engineering / construction materials development.

Several important properties of concrete or mortar containing various types of plastic as a partial or full replacement of natural aggregate, filler or fiber in the preparation of concrete/mortar are available in the literature. Some of these properties are: bulk density, air content, workability, compressive strength, splitting tensile strength, modulus of elasticity, impact resistance, permeability, and abrasion resistance, toughness, failure characteristics, thermo-physical properties, durability performance, etc.

Nevertheless, new approach to use plastic as binding material is not well documented and going to the exploration of that material as the only binder for making concrete or mortar will contribute to add more values to research and bring new materials of qualities to the construction field and reduce as much as possible the negative impacts of plastic wastes.

1.2 Research problem and rationale

In recent decades, many efforts went to the development of technologies that recycle plastics into useful products. Some of the most popular methods used plastic wastes as a substitute/additive to sand or gravel in concrete/mortar (Al-Manaseer and Dalal (1997); Azhdarpour et al. (2016); Babafemi et al. (2018); Bayasi and Zeng (1993); Coppola et al. (2018); Coppola et al. (2016), Hannawi et al. (2010); Ismail and Enas (2008); Kurad et al. (2017); Kurda et al. (2018); Mazouk et al. (2007); Nehdi and Khan (2001); Ruiz-Herrero et al. (2016); Saikia and de Brito (2014); Saikia and de Brito (2012); Siddique et al. (2008); Soroushian et al. (2003); Tosun and Şahin (2015)). In the other methods melted plastics are added to bitumen for road construction (Donnchadh et al. 2008; Hassani et al. 2005; Hınıslioğlu and Ağar, 2004; Modarres and Hamed, 2014). None of these experiments used melted plastics as the only binder. Therefore, to date in the literature, the use plastic as the only binder is not well documented with few research on that subject, thus there is a lack of information on the use of melted plastics as the sole binder to make concrete or mortar like materials and this research fits in this direction. In this PhD thesis, we will examine the possibility of developing PlasticWasteCrete (PWC) and mortar with plastic binder (MPB) prepared with melted HDPE and LDPE as the only binding material.

The desirable qualities for any construction material are safety, durability, cost effectiveness and environmental sustainability. These qualities are required in order to comply with norms and regulations, and affect its adoption by the industry and the general population.

One of the challenge for MPB and PWC is to find the optimal formulation that will give them the desired properties. To do so, early and long-term experiments must be performed to assess various engineering properties of the proposed new products (strength, adhesion between different components, microstructure, density, permeability, etc.). An understanding of these engineering properties and behavior of the MPB and PWC is crucial for reliably assessing the performance and cost-effective design of future structures using the new environmental friendly products. Thus, this PhD study will address the aforementioned issues for the MPB and PWC using melted plastic wastes (HDPE and LDPE) as the only binder.



Figure 1-2: Overview of the waste management chain in commune II and IV of Bamako district, Mali.

1.3 Objectives of the research

The main objectives of this research are to conduct experimental investigations on the use of molten plastic wastes as the only binder to develop MPB and PWC. Thus, the specific objectives of this thesis are:

- a- Find optimal formulations (specific plastic contents with given ratio of different plastics types, sand and gravel contents) for the MPB and PWC, which enable to obtain the best strengths performance.
- b- Study strength, deformation behaviour and microstructural properties of PWC at early and advanced ages for various formulations.
- c- Study strength, deformation behaviour and microstructural properties of MPB at early and advanced ages for various formulations.
- d- Study the effect of curing conditions and granular materials sizes on the engineering properties of the new PWC material.
- e- Study the effect of curing conditions and granular materials sizes on the engineering properties of the new MPB material.
- f- Compare MPB and PWC pavers made from this PhD research to the commercial pavers available in Bamako made using concrete containing Portland cement.
- g- Formulate some recommendations for future works and large-scale construction of infrastructures using these new products.

1.4 Research approach and method

The research approach and methods adopted in this study are schematically shown in Figure 1.3 and discussed below.

In this Ph.D. study, a comprehensive literature review is conducted in order to provide theoretical basis and fundamental tools to facilitate the understanding of the issues addressed in this thesis and the engineering properties/behavior of the proposed new construction materials as well as to provide a review of previous studies on the use of plastics waste in cementitious materials.

In addition, to achieve the objectives of this study, key engineering properties and behaviour of the new type of MPB and PWC materials using molten plastic wastes (HDPE and LDPE) as the only binding material have been experimentally studied.

Two types of experimental approach or method with different conditions were adopted and/or improved for the purposes of this study. Large-scale system with manual oven capable of producing small and big samples in Mali. Small-scale system in the laboratory at the University of Ottawa using heat plate and automatic mixer improved in the machine shop to meet the requirements of the experiment.

Using these experimental approaches, various samples with different shapes (cylindrical with various height and diameter, commercial pavers' forms, etc.) of MPB and PWC from different formulations were prepared and cured under different conditions (in water and air dried at ambient temperature). Samples from these formulations that have been cured at different ages (i.e., 1, 3, 7,

28 days) are then subjected to different tests, such as uniaxial compressive strength and splitting tensile strength tests, density measurement, capillary and immersion absorption tests, etc. All of the experiments are conducted in accordance with the ASTM (American Society for Testing and Materials) standards.

The first part of the experimental campaign mostly focused on finding the optimal formulations leading to the best strength results of the MPB and PWC with respect to the curing time, preparation conditions at small and large scale using two types of plastics wastes Low Density Polyethylene (LDPE) and High Density Polyethylene (HDPE) and coarse/fine grain materials (sand and gravel). Then, various macro- and microstructural properties such as density, tensile strength, permeability behavior were analyzed as a function of plastic content and time. Finally, microstructural (MIP, SEM) and thermal analysis were performed on a number of MPB and PWC samples.

The obtained experimental results allow fundamental knowledge to be gained about the MPB and PWC behaviour as well as a better understanding of the impact of plastic content and/or curing conditions on their performance and optimal design for future structures. In addition, for providing more practical information on future uses of the new products in construction, some pavers were made using the MPB/PWC materials and then compared in terms of cost and strength performances (compressive strength, splitting tensile strength, deformation behavior, etc.) to the commercial pavers produced in Bamako using the conventional concrete. All the findings results gave valuable insight into the MPB /PWC performance under different conditions. Moreover, recommendations for their optimal applications will be provided.

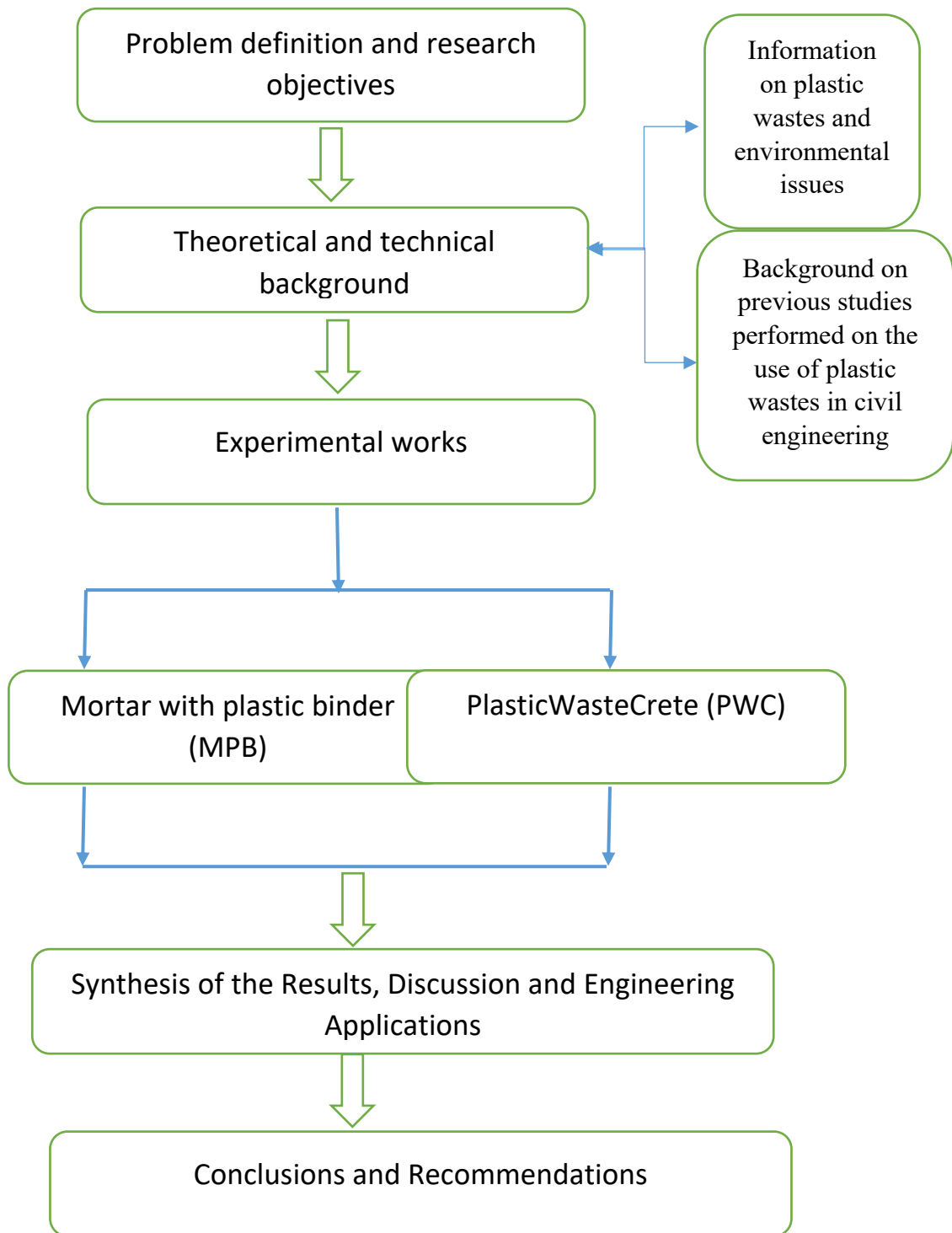


Figure 1-3: Flowchart of the research and study approach

1.5 Tasks and organization of the thesis

This thesis is organized into seven chapters, which contain discussions of the different tasks and objectives of the current PhD research. Figure 1.4 presents the structure of the main tasks that have been carried out.

Chapter One is a general introduction, which comprises problem statements, objectives, and research methodologies employed in this research.

Chapter Two provides general information on plastic wastes, their advantages, inconvenient and environmental concerns about these types of wastes.

Chapter Three presents a comprehensive literature review and/or background information on previous studies performed on the use of plastic wastes in civil engineering and construction materials development sector.

Chapters Four and Five are structured into a paper-based thesis format, which comprises four technical papers. In accordance with the instructions of manuscript preparation of the corresponding publication medium, these papers are independently written, without taking into consideration the content of the others or the rest of the document. Please be aware that, the main results of these chapters are presented as technical papers, some information is repeated in these papers. In these chapters' strength results, microstructural properties, deformation behaviour, effect of curing time and more other information's are discussed on the MPB and PWC.

In Chapter Six, the obtained results are synthesized to provide valuable insight on the use of plastic wastes as the only binding material to develop MPB/PWC with required engineering properties. In the other hand, study have been performed to understand the strength properties and deformation behaviour of pavers made using the MPB and PWC by comparison to the ones available on Malian' market prepared using the conventional concrete with Portland cement, that can help engineers to design desired structures with the new cementitious materials.

Chapter Seven, presents the summary, large-scale tests, conclusions and directions for future research.

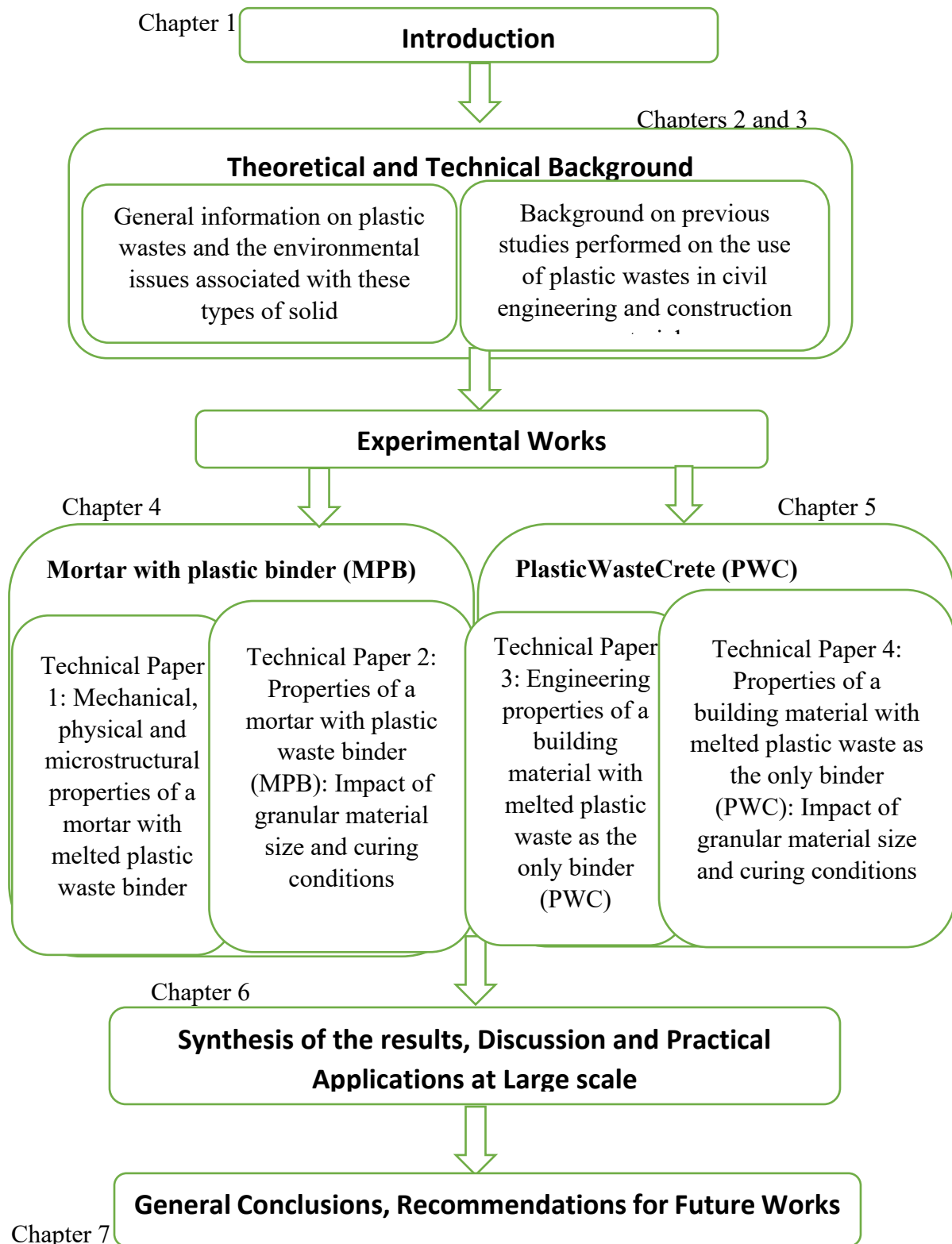


Figure 1-4: Organization of the thesis

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Chapter 2. Overview of plastic wastes, advantages, disadvantages, environmental problems associated with these types of solid waste.

2.1 Introduction

To better address the subject of this research, it is more than necessary to obtain a real idea of the different types of plastics and know how to characterize them according to their physicochemical properties. Going to that direction, the first part of this chapter will focus on the description of the characteristics of the different types of plastic. Then, the behavior of plastic wastes from the production to transportation, passing by sorting and recycling stages until to the final repository is discussed.

2.2 Different types of plastics and their properties

Plastic invented in the twentieth century have replaced traditional materials such as wood or metal. Research to improve and diversify their properties made them suitable for many applications. Plastics are lightweight, hygienic, made to measure and durable. All these qualities made plastics irreplaceable and omnipresent in our daily life style and objects (Brydson, 1999; Hopewell et al, 2009). Manufacturers offer a very wide range of products, but there are three major categories of synthetic plastics: thermoplastics, thermosets and elastomers.

In 1988, the Society of the Plastics Industry (SPI) has proposed a voluntary coding system to differentiate the various plastic resins. A digit placed in the center of a triangle symbol formed by three arrows indicating the plastic category of the product.

2.2.1 The Thermoplastic

Thermoplastics soften when heated. They become supple, malleable and harden again when cooled. Since this transformation is reversible, these materials retain their properties and are easily recyclable. Their base polymers consist of linear macromolecules interconnected by weak bonds, which can be broken under the effect of heat or high stresses. They can then slide relative to each other to take a different form and when the material cools, the bonds are reformed and the thermoplastic retain their new shape. Generally ductile, thermoplastics are synthetic materials consisting of linear or branched polymers.

Before processing, they are in the form of granules or powders into stable and definitive chemical state because there is no chemical change in the layout. The granules are then heated, injected in the molds and the crushed material is reusable. In the class of thermoplastic, we can find: Polyethylene (PE), Polypropylene (PP), Polystyrene (PS), Polyacetal or Polyoxymethylene (POM), Polyamides (PA), PVC polyvinyl chloride. Table 2-1 shows some characteristics of the most commonly used thermoplastic polymers.

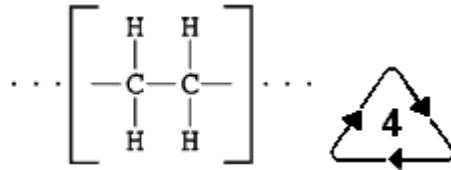
Table 2-1: Some characteristics of the most commonly used thermoplastic polymers (Morin 2000, adapted from Slama, 2008).

Polymer	Density (g/cm ³)	R (N/mm ²)	FME (N/mm ²)	E (%)	R _(IZOD) (KJ/m ²)	T _{flc} (° C)
PVC	1.5	36	2400	40	-	60
PS	1.05	-	2800 – 3500	1 – 2	-	90
HDPE	0.95	-	1000	10	5	77
PET	1.39	-	3400	15	3	80
PMMA	1.19	5	3300	6	15	95
PP	0.91	46	-	9	-	100

R: Tensile strength; FME: Flexural modulus of elasticity; E: Elongation at rupture; R_(IZOD): Shock resistance (IZOD); T_{flc}: Deflection temperature under load (1.8 N/mm²). PVC: Polyvinyl chloride rigid; PS: Polystyrene at crystal state; HDPE: High-density polyethylene; PET: polyethylene Terephthalate; PMMA: Methyl polymethacrylate in the amorphous state; PP: Polypropylene at semi crystalline state.

2.2.1.1 Polyethylene (PE)

Having the following chemical formula and labelled by the code number 4:



This plastic material alone counts for about a third of the total production of synthetic materials and constitutes half of plastic packaging as shown in the Figure 2-1 (Schultz, 2000). Several million tons of polyethylene are produced every year because it is an extremely versatile material, substantial ecologically and on the economy. With its simple chemical structure, polyethylene takes precedence over most other materials because of its possibility to be reused. During recent years, recycling of PE used products has become more and more important, 50% of the PE component trash bags are recycled. Polyethylene is translucent, inert, easy to handle and resistant to cold. There are various types of polyethylene classified according to their density. It depends on the number and length of branches present in the material. There are two families: LDPE or Low-Density Polyethylene and HDPE or High-Density Polyethylene.

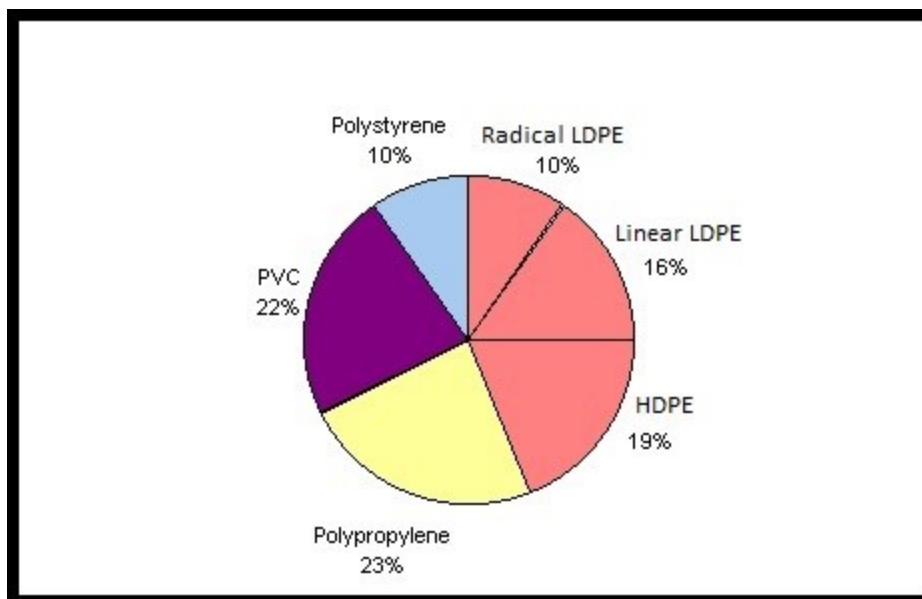


Figure 2-1: Breakdown of Thermoplastics in the World (adapted from Schultz, 2000).

British engineers EW Fawcett and RO Gibson from ICI chemical firm in UK invented low-density polyethylene (LDPE) in 1933. This thermoplastic polymer of high consumption is obtained by radical polymerization of ethylene (or ethene) by operating under very high pressure (1800 to 3 000 bar) to about 200° C.

Its density in the range of 0.915-0.940 g cm⁻³, is lower than that of the High Density Polyethylene (HDPE; 0.940-0.965 g cm⁻³) and water (1 g cm⁻³), since its structure revealed a degree of branching greater than that of HDPE.

LDPE is used in many different fields. It has good chemical resistance; it is olfactory, gustatory and chemically neutral for foodstuffs. It is transparent, can be easily transformed and is well suited to welding. Its lifetime is very long due to its high stability but it can be well recycled. The main applications of LDPE (Figure 2.2) are flexible products: manufacturing various and flexible containers (bottles ketchup, shampoo, cosmetic cream tubes, etc.), films, dispensing bottles, wash bottles, tubing, plastic bags for computer components, and various molded laboratory equipment, garbage bags. Its most common use is in plastic bags.



Figure 2-2: Some main applications of LDPE (LDPE, 2018; Shutterstock, 2019).

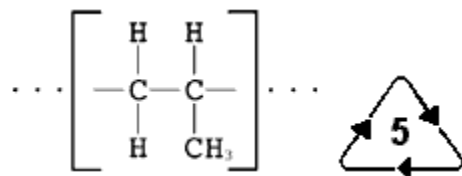
High-density polyethylene (HDPE) or polyethylene high-density (PEHD) is a thermoplastic polyethylene made from petroleum. HDPE has large strength to density ratio and its density can range from 0.93 to 0.97 g/cm³ (HDPE, 2018). Although the density of HDPE is only marginally higher than that of low-density polyethylene, HDPE has little branching, giving it stronger intermolecular forces and tensile strength than LDPE. The difference in strength exceeds the difference in density, giving HDPE a higher specific strength. It is also harder and more opaque and can withstand somewhat higher temperatures (120 °C/ 248 °F for short periods, 110 °C /230 °F continuously). High-density polyethylene cannot withstand like polypropylene in normal required autoclaving conditions. The lack of branching is ensured by an appropriate choice of catalyst (e.g., Ziegler-Natta catalysts) and reaction conditions. It is commonly used in the production of plastic bottles, corrosion-resistant piping, geo-membranes and plastic lumber. HDPE is generally recycled and has the number "2" as its resin identification code (formerly known as recycling symbol) (Figure 2-3). In 2007, the global HDPE market reached a volume of more than 30 million tons (HDPE, 2018).



Figure 2-3: Some main applications of LDPE (Images of HDPE, 2018).

2.2.1.2 Polypropylene (PP):

Labelled by the code number 5 as shown below and having the following chemical formula:



Polypropylene (PP), also known as polypropene, is a thermoplastic polymer used in a wide variety of applications including packaging and labelling, textiles (e.g., ropes, thermal underwear and carpets), stationery, plastic parts and reusable containers of various types, laboratory equipment, loudspeakers, automotive components, and polymer banknotes. It is rugged and unusually resistant to many chemical solvents, bases and acids. In 2008, the global market for polypropylene had a volume of 45.1 million metric tons, which led to a turnover of about \$65 billion (Polypropylene, 2018). Its density is 0.85 g/cm³ at amorphous state and 0.95 g/cm³ when it is crystalline.

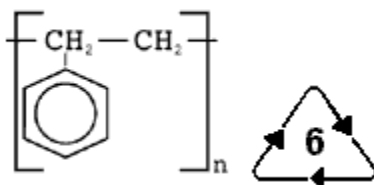
In addition, this very versatile polymer serves as both thermoplastic and fiber. It is very easy to color and does not absorb water. It is usually in the form of molded articles, which can be seen, in outdoor furniture and automotive equipment (bumpers, dashboards, trim the cabin or cut off) (Figure 2.4). This material is used to make foods boxes which are dishwasher - safe because it does not melt below 160° C. Polypropylene is also used in the manufacture of synthetic fibers (carpets, ropes, twines), but also for food packaging because of its glossy appearance and its resistance (bottles, films, pots). However, the PP film is one of the most usual plastics difficult to recycle especially when it is printed. The catalyzed polymerization control allows you to play on the last structure to produce elastomeric polypropylene.



Figure 2-4: Some main applications of PP (Images of PP, 2018; Polypropylene, 2018).

2.2.1.3 Polystyrene (PS):

Polystyrene is a hard plastic, brittle and transparent. It is a common industrial product widely circulated, providing numerous uses. Labelled by the code 6 as shown below and having the following chemical formula:



It is easily recognized in the bleaching stress areas before failure or its black smoke and its characteristic odor when burned. It is used to make furniture, packaging, ventilation grills, toys, plastic glasses (Figure 2.5). There are three types of polystyrene:

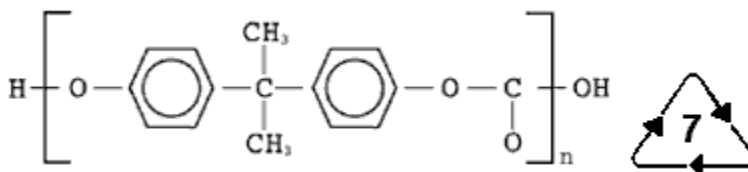
- ✓ Polystyrene "crystal" does not have a crystalline structure, but this name because of its transparent appearance. It polymerizes in the form of pearls at high temperature in the presence of a plasticizer adjuvant. It is hard and brittle plastic used for many types of boxes, such as CD and DVD cases.
- ✓ Polystyrene "shock" or HIPS (high-impact polystyrene) or acrylonitrile butadiene styrene (ABS) is a copolymer of styrene and polybutadiene. It is the most common of the family of styrenic plastics because it is durable, able to withstand stronger impact than standard polystyrene. This ABS is used by industry for the products (for example shower tubs) which rigid, light and molded. Polybutadiene has been one of the first synthetic elastomers to be invented; it is very similar to the natural rubber.
- ✓ The best-known material for the range of PS is expanded polystyrene (EPS). This polystyrene is solid at 20 °C, pastes at 120 °C and melts at 160 °C. EPS is flammable and combustible compact white foam type. There are two types of EPS, which are molded expanded polystyrene (EPS-M) obtained from a polystyrene "expandable" and the extruded expanded polystyrene (EPS-E). A first expansion is made to water vapor and a resting period allows the pre-expanded pearls of PS to lose their excess water. Finally, they are expanded and molded to water vapor at the desired shape. This material is used to pack the equipment sensitive to shocks and is a very good thermal insulation for the burn plates of the walls.



Figure 2-5: Some main applications of PS (Images of PS, 2018; Polystyrene, 2018).

2.2.1.4 Polycarbonate (PC)

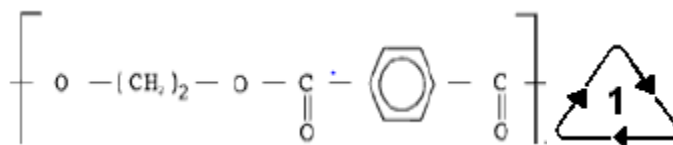
The polycarbonate is a plastic material having excellent mechanical properties and good thermal resistance up to 120 °C. With its chemical formula as shown below, this type of plastic is represented by the number “7” in the code of SPI, corresponding to other variety of resins and composite materials.



PC is used for manufacturing motorcycle helmets and police shields. Since it is very transparent, it is also used to manufacture CDs and DVDs, glazing stop shops to bulletproof and headlights, taillights and turn signals cars. Finally, its physiological neutrality allows its use in the medical field for the manufacture of equipment's and prostheses. By against, PC has poor resistance to prolonged contact with water, chemicals agents and ultraviolet rays.

2.2.1.5 Polyesters and polyethylene terephthalate (PET)

Represented by the number “1” in SPI code, this type of plastic has the following chemical formula shown below



It is a polymer obtained by poly-condensation of two components: dimethyl terephthalate and ethylene glycol. The chains will be arranged and form strong fibers. PET is mainly used for the production of textile yarn, films and bottles. The inventor of PET bottles, Nathaniel Wyeth wanted to make an unbreakable bottle. However, this plastic becomes soft at medium temperature. This property prevents to consign PET bottles since they should be washed at too high temperature. For the same reason, it cannot be used for jams that are hot cast in the pots. There is now a new type of polyester more resistant to heat, which corresponds to the need people are looking for jam jars and returnable bottles. It is polyethylene naphthalate or PEN.

2.2.1.6 Polyacetal or polyoxymethylene (POM):

Polyoxymethylene (or polyformaldehyde), POM as acronym according to ISO 1043, is a polymer from the polyacetals family. It can be found in the form of homopolymer (POMh) or in copolymer form (POMC), the two forms differ slightly. POM is an opaque semi-crystalline material, and its natural color is white but it is often colored. The homopolymer form has slightly better mechanical

properties. The copolymer is the only form that is suitable for continuous use in contact with hot water. POM is used in the production of automotive parts, sports and leisure equipment, electronics, etc.

Polyacetals have properties that make them irreplaceable for pieces with high mechanical requirements such as gears and pulleys. They are solid, have metal qualities such as steel, aluminum or zinc. They are resistant to most chemical agents and have a low coefficient of friction. They have a high density and are relatively low temperature resistance. The Research has been conducted to increase their impact resistance and allow the realization of larger pieces.

2.2.1.7 PVC polyvinyl chloride:

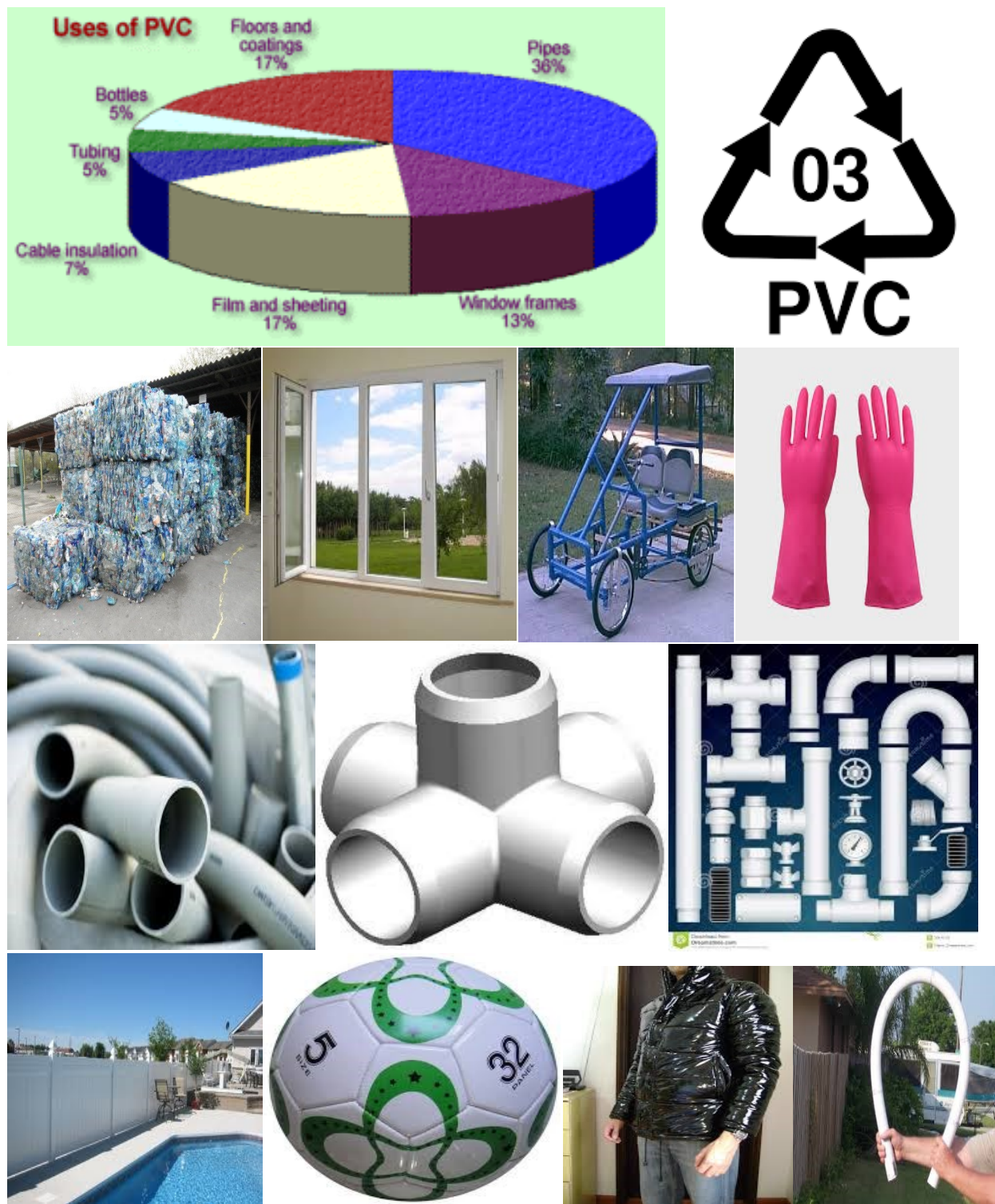
Polyvinyl chloride is a thermoplastic polymer widely consumed, amorphous or poorly crystalline, generally known by the acronym PVC and identified by the number "3" in the synthetic resin coding system. It is prepared from two raw materials: 57% salt and 43% petroleum (PVC, 2018). PVC is the only plastic commonly used constituted by more than 50% of raw material from mineral origin existing abundantly in nature (PVC, 2018). In this form, it is also used in clothing, upholstery industry and other commercial products.

It is obtained by the polymerization of vinyl chloride monomers $\text{CH}=\text{CH}-\text{Cl}$. The polymer of formula $-(\text{CH}_2-\text{CH}-\text{Cl})_n-$ is derived from a chemical reaction between ethylene and hydrochloric acid in the presence of oxygen, it can be either rigid or flexible depending on the ingredients that is incorporated in it. Rigid PVC that has a smooth and hard appearance is used for line pipe, drainage, etc. Flexible PVC, which covers certain parts of articles such as pliers handles, has a shiny appearance. After the plastics PE, PVC is the most widely used plastic in the world. It is widely used in construction or civil engineering (an average of 36% are used for piping) and in the furnishings industry (Images of PVC, 2018; PVC, 2018). Figure 2-6 shows some of its applications.

2.2.1.8 Polyamides (PA):

This is the first plastic material to be discovered in 1938. According to the chain length, different types of PA can be obtained and distinguished by the numbers, for example PA 6.6 is nylon.

These polymers offer a good compromise between various properties (mechanical, thermal and chemical). The polyamides are used for producing molded articles in the automotive and household equipment, carpets and rugs, faucets, locksmith, gears, textile (lingerie and net curtains), etc. The main disadvantage of all polyamides is that they are hydrophilic which limits their use for some mechanical pieces.



2.2.2 The Thermosets

Thermoset plastics are made of polymers which, having undergone a chemical reaction (initiated by heat, catalysts or by UV light), are transformed into a relatively infusible and insoluble material; they take their final form in the first cooling.

The reversibility of the form is impossible because they cannot be soften once molded. Under excessively high temperatures, they degrade and burn (charring). The molecules of these polymers are arranged in long chains in which a large number of strong chemical covalent bonds and three-dimensional network of bonds (crosslinking) cannot be broken easily and get reinforcing when the plastic is heated. The thermosetting material always keeps its shape because of these cross-links and highly resistant bypasses preventing slippage between the chains, and are suited to high-temperature applications up to the decomposition temperature.

The best known of this type are polyurethanes, polyesters, phenoplasts, aminoplasts, elastomers, epoxy and phenolic resins. Initially thermosetting plastics are in the form of powders or resins, which undergo a chemical change during their heating, their cooling or by the action of curing agents.

Adhesives, or thermosetting polymers, are widely used for bonding wood or composite wood-based, in particular, those based on cellulosic fibers. As some examples shown in the Figure 2.7, most resins used in the composites industry are thermosets. Table 2-2 shows the main characteristics of some thermosetting resins.

Table 2-2: Characteristics of some thermoset polymers adapted from (Berreur et al., 2002; Slama, 2008).

Resins	Density (g/cm³)	R (GPa)	FME (GPa)	T_c (° C)
Polyester	1.2	50 – 65	3	120
phenol formaldehyde	1.2	40 – 50	3	120– 150
Epoxide	1.1 – 1.4	50 – 90	3	120 – 200
Polyurethane	1.1 – 1.5	20 – 50	1	100– 120
vinyl ester	1.15	70 – 80	3.5	140

R: Tensile strength; FME: Flexural modulus of elasticity; T_c: content of a continuous heat.



Figure 2-7: Some main applications of thermoset plastics (Images of Thermosets, 2018; Thermodurcissable, 2018).

2.2.2.1 Polyurethanes (PUR):

These materials have varied characteristics with a wide variety of textures and hardness's. Polyurethanes are the most commonly used polymers to make the foams. They are formed by the combination of an isocyanate (organic compound having the sequence $-N = C = O$) and an alcohol (organic compound having one or more carbons bonded to one hydroxyl groups $-OH$) (Figure 2-8). Depending on the chemical associations made with different monomers, we can obtain glue, elastomers, fibers (Lycra) of flexible or rigid foams due to expanding agents, strong and compact polyurethane that can be reinforced by the fiberglass. They are used to make mattresses, car seats, dashboards, wheel roller skates or ski boots.

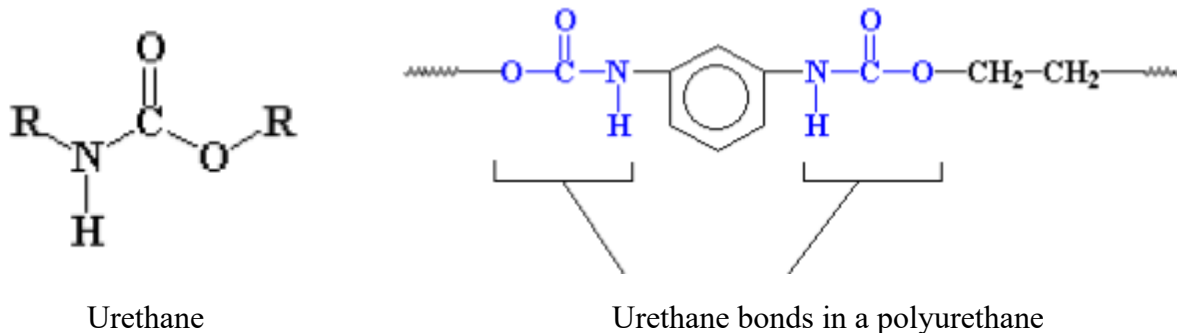


Figure 2-8: Urethane and urethane bonds in a polyurethane

2.2.2.2 Unsaturated polyesters:

The unsaturated polyesters are obtained by condensation reaction between different polyacids and glycols (ethylene glycol, propylene glycol). These products called epoxy are chemical substances, including oxygen bridged on a carbon-carbon bond. They are subsequently diluted in an unsaturated monomer such as styrene. When a catalyst is introduced into the resin, the products are combined causing irreversible hardening called cross-linking which corresponds to the appearance of chemical bonds forming a three-dimensional macromolecular network.

The polyester is mainly used to manufacture artificial textile fibers, the tissues products are patented under the name Dacron, Tergal or Terylene. The polyester fiber is the most produced in the world because of its widespread use in clothing. Its applications are as diverse in the industry, particularly in the form of films for agriculture, public works, cockles and ship cabins, with automotive parks, pools.

2.2.2.3 Phenoplasts (PF):

In this group, one of the oldest known plastic is Bakelite. This providential material has had countless applications in science and in the realization of objects: telephones, radios, etc. These thermosetting resins are highly resistant to chemicals and heat. Electrically insulating, they can be transformed by molding and by compression to make handles for pan, iron and coating plates.

2.2.2.4 Aminoplast (MF)

These resinous products are mainly used in stratification on plasticized textiles, wood agglomerates panels for kitchen cabinets and workbench.

2.2.3 Elastomers

These polymers have the same elastic properties as rubber. An elastomer break consists of long molecular chains folded back on them. Under the action of a stress, the molecules can slide relative to each other and be deformed. In order for the base material to present a good elasticity, it

undergoes vulcanization. This is a cooking process and curing which creates a more or less rigid three-dimensional network without removing the flexibility of the molecular chains. During the vulcanization sulfur, carbon, and various chemical agents are introduced in the elastomer. Different formulations are used to produce synthetic rubbers for specific uses. Elastomers are used in the manufacture of cushions, some insulations, shoe soles or tires (Figure 2-9).

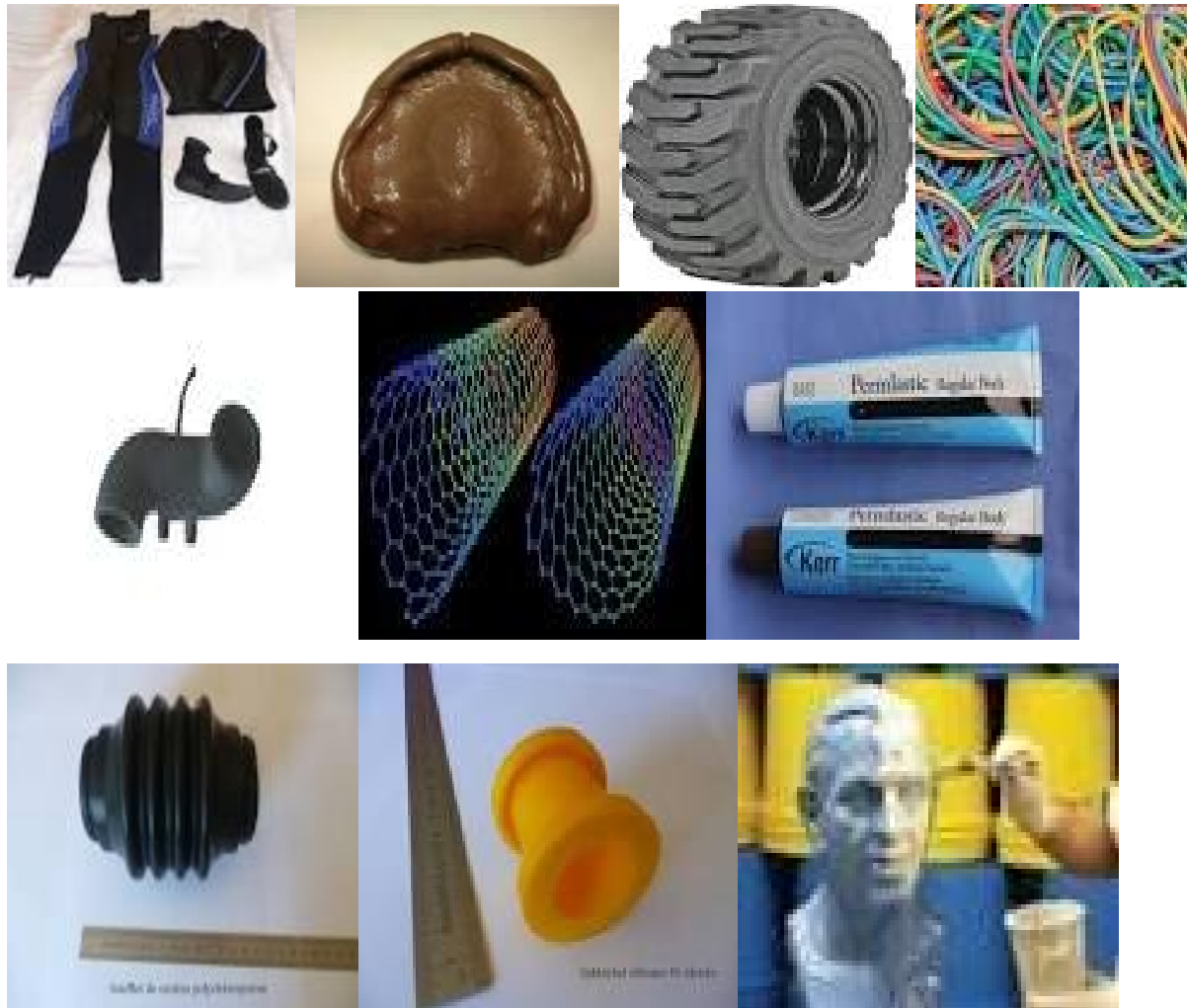


Figure 2-9: Some main uses of elastomers (Elastomer, 2018; Images of Elastomers, 2018).

2.3 Environmental issues

Plastics are prominent in all consumer products and two divergent views exist because of their known properties. However, these same properties such as resistance to physicochemical factors are the main causes for which plastics are reproached on the environmental level.

The presence of plastics dispersed in nature and longevity associated with them create impacts on terrestrial and marine ecosystems. Contamination of the marine environment by plastic is

important; in fact, the deposition of such wastes in the oceans is killing lot of animal species and destroying the flora (Cózar et al, 2014; Jambeck et al, 2015). Fragmented into small parts, plastics can be confused with food and thus enter the food chain. In addition, these plastic particles ingested by small marine creatures can contribute to the concentration of persistent organic pollutants (POPs) in the seas.

The manufacture of plastic products is also linked to oil industries and contribute to the depletion of oil, which is a non-renewable resource. Furthermore, products made from PVC are sometimes stigmatized because they are associated with potentially toxic elements (such as phthalates and chlorine) that are responsible for diseases such as cancer (Barboza et al., 2018; Schwarz et al. 2019; Siedmto, 2019).

On the other hand, some researchers argue that the resistance of the plastic allows it to transport more products per packing unit than other materials (Pratama and Saptoadi, 2014). Films and containers can be slimmer. In addition, the plastic is lighter than other materials used in the packaging, it contributes to reduce the amount of energy required to transportation and thereby reduce emissions of greenhouse gases. In addition, it was pointed out that the total plastic production requires only 4% of global oil reserves. When various wastes materials are transported to the sanitary landfill site, they will have different environmental impact, thus the traditional plastic does not degrade easily, remains stable and inert for long time. The plastic is unlikely to affect the soils, produce greenhouse gases or generate leachate that may affect the water table. Its impact lies primarily in reducing the lifetime of the landfill.

2.4 General overview of plastic waste in municipal solid waste (MSW) stream

An integrated waste management concept is the one, which will have some kind of compromises between the following steps: (i) source reduction; (ii) reuse; (iii) recycling; (iv) landfill and (v) waste-to energy conversion.

As shown in the following Figure 2-10, the major operations involved in a given waste management process may include the collection of the plastic waste outside or inside the municipal waste stream, its disposal in landfills, its energy recovery, recycling into useful products, and the establishment of markets for the recycled products (SANCO, 2019). Each component of the management chain is important in order to reduce as much as possible the nuisances on population and environment for the given part of the process. The following next sections will provide more details about the different parts included in the waste management process.



Figure 2-10: Integrated solid waste management steps (SANCO, 2019)

2.4.1 Collection

The collection of municipal solid waste is a public service that has important impacts on public health and the appearance of towns and cities. In some developing areas, this very important part is not well organized and there are many hazards for the environment and the population. The following Figure 2-11 provides a brief view about MSW of some municipalities in Bamako.

Plastic wastes could be retrieved in two ways by referring to the MSW stream. The first method consists of collecting plastics after they enter the municipal waste stream, and the second method involves collection of plastics before they enter the municipal waste stream. Major part (more than 50% in some countries) of post-consumer wastes end up in the municipal waste stream (Siddique et al., 2008), and plastic wastes in MSW stream are usually very contaminated, that may cause some difficulties for collection and recycling them more economically.

In order to reduce the volume and/or recover the energy content, the wastes are either disposed in landfills or incinerated with some environmental concerns. Conversely, plastic wastes collected outside the municipal waste stream are relatively clean and can be reused or recycled after undergoing some separation and purification processes (Curlee, 1986).



Figure 2-11: Some images to highlight waste management system in Bamako.

2.4.2 Landfilling of plastics wastes

The disposal of plastics in landfills raises some concerns since the material degrades very slowly comparatively to paper and food wastes. Plastic wastes do not create difficulties in landfill operations and do not contribute to the toxicity of leachate from the landfills (Park et al. 1991). Biodegradation (such as incorporating starch additives to the plastic) and photo degradation (such as incorporating photosensitive additives to the plastic) are the two technologies that are being explored for commercial applications. Light and air must be present for these materials to decompose, along with sufficient moisture and nutrients to sustain microbial action (Siddique et al., 2008). These technologies can contribute to increase the long-term risks of contamination for groundwater and soils by the added products to catalyze the decomposition or plastic by-products breakdown, which can become persistent organic pollutants (Jefferson et al. 2009; Jörg et al., 2009).

These requirements are not meet for materials buried in landfills. Accordingly, some researchers do not believe that the use of degradable plastics will help to solve landfill capacity problems (Park et al. 1991). Furthermore, the environmental impact of degradable residues is still not well understood. Moreover, making plastics degradable would lower the quality and performance of the material, therefore would compromise some of its major desirable features in various applications.

Another aspect to take into consideration is the amount of plastics not landfilled and which will generally end up their life in the oceans causing damages on the oceans animals and the quality of marine environment.

2.4.3 Incineration of plastics

The heat content of plastic wastes can be recovered by incineration. Plastic wastes are a good fuel source because most resins have a heating value almost equivalent to that of the coal. In addition to providing an attractive source of alternative energy, preserving natural resources and minimizing the impact of dependency on energy, incineration greatly reduces the volume of garbage by about 90–95% (Siddique et al., 2008). Nevertheless, there is always public resistance emerging against incineration because of the emission of some toxic fumes. However, current technology makes it possible to operate incineration plants in a way that emissions would not be a problem and, therefore, would conform to the Clean Air Act Amendments of 1990 (Alter, 1993).

Two types of ash are produced by incineration process; fly ash (the very fine particles entrained in incinerator exhaust gases) and bottom ash (the large and heavy particles removed from the bed of the incinerator), which require disposal. Landfilling these ash residues may not always be acceptable because of the potential hazards for groundwater and soil pollution, due to leachate carrying heavy metals such as lead and cadmium. Methods of protecting groundwater and soil from leachate, such as lining the landfill, can be expensive and are not always effective from an environmental standpoint. Accordingly, some studies are being undertaken to effectively stabilize and recycle incineration residues in construction applications (Goumans et al. 1991).

2.4.4 Plastics recycling

Plastics recycling have to be taken into consideration in any plastic wastes management program. Recycling contributes to reduce the amount of wastes disposed in landfills; it can also significantly contribute to the conservation of raw petrochemical products, as well as energy savings (Park et al. 1991).

There are several ways to recycle plastic wastes, each of them with their unique advantages and inconvenient. The most common recycling techniques are:

- ✓ Mechanical recycling: Mechanical recycling of plastics refers to processes that involve melting, shredding or granulation of plastic wastes.
- ✓ Chemical or feedstock recycling: Feedstock recycling describes a range of plastic recovery techniques to make plastics, by breaking down polymers into their constituent monomers, which in turn can be used again in refineries, or petrochemical and chemical production.

It has been reported that there are few technological and economic constraints that currently limit the full and efficient recycling of plastic wastes into useful products (Rebeiz and Craft, 1995). Some of these constraints are: (i) contamination of plastic wastes with other materials such as dirt and metals that can damage the equipment used in the reprocessing of the waste; (ii) plastics are not homogeneous materials like aluminum or paper, but consist of a large number of grades with different molecular structures and properties. Each plastic component in a mixed waste has a different melting behavior, rheology, and thermal stability; (iii) plastic mixtures are usually insoluble and form discrete phases within a continuous phase; (iv) plastic waste feedstock is not usually uniform over time and (v) plastic wastes have a relatively low density. Therefore, they are usually compacted or ground-up before transportation to reduce shipping costs.

2.5 Advantages and Disadvantages of plastics

2.5.1 Benefits/advantages of plastics

It is unimaginable to conceive a world without plastic. This material made from petroleum derivatives has literally invaded our daily lives. The considerable growth in the use of plastic is due to its beneficial properties, which include:

- ✓ Extreme versatility and ability to be tailored to meet specific technical needs.
- ✓ Lighter weight than competing materials reducing fuel consumption during transportation.
- ✓ Its unfailing solidity and robustness, allow it to be used for various applications (construction, packaging, etc.)
- ✓ Durability and longevity.
- ✓ Good safety and hygiene properties for food packaging.
- ✓ Excellent thermal and electrical insulation properties.
- ✓ Higher Resistance to chemicals actions, water and other impacts.
- ✓ Relatively inexpensive to produce (comparatively to other materials, it has lesser production cost).
- ✓ Unique ability to combine with other materials like aluminum foil, paper, adhesives.

- ✓ Superior aesthetic appeal.
- ✓ Material of choice, it is inseparable from human life style nowadays.
- ✓ Intelligent features, smart materials and smart systems.

2.5.2 Disadvantages of plastics

The lifetime of the plastic that is an advantage, can also be a disadvantage for the future generations who will suffer from the impact of plastic packaging on the environment. Its chemical components are decried at this moment. Plastics production involves the use of potentially harmful chemicals, which are added as stabilizers or colorants. Many of these have not undergone an environmental risk assessment and their impact on human health and the environment is currently uncertain. Such an example used in the manufacture of PVC is phthalates. In addition, bisphenol A is another one, which is in the center of all scientific discussions about its toxicity (Siddique et al., 2008).

PVC has in the past been used in toys for children and there has been concern that phthalates may be released when these toys are sucked (come into contact with saliva). Risk assessments of the effects of phthalates on the environment are currently being carried out. The disposal of plastics products also contributes significantly to their environmental impact. Because most plastics are non-degradable, they take a long time to break down, possibly up to hundreds of years or more. Although no one knows for certain as plastics have not existed for long enough when they are landfilled. With more and more plastics products, particularly plastics packaging, being disposed soon after their purchase, the landfill space required by plastics wastes is a growing concern. However, the fossil energy will disappear according to some researchers, that will have huge impact on plastic production: no oil, no plastic. Before then, let us try to have alternatives to reduce impacts of plastic related wastes on the environment.

2.6 Conclusion

Considering all the advantages offered by plastic waste products in the world and despite some opinions that stand against these products very often non-biodegradable, humanity will probably have to use these products for a long time. Therefore, engineers and researchers should be ready to get on the line to find alternatives like some countries around the world already started, that will be excellent options to consider in order to protect environment and improve the living conditions especially for the developing areas. One aspect to consider can be the exploration of using plastic wastes to develop cementitious construction materials (concrete, mortar, etc.) in order to better participate in sustainable development and fight against the harmful effects of plastic waste. Several aspects can be addressed (technical, social-economic but especially environmental) in that direction.

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Chapter 3. Review of previous studies on the use of plastics waste in cementitious materials (concrete, mortar)

3.1 Introduction

In this ever-changing world, the density of cities is constantly increasing, that require necessarily to find ways and means to reinforce the convenience in various localities and sectors in order to satisfy the population needs. This involves essential steps contributing to improve the life quality in our cities, including the construction of buildings and road infrastructures that meet the standards but above all accessible to the budget of individuals and/or communities.

Another aspect to take in consideration from the massive movement of the population is the consumption and as the society becomes more modern, the citizens' needs will follow the trend. More consumption will lead to more production of wastes, which can have significant harmful consequences on human and environment if not well managed and disposed. Thus, wastes related problems are part of the daily equation to solve by the authorities, researchers, social scientists and engineers.

That why in recent years, the sector of wastes has gained more attention from decisions makers, some researchers have focused their works on how to recycle and/or reuse certain types of wastes to meet specific needs, inventions or innovations (Peng et al, 1997; De Rezende and de Carvalho, 2003; Widmer et al, 2005). However, it is very important to recognize the existence of huge difference in term of efforts and engagements between countries across the world and the developing countries have not make significant progress in this area. Nevertheless, whether developed countries or developing ones, they all face the challenges of giving a second life to plastic wastes that can remain in nature for more than 100 years without degradation that contributes to pollute the environment and endanger the lives of animals in the oceans.

In this chapter, we will summarize and discuss previous works related to the use of plastics in civil engineering materials, such as concrete and mortar.

3.2 Engineering properties of cementitious construction materials containing plastics

This section includes three major's parts. The first one concerns the review of previous studies on properties (air content, bulk density, slump) of fresh cementitious construction materials (concrete and/or mortar) containing plastics wastes (CCMCP). Then, previous studies on key properties (e.g., compressive and splitting tensile strength, modulus of elasticity, abrasion resistance, permeability) of hardened CCMCP will be discussed. Finally, past studies on special properties of CCMCP will be highlighted and discussed.

3.2.1 Properties of fresh cementitious construction materials that contain plastics wastes

3.2.1.1 Air content

Air content is an important parameter for concrete that can have impact on the concrete workability or allow it to better respond to the effects of freezing-thawing behavior especially in region with winter and summer period.

Choi et al. (2012), and Saikia and de Brito (2005) reported about the air content of concrete containing sand stone coated PET as partial replacement of fine aggregate (Table 3-1). They used four different values of w/c ratio and three different values in term of replacement in percentage (%) of sand by PET aggregates. The air contents of concrete mixes containing PET aggregates were slightly lower than that of the control concrete for the same w/c ratio and a reducing trend has been observed with an increasing PET content in the concrete.

Table 3-1: Air content of fresh concrete, adapted from (Choi et al. 2005; Saikia and de Brito, 2012).

W/C	Sand replaced by PET aggregate (%)	Air Content (%)
0.53	0	4.5
	25	4.2
	50	4.1
	75	4.1
0.49	0	5.0
	25	4.5
	50	4.3
	75	4.2
0.45	0	5.0
	25	4.8
	50	4.0

With the same conceptual idea, Bayasi and Zeng (1993) performed studies to understand the effect of polypropylene fibers on the air content of concrete. For that purpose, seven samples of concrete mixtures reinforced by polypropylene fibers were prepared. The control concrete represented by the Mix 1 is the one without fibers. It has been prepared using 424 kg/m³ of cement content, a water–cement ratio (w/c) of 0.41, an aggregate–cement of 4.0 with 1696 kg/m³ of dry aggregate content and superplasticizer cement ratio of 0.01. From that control concrete, they prepared six other mixtures by reinforcing the control concrete with six different percentages of polypropylene fibers of given dimensions. The following Table 3.2 provides more details about different mixture proportions and some characteristics of polypropylene fibers (length and percentages).

As shown in the Figure 3.1, it has been reported that the air content increased with the inclusion of polypropylene fibers, and no detectable effect on air content of fresh concrete for fibers volume below 0.3%. Soroushian et al (2003) confirmed this result in 2003 for recycled plastic used in concrete.

Table 3-2: Air content properties of polypropylene reinforced concrete adapted from (Bayasi and Zeng, 1993; Saikia and de Brito, 2012)

Mix no.	Fiber length (mm)	Fiber volume fraction (%)	Air content (%)
1 ^a	-	0	2.0
2	12.7	0.1	1.5
3	12.7	0.3	2.5
4	12.7	0.5	4.5
5	19.0	0.1	1.5
6	19.0	0.3	3.5
7	19.0	0.5	5.0

^a Mix 1 is the control mix in which there are no fibers (consists of cement content 424 kg/m³, water–cement ratio = 0.41, aggregate–cement = 4.0, dry aggregate content = 1696 kg/m³, superplasticizer cement ratio = 0.01).

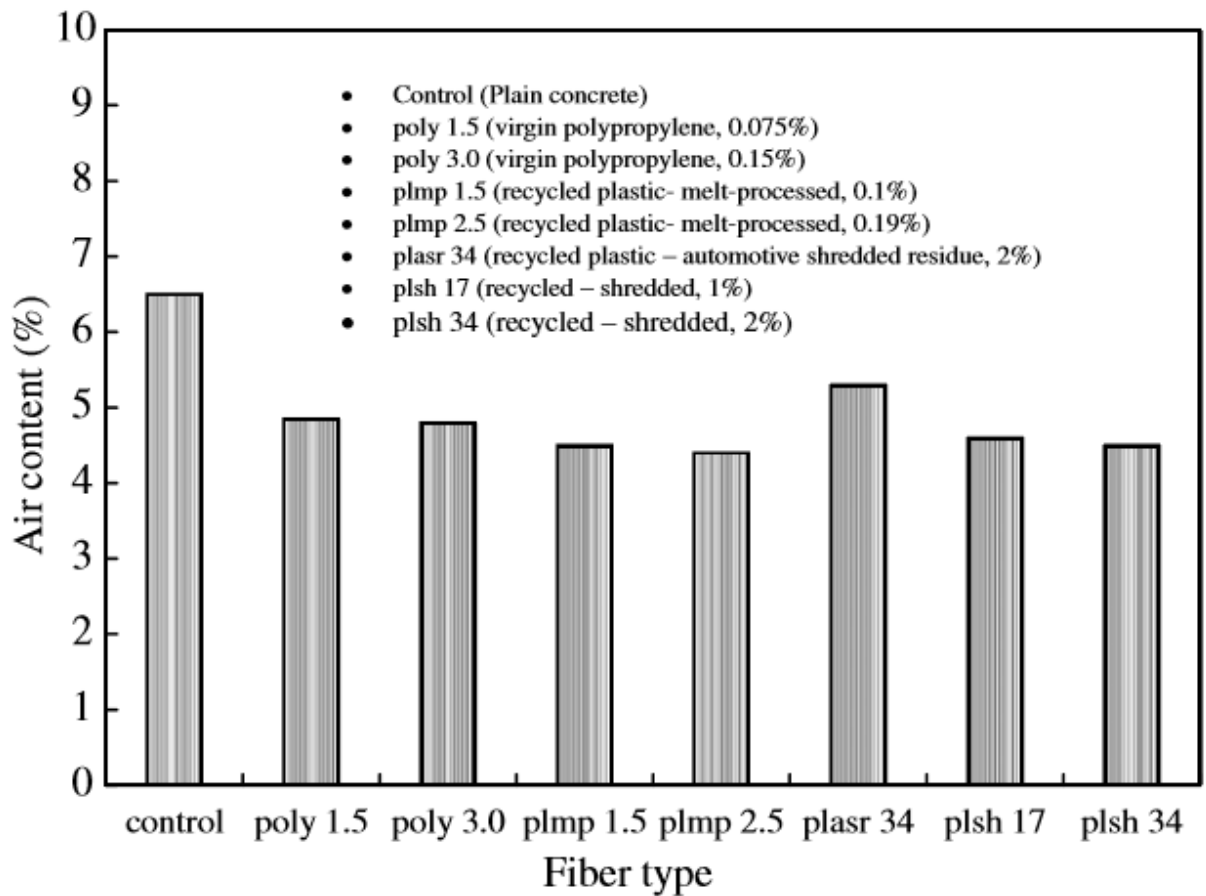


Figure 3-1: Air content versus plastic fiber type adapted from (Saikia and de Brito, 2012; Soroushian et al. 2003).

3.2.1.2 Bulk density

Due to the lightweight nature of plastic aggregates, many authors arrived to the conclusion that the fact to introduce plastic aggregates in given concrete would generally generate decreases of fresh and dry densities of the corresponding concrete. This behaviour is not dependent on the size and the substitution quantity of plastic aggregates (Al-Manaseer and Dalal, 1997; Choi et al. 2005; Hannawi et al. 2010; Ismail and AL-Hashmi, 2008; Kou et al. 2009; Marzouk et al. 2007; Wang Choi et al. 2009).

Al-Manaseer and Dalal (1997) investigated the effect of plastic aggregates on the bulk density of concrete. By using angular post-consumer plastic aggregates having a maximum size of 13 mm, twelve (12) concrete mixes were made with different w/c and having various percentages (0%, 10%, 30%, and 50%) of plastic aggregates. Some major conclusions came out from their works. Firstly, an increase in plastic aggregates content leads to the decrease of the concrete bulk density (Figure 3.2) and the reduction in bulk density was directly proportional to the plastic aggregates content. In addition, the density was reduced by 2.5%, 6%, and 13%, respectively, for concrete containing 10%, 30%, and 50% of plastic aggregates, and the reduction in density was attributed to the lower unit weight of the plastics.

Choi et al. (2005) studied the effects of polyethylene terephthalate (PET) bottles lightweight aggregates (WPLA) on the density of concrete. Mixture proportions of concrete were planned so that the water – cement ratios were 45%, 49%, and 53%, and the replacement ratios of WPLA were 0%, 25%, 50%, and 75% by volume of fine aggregates. They have been able to observe the decreasing of the concrete mixtures density with the increase in WPLA content (Choi et al., 2005).

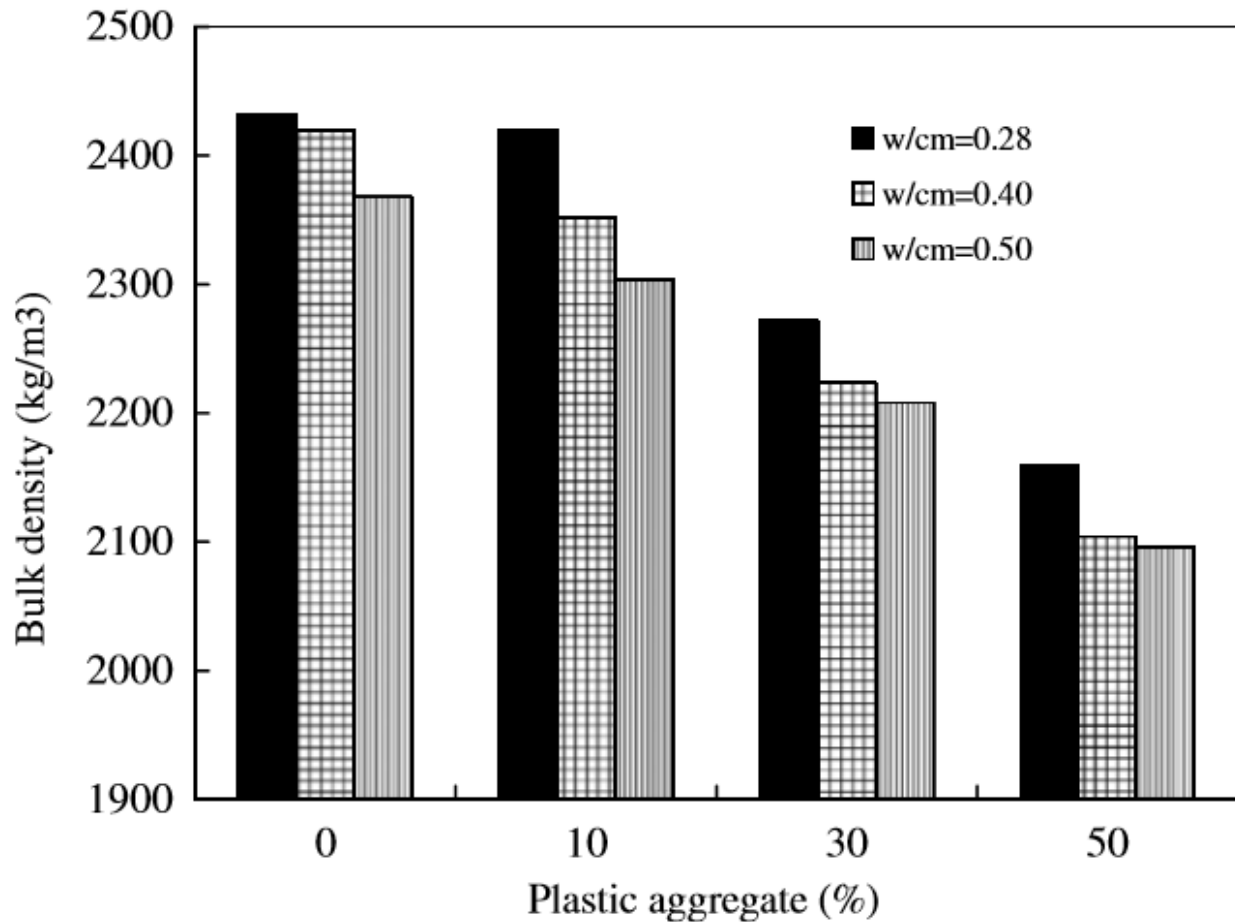


Figure 3-2: Bulk density versus plastic aggregates percentage (Al-Manaseer and Dalal, 1997).

Hannawi et al (2010) reported the fresh and dry densities of concrete containing PET wastes and polycarbonate (PC) wastes as aggregates. They arrived to the results that fresh and dry densities decrease while plastic aggregates content increases. The dry density decreased from 2173 kg/m³ for mixes containing 0% of plastic aggregates to 1755 kg/m³ for mixes containing 50% of PET and 1643 kg/m³ for mixes containing 50% of PC plastic aggregates. These values were lower than 2000 kg/m³, the minimum dry density required for structural lightweight concrete according to RILEM LC2 classification. When 50% of fine aggregates has been replaced by PET and PC respectively, that contributed to reduce the dry density by up to 19% and 24% in reference to the density of normal concrete with 0% of replacement. That decrease mainly was attributed to the lower specific weight of the plastic particles according to the authors.

Ismail and Al-Hashmi (2008) reported the fresh density of concrete containing plastic as fine aggregate. Their results indicated that the fresh density of concrete containing 10%, 15%, and 20% of plastic aggregates as a replacement of fine aggregates tends to decrease by 5%, 7%, and 8.7% respectively, below the reference concrete without any replacement.

Saikia and de Brito (2014) observed a reduction of concrete fresh density with an increase of embedded PET aggregates volume in the corresponding concrete. The authors found a trend of this density reduction for three different types of PET aggregates used in their investigations. Density for the use of pellet plastic aggregates was found to be the smallest followed by the ones from fine fraction of flaky plastic aggregates and the density results were the highest when using coarse fraction of flaky plastic aggregates.

Marzouk et al (2007) reported about the bulk density of cement mortar mixes prepared by replacing 0 to 100% in volume of sand by two different sizes of PET aggregates. Their results showed small reduction of bulk density when the volume occupied by aggregates varies between 0% and 30%, regardless of their size. However, when this volume exceeded 50%, the composite bulk densities started to decrease until reaching a value of 1000 kg/m³. They also found that for the same volumetric percentage of substitution the bulk density decreased with decreasing particle size.

Fraj et al (2010) observed a significant reduction in fresh density and 28-day air-dried density of concrete containing coarse rigid polyurethane (PUR) foam waste aggregates due to the lower density of the PUR foam aggregates. According to the authors, the fresh densities of different concrete mixes containing dry and water saturated PUR foam aggregates can be considered as lightweight concrete and these values were 27 – 33% lower than the control concrete's density. The density values decreased as foam proportioning increased.

3.2.1.3 Slump

Slump tests, inverted slump cone and K-test, are commonly used for measuring the workability or consistency of fresh concrete mix. Workability of concrete is defined as the ease with which concrete can be mixed, flowed, transported, filled the form/molded properly with the desired vibration and without reducing the concrete's quality (placed and finished easily without segregation).

There are two main opinions about the workability behaviour of concrete containing plastic aggregates. Many researchers arrived to the result that the slump value of fresh concrete having several types of plastic aggregates is lower than that of the conventional concrete mix. Also, an addition of more plastic aggregates content in the concrete, contributes to further decrease the slump value of the fresh concrete (Batayneh et al. 2007; Frigione, 2010; Ismail and AL-Hashmi, 2008; Kou et al. 2009; Mounanga et al, 2008). The reasons for the lower slump value of the concrete mix containing plastic aggregates are the sharp edges and angular particle size of plastic aggregates.

On the other hand, some research found an increase in the slump value when incorporating plastic aggregates in the concrete (Al-Manaseer and Dalal, 1997; Choi et al. 2005; Wang Choi et al. 2009). Unlike natural aggregates, plastic aggregates cannot absorb water during mixing; this will lead to have more free water in the concrete, thus the increasing of the slump of concrete mixes containing plastic aggregates.

Bayasi and Zeng (1993) studied the effects of polypropylene fibers on the slump and inverted slump cone of various concrete mixes. The results, given in Table 3.3 reported the following remarks: (i) increasing of inverted slump cone values; (ii) for fiber volume fractions less than or equal to 0.3%; fiber effect on fresh mix workability is insignificant and rather inconsistent. (iii) for fiber volume of 0.5%, however, fibers appeared to adversely affect fresh mix workability, more evident by the increase in inverted slump cone for 19 mm fibers with a more pronounced effect than that of 12.7 mm fibers (Saikia and de Brito, 2012).

Table 3-3: Air content, slump and inverted slump properties of polypropylene reinforced concrete ((Bayasi and Zeng, 1993) adapted from (Saikia and de Brito, 2012)).

Mix no.	Fiber length (mm)	Fiber volume fraction (%)	Slump (mm)	Inverted slump cone (s)
1 ^a	-	0	216	-
2	12.7	0.1	241	-
3	12.7	0.3	203	-
4	12.7	0.5	191	14
5	19.0	0.1	267	-
6	19.0	0.3	241	-
7	19.0	0.5	25	18

^a Mix 1 is the control mix in which there are no fibers (consists of cement content 424 kg/m³, water–cement ratio = 0.41, aggregate-cement = 4.0, dry aggregate content = 1696 kg/m³, superplasticizer cement ratio = 0.01).

Al-Manaseer and Dalal (1997) determined the slump of concrete mixes made with plastic aggregates. Table 3.4 shows the cone and K–slump data for all mixes. The following points were reported in their research: (i) increasing in slump according to plastic aggregates incorporation in concrete. The concrete containing 50% of plastic aggregates had a slightly higher cone slump than the concrete without plastic aggregates. (ii) K–slump consistency results showed a similar behaviour (pattern) to that obtained from the cone slump. Plastic aggregates neither absorbed nor added any water to the concrete mix. Due to this non-absorptive characteristic, concrete mixes containing plastic aggregates will have more free water. Consequently, the slump increased.

Soroushian et al. (2003) reported reduction in slump with the use of recycled plastic in concrete. Slump test results are shown in Figure 3-3, which allow to see an evident slump loss with addition of any plastic discrete reinforcement. While non-slender plastic particles, automobile shredded residue, and flakes were used at dosages that were in order of magnitude of those of slender fibers, their effects on fresh mixture properties were comparable. This could be attributed to the pronounced adverse effects of highly slender fibers on fresh mixture workability. Mehta and Monteiro (1993) concluded that the slump loss reduced the efficiency of air entrainment in the fresh concrete.

Table 3-4: Cone and K-slump data ((Al-Manaseer and Dalal, 1997), adapted from (Siddique et al., 2008)).

Plastic aggregate (%)	Cone Slump (mm)*			Consistency (mm)*			Workability (mm)*		
	w/cm	w/cm	w/cm	w/cm	w/cm	w/cm	w/cm	w/cm	w/cm
	0.28	0.40	0.50	0.28	0.4	0.50	0.28	0.40	0.50
0	178	190	-	65	70	70	50	55	55
10	-	190	-	60	73	65	55	60	45
30	178	-	-	75	70	75	60	45	50
50	206	216	-	73	83	80	55	60	50

*Definitions given in Al-Manaseer and Dalal (1997) and Siddique et al. (2008)

Choi et al. (2005) investigated the influence of polyethylene terephthalate (PET) bottles lightweight aggregate (WPLA) on the workability of concrete. Mixture proportions of concrete were planned for various water–cement ratios (45%, 49%, and 53%) and different WPLA replacement ratios (0%, 25%, 50%, and 75%) by volume of fine aggregates. They reported that slump value of waste PET bottles lightweight aggregate concrete (WPLAC) increased with the increase in water–cement ratio and the replacement ratio. The improvement ratios of workability represent 52%, 104%, and 123% in comparison with that of normal concrete at the water–cement ratios of 45%, 49%, and 53%, respectively. This may be attributed to not only the spherical and smooth shape but also to the absorption properties of WPLA.

In the same order of idea, Wang Choi et al. 2009 reported an increase in the slump value of concrete with increasing content of two types of treated PET-bottle aggregate in concrete. The aggregates were spherical in shape. According to the authors, this trend is due to the spherical shape of the PET aggregates as well as the slippery surface texture, which decreases the inner friction between the mortar and the PET aggregates and therefore increases the slump value.

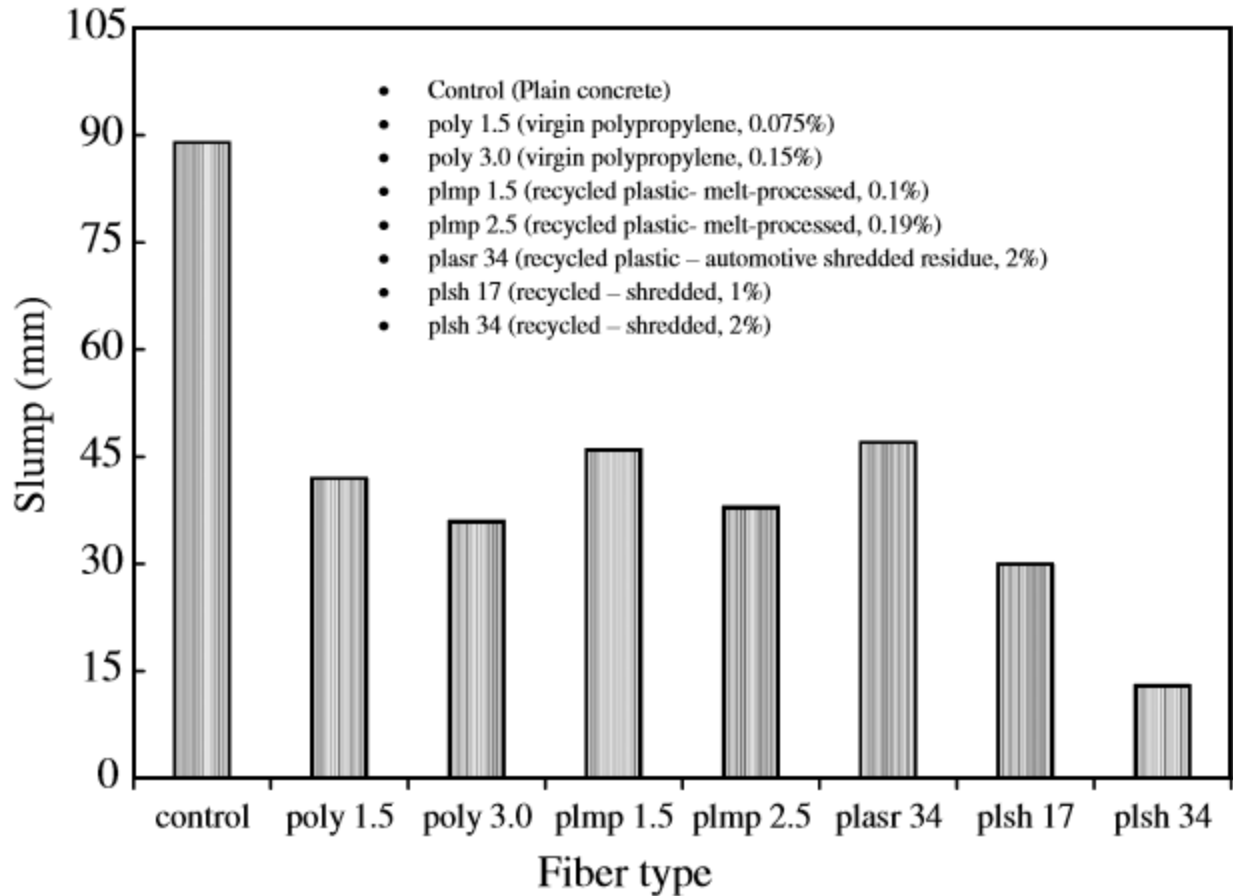


Figure 3-3: Slump test versus plastic fiber type (Soroushian et al, 2003).

Batayneh et al. (2007) investigated the effect of ground plastic on the slump of concrete. They replaced fine aggregates in concrete with plastic particles by the replacement ratio up to 20%. Their research outcomes showed the following remarks: (i) decreasing in the slump with the increasing in the plastic particle content; and (ii) for 20% replacement, the slump decreased to 25% of the initial slump value with 0% of plastic particle content. This decrease in the slump value is due to the shape of plastic particles, because the plastic particles have sharper edges than the fine natural aggregate. Since the slump value at 20% plastic particle content is 58 mm, this value can be considered acceptable and the mix can be considered workable.

Saikia and de Brito (2012) found two types of workability behaviour in concrete mixes containing two differently shaped PET aggregates. In their work, a pellet-shaped PET aggregate with very smooth surface texture and two different size fractions of a flaky PET aggregates were used to partially replace coarse and fine sized natural aggregates. All the PET aggregates were obtained from the same type of plastic waste materials.

To achieve a constant slump value, the concrete mix containing pellet plastic aggregate required a slightly lower w/c value and the concrete mixes containing the two flaky plastic aggregates with different particle size required much higher w/c values than that required by the concrete mix containing natural aggregate. On the other hand, a substantially higher w/c value was obtained for

the concrete mix containing coarse flaky PET aggregates than that observed for the concrete mix containing fine flaky PET aggregates.

This clearly indicated that the addition of pellet PET aggregates increased the slump value of the resulting concrete mix, due to its spherical nature and smooth surface texture. The decreasing slump values due to the addition of fine and coarse flaky plastic aggregates were attributed to the sharper edges of PET aggregates in reference to the natural aggregates (NA). Moreover, in comparison to NA, these flaky aggregates are angular and non-uniform in nature.

The addition of some types of plastic aggregates such as rigid polyurethane foam waste or heat-treated expanded polystyrene foam (MEPS) decrease the slump value of the resulting concrete mix due to the presence of large amounts of pores surface in these aggregates (Fraj et al. 2010; Kan and Demirboğa, 2009; Mounanga et al. 2008).

3.2.2 Properties of hardened cementitious construction materials that contain plastics wastes

3.2.2.1 Compressive strength

Several studies revealed that the incorporation of plastic aggregate decreases the compressive strength of the resulting concrete/mortar, (Al-Manaseer and Dalal, 1997; Babafemi, 2018; Gesoglu et al. 2017; Islam et al. 2016; Jacob-Vaillancourt and Sorelli, 2018; Kou et al. 2009; Nabajyoti and Jorge, 2012; Saikia and de Brito, 2012; Saikia, and de Brito, 2014; Siddique et al., 2008; Slama, 2008; Subramanian, 2000; Wang Choi et al. 2009). The factors responsible for low compressive strength of concrete containing plastic aggregate can be: (1) the very low bond strength between the surface of the cement paste and the plastic wastes, or low strength of the interfacial transition zone between plastic materials and cement paste; (2) the hydrophobic behaviour of plastic wastes, which contributes to inhibit cement hydration reaction by restricting water movement; (3) lower stiffness and strength for plastic aggregates by comparison to natural ones which can be considered as weak zone (or stress concentration area) allowing damage propagation; (4) increased in air content and less absorption capacity, which will accumulate more water in the transition area between various components causing more pores in the materials and decrease the compressive strength.

Albano et al (2009) reported that concrete with 10% of recycled PET exhibits a compressive strength that meets the standard strength values for concrete with moderate strength (21-30 MPa at 28 curing days). According to the authors, there is no big difference between the compressive strength values at 28 days and 60 days. They identified many factors responsible for lower compressive strength of concrete containing PET aggregate than concrete containing natural aggregates. Some of these factors are low workability, particle size, the failure type and the formation of honeycombs. The reduction in compressive strength was more pronounced in concrete containing larger flaky PET aggregates than smaller ones. Saikia and de Brito (2014) observed similar trends in compressive strength for concrete containing fine and coarse flaky PET

aggregates, which was mainly due to the loss of workability of the concrete mix due to the shape of the PET aggregates, especially for larger particles.

In 1993, Bayasi and Zeng reported the effects of polypropylene fibers on the compressive strength of concrete. Table 3.5 summarizes some of the compressive behaviour characteristics such as compressive strength, strain at peak stress and compressive toughness index for various samples with different plastic contents. According to their results, the 12.7 mm long polypropylene fibers improved the compressive strength of concrete when used at volumes less than 0.5% without adverse effects on the workability. Compressive toughness index, which is the quotient of the total compressive energy absorbed (total area under compressive stress–strain curve) by the pre-peak compressive energy absorbed (area under the stress–strain diagram up to peak stress). From the compressive test results, Bayasi and Zeng (1993) concluded that 19 mm polypropylene fibers had no obvious effect on the compressive strength of concrete. However, 19 mm fibrillated polypropylene fibers enhanced the energy absorption and an increasing of concrete toughness characteristics under compression. An evident increase in compressive toughness index of concrete derived from their works as the result of fiber addition.

Batayneh et al. (2007) also observed a reduction in the compressive strength of concrete due to the addition of plastic wastes as a partial substitution of fine aggregates. For 20% replacement compressive strength shows a sharp reduction up to 72% of the original strength and for 5% replacement, the compressive strength drops by 23%. Similar behaviour, but in a lower effect, was observed in both the splitting and flexural strengths of the tested samples. According to the authors, this reduction in strength was due to the fact that the strength of the plastic particles is lower than that of the natural aggregates. Ismail and Al-Hashmi (2008) reported that the compressive strength of concrete prepared by replacing 10%, 15% and 20% of fine natural aggregate by PET aggregates are lower than the compressive strength of concrete containing only natural aggregates, but higher than the minimum compressive strength required for structural concrete, which is 17.24 MPa. Thus, their use can be allowed and respect the structural conditions.

Table 3-5: Hardened concrete properties of polypropylene fiber reinforced concrete (Siddique et al., 2008; adapted from Bayasi and Zeng, 1993).

Mix No.	Fiber length (mm)	Fiber Volume fraction (%)	Compressive behaviour characteristics		
			Strength (MPa)	Strain at peak	Toughness index
1	-	0	39.5	0.0016	1.167
2	12.7	0.1	46.9	0.0019	1.173
3	12.7	0.3	46.9	0.0017	2.031
4	12.7	0.5	38.3	0.0022	1.243
5	19.0	0.1	37.2	0.0017	1.451
6	19.0	0.3	40.0	0.0021	1.440
7	19.0	0.5	38.6	0.0017	1.600

Al-Manaseer and Dalal (1997) investigated the effects of inclusion of plastic aggregates on the compressive strength of concrete. By using different w/c ratios for various plastic aggregates content in concrete mixtures, they arrived to the following results as shown by the Figure 3.4. By analyzing that graph, they observed a decrease of compressive strength when plastic aggregates content increased. An increase of w/c ratio for any given plastic aggregates content was found to lead to the decrease of the compressive strength. Figure 3.5 shows the percentage of reduction in the compressive strength due to the addition of plastic aggregates with various w/c ratios. In general, the rate of reduction in strength was found to decrease with the increase in plastic aggregates content. It has been observed 34%, 51%, and 67% reduction in the compressive strength for concrete containing 10%, 30%, and 50% plastic aggregates, respectively. The reduction in the compressive strength due to the addition of plastic aggregates might be due to either a poor bonding between the cement paste and plastic aggregates or to the low strength that characterizes plastic aggregates (Al-Manaseer and Dalal, 1997).

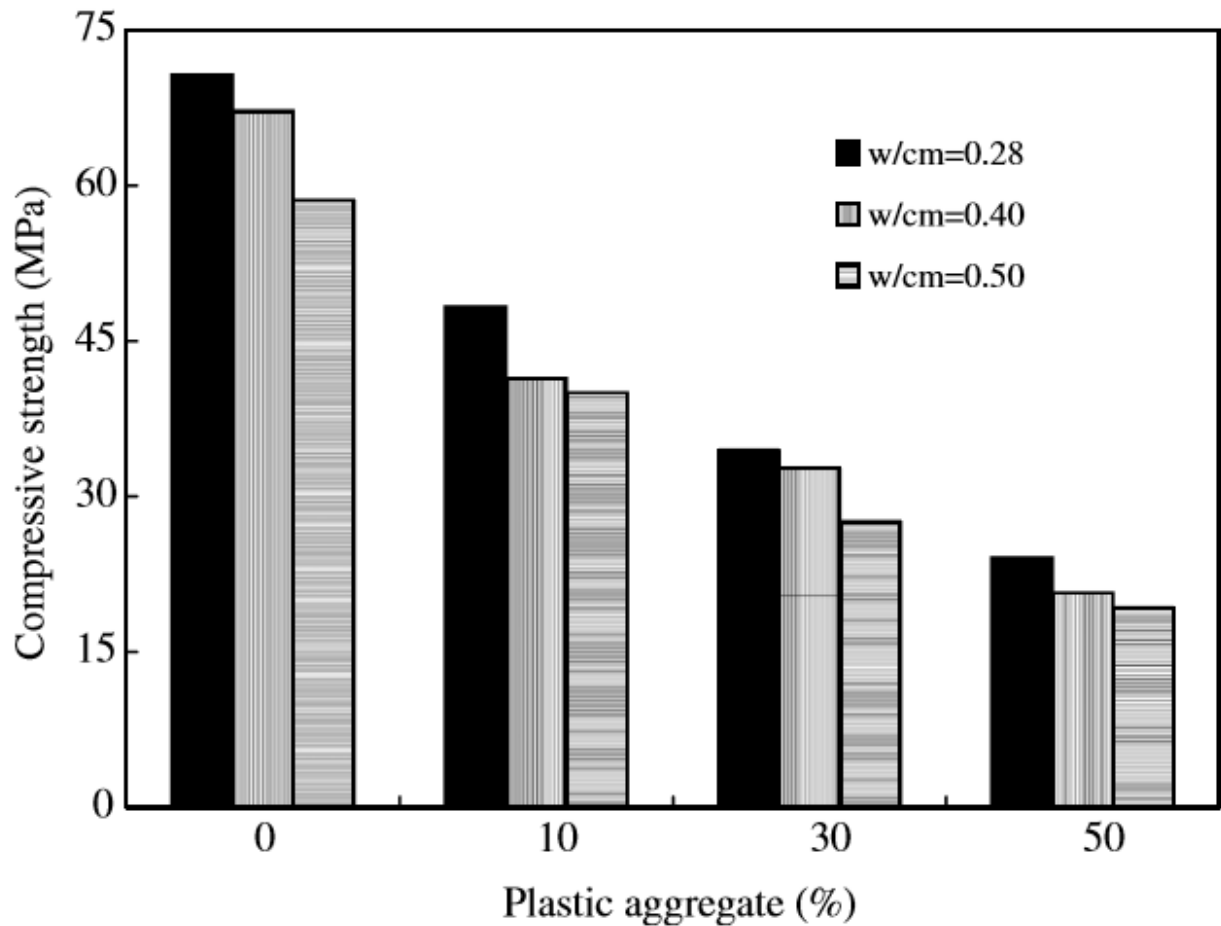


Figure 3-4: Compressive strength versus plastic fiber percentage adapted from (Al-Manaseer and Dalal, 1997; and Siddique et al., 2008).

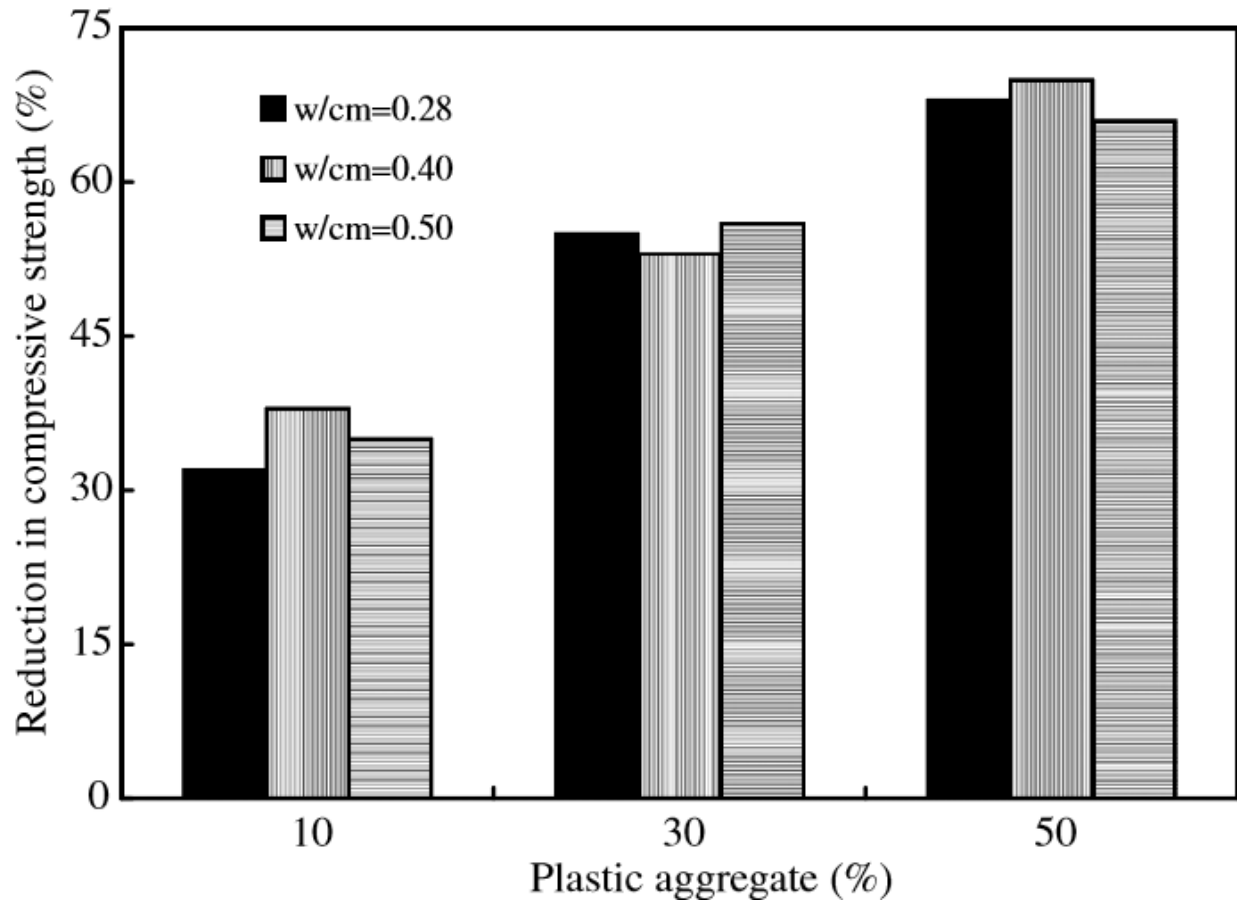


Figure 3-5: Percentage reduction in compressive strength versus plastic fiber percentage adapted from (Al-Manaseer and Dalal, 1997; and Siddique et al., 2008).

Choi et al. (2005) studied the effects of polyethylene terephthalate (PET) bottles lightweight aggregate (WPLA) on the compressive strength of concrete. Mixture proportions of concrete were planned so that the water–cement ratios were 45%, 49%, and 53%, and the replacement ratios of WPLA were 0%, 25%, 50%, and 75% by volume of fine aggregate. Analysis of compressive strength test results given in the Table 3.6 leads to the following observations: (i) compressive strength of concrete mixtures decreased with an increase in PET aggregates; and (ii) for a particular PET aggregate content, compressive strength increased with the reduction in w/cm ratio (Choi et al., 2005).

Table 3-6: Hardened concrete properties (Siddique et al., 2008; adapted from Choi et al., 2005)

w/c ratio	PET aggregate (%)	Compressive strength (MPa)		
		3 days	7 days	28 days
53	0	18.4	24.0	31.5
	25	17.6	23.4	29.7
	50	17.1	21.5	26.3
	75	14.8	19.2	21.8
49	0	19.0	27.8	34.6
	25	18.8	26.7	33.7
	50	18.6	24.3	29.1
	75	15.8	21.6	23.2
45	0	24.8	31.3	37.2
	25	23.2	27.4	33.8
	50	22.0	26.5	31.8
	75	20.7	24.8	24.9

Frigione (2010) prepared a concrete mixture by replacing 5% in weight of natural fine aggregate by PET waste aggregate (PETW). He observed slightly lower compressive strength for concrete containing PETW than natural aggregate concrete. The compressive strength of both concrete having and without PETW aggregate was observed to increase between 28 - 365 days. The considerable difference in strength between concrete containing PETW aggregate and that of the normal concrete having natural aggregate was observed for low cement content and/or high values of the w/c ratio. According to the author, this is due to the higher content of bleeding water in concrete mixes containing PETW than the samples made with the conventional concrete mix. The water in the concrete mix containing PETW is located mostly around the PETW aggregate particles and produced a weaker bond between the cement matrix and PETW materials.

Kou et al (2009) reported that the compressive strength of concrete containing PVC granules derived from scraped PVC pipes decreased with the increase in PVC granules content. The reduction in 28- day compressive strength of the lightweight concrete mixes prepared by replacing 5%, 15%, 30% and 45% of natural fine aggregate by PVC granules were respectively 9.1%, 18.6%, 21.8% and 47.3% with respect to the control mix. According to the authors, the main reasons behind the strength reduction were the lower elastic modulus of PVC aggregate compared to the normal fine aggregate and the higher particle size of PVC aggregates in reference to the natural fine aggregate. In addition, the low bonding strength between PVC aggregate and cement paste due to internal bleed water from the fully saturated lightweight aggregates that accumulated and surrounded the PVC granules have contributed to decrease the strength.

Hannawi et al (2010) made some cement mortar samples containing PET and polycarbonate (PC) aggregates by replacing sand at different rates: 3%, 10%, 20% and 50%. They studied the compressive strength at 28 days for various samples. A decrease in compressive strength was observed when the amount of plastic aggregates in mortar increased. For the same substitution rate, the reduction in compressive strength of the mortar containing PET aggregate was greater

than that of the mortar having PC aggregate. For the different plastic aggregate content i.e. 3%, 10%, 20% and 50%, they observed a decrease in compressive strength by comparison to the reference concrete with natural aggregate. The decreasing rates for different aggregate contents were 9.8%, 30.5%, 47.1% and 69% for PET; and 6.8%, 27.2%, 46.1% and 63.9% for PC. The compressive strength of the mortar was proportional to the dry unit weight.

Marzouk (2007) studied the innovative use of consumed plastic bottle waste as sand-substitution aggregate within composite materials for building application. Polyethylene terephthalate (PET) bottles were used as partial and/or complete substitutes for sand in concrete composites. The same volume of granulated plastic with different sizes of PET aggregates substituted various volume fractions of sand varying from 2% to 100%. They arrived to the following conclusions: (i) when the sand volume replaced by plastic aggregates increased from 0% to 50%, the 28-days compressive strength of mortar containing plastic aggregate decreased slightly by 15.7% in comparison to the reference mortar with 0% of plastic. However, when the rate of substituted aggregate exceeded 50%, the mechanical properties including compressive strength dropped sharply; (ii) substituting sand below 50% by volume with granulated PET, whose upper granular limit equals 5 mm, affected neither the compressive strength nor the flexural strength of composites; (iii) plastic bottles shredded into small PET particles may be used successfully as sand-substitution aggregates in composite concrete. These composites appeared to offer an attractive low-cost material with consistent properties, which can be very useful for solving solid waste problems, and reduce energy consumption.

Akcaozoglu et al (2010) investigated the utilization of shredded polyethylene terephthalate (PET) bottle granules from waste collection system as a lightweight aggregate in mortar preparation using two types of binders: normal Portland cement (NPC) and 50:50 mixture of blast furnace slag (bfs) and NPC. The authors found the compressive strength of mortar containing PET aggregate higher for the binder prepared using NPC-bfs than the same property for only NPC mortar.

Fraj et al (2010) compared the concrete containing rigid polyurethane (PUR) foam with a size of 8–20 mm and the control concrete made with natural aggregate; they observed the decreasing rates between 57% and 78% for the 28-days compressive strength. That difference was due to the lightweight nature of the concrete as well as the low mechanical properties and the high porosity of PUR foam aggregate according to the authors. When pre-wetting the PUR foam aggregate, this leads to increase the concrete porosity, thus further lowers the compressive strength. On the other hand, they observed that, the addition of superplasticizer gave the possibility to decrease cement content by 15% and increase PUR foam content by 33%, which allowed to have an acceptable reduction (15%) of compressive strength. The concrete containing dry PUR foam aggregate almost satisfied the criteria of structural lightweight aggregate concrete as defined in ACI 318 and ASTM C 330.

Mounanga et al. (2008) reported that water curing of concrete containing PUR foam aggregate and normal aggregate slightly contribute to improve the compressive strength compared to the corresponding value after dry-state curing. For normal lightweight concrete the increase in strength was about 69% and this improvement for concrete containing 13.1%, 21.2% and 32.7% in volume of PUR foam aggregate was 39%, 34% and 5% respectively.

Laukaitis et al. (2005) found that the compressive strength of the composite depends on the density of the composite and the type of granules used. For the purpose of their experiments, composite concrete samples were prepared using crumbled recycled foam polystyrene waste as well as spherical large and fine blown polystyrene waste as granular additive. For the same density for various composite concrete with different plastic aggregate, the results showed the higher compressive strength for the fine granules; followed by the large granules, which had also higher strength than the samples containing crumbled granules. According to the authors, the higher compressive strength of composite containing fine granules was due to the formation of uniform monolithic bulk structure with uninterrupted pores where the fine polystyrene granules were evenly spread. On the other hand, the structure of the composite containing large granules was damaged, and the pores were partially disintegrated.

Soroushian et al. (2003) demonstrated that compressive strength of concrete decreased with the inclusion of recycled plastic in it. In their experiments, nine samples were made, three specimens per mixture, three replications of each mixture. According to the test done on those samples, the average values and 95% confidence intervals were determined for more precisions about the results as shown in the Figure 3.6. All mixtures containing slender fibers (poly, and plmp) showed a slight increase in compressive strength. The mixtures containing non-slender fibers (plasr and plsh) showed a relatively small (approximately 5%) loss in compressive strength, which could be attributed to the relatively low elastic modulus of these non-slender fibers.

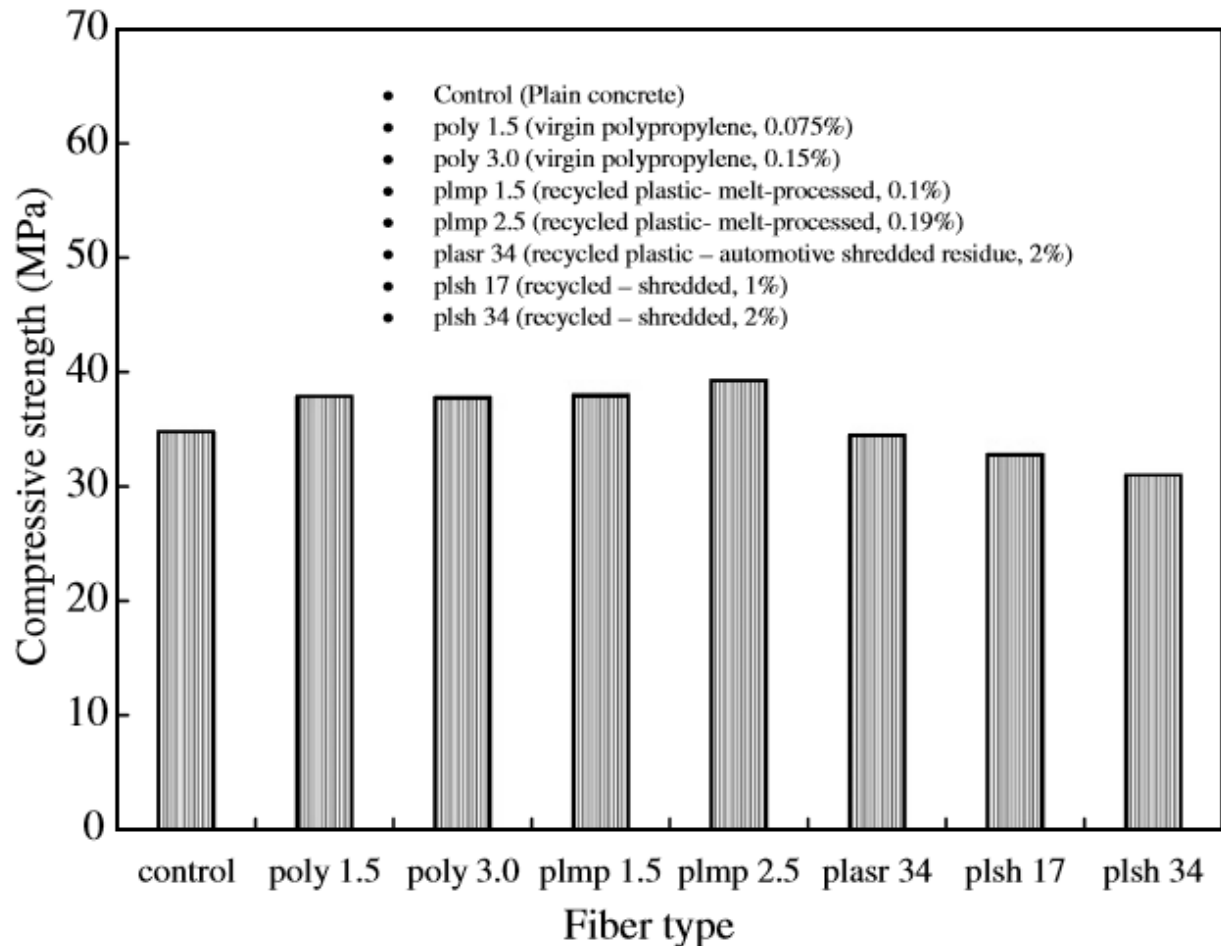


Figure 3-6: Compressive strength versus plastic fiber type ((Soroushian et al., 2003); adapted from (Siddique et al., 2008)).

3.2.2.2 Splitting tensile strength

As for the compressive strength, the incorporation of any type of plastic aggregate contributes to decrease the splitting tensile strength of concrete. For various authors in the literature, the causes for the reductions observed in splitting tensile strength were similar to those used to explain the decrease in compressive strength due to the incorporation of plastic aggregate.

Al-Manaseer and Dalal (1997) studied the effects of plastic aggregates on the splitting tensile strength of concrete. The splitting tensile strength of concrete made with different w/c ratios and various percentages of plastic aggregates were tested during their works in lab. The details of the results are shown in Figure 3.7. Several conclusions have been deduced after analysis: (i) splitting tensile strength decreased with the increase in plastic aggregates percentage (the splitting tensile strength was found to decrease by 17% for concrete containing 10% plastic aggregates); (ii) for a given plastic aggregate content, the splitting tensile strength was found to decrease when w/c increased; and (iii) splitting failure of concrete samples having plastic aggregates did not exhibit the typical brittle failure observed in the case of conventional concrete with natural aggregates. As

for compression load samples, the splitting tensile had a gradual failure mode. In general, the samples containing plastic aggregates were found to have more resisting capacity to the splitting load after failure without full disintegration. The failure was found to be more ductile when the percentage of plastic aggregates increased.

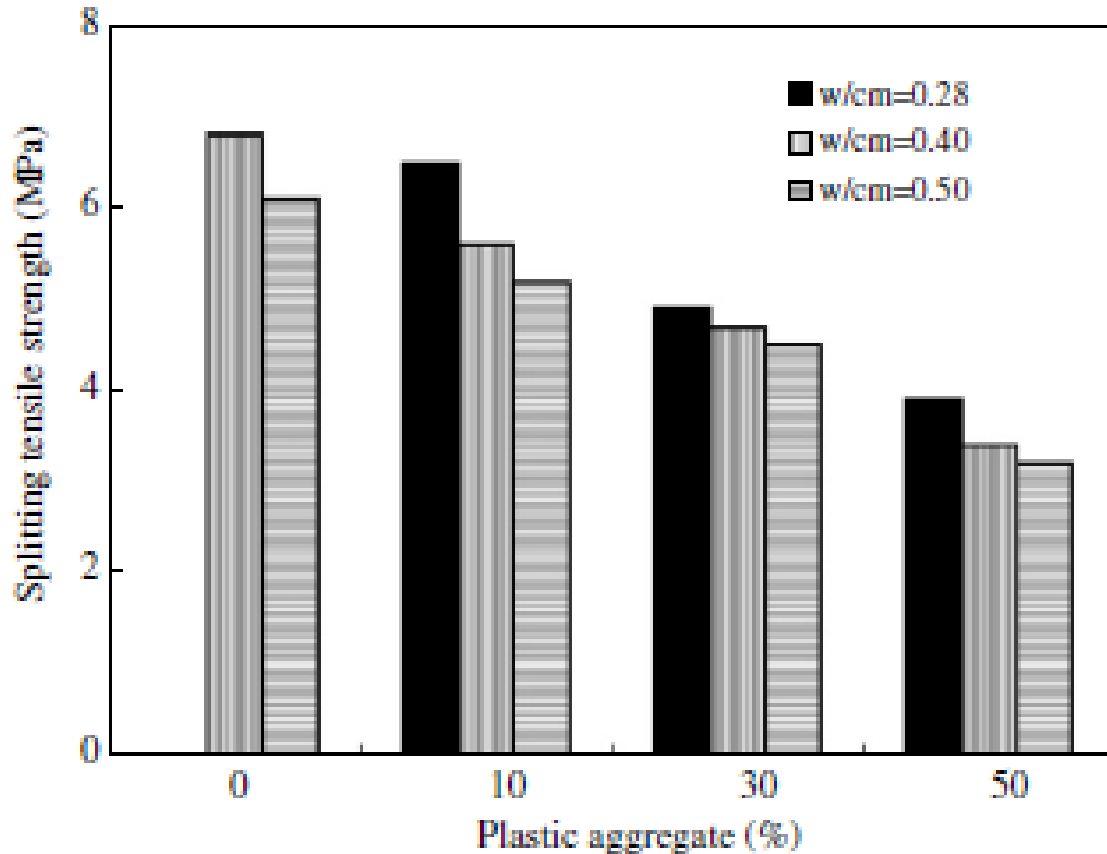


Figure 3-7: Splitting tensile strength versus plastic aggregate percentage ((Al-Manaseer and Dalal, 1997), adapted from (Siddique et al., 2008)).

Choi et al. (2005) studied the influence of polyethylene terephthalate (PET) bottles lightweight aggregate (WPLA) on the splitting tensile strength of concrete. Mixture proportions of concrete were planned in a manner to have 45%, 49%, and 53% as the water– cement ratios values and the replacement ratios of WPLA were 0%, 25%, 50%, and 75% by volume of fine aggregate. Splitting tensile strength test results are given in Table 3.7. According to these data, it is clear that: (i) the splitting tensile strength of concrete mixtures decreases with the increase in PET aggregates; and (ii) for a particular PET aggregate content, splitting tensile strength increased with the reduction in w/c ratio.

Table 3-7: Hardened concrete properties ((Choi et al., 2005; adapted from Siddique et al., 2008).

w/c ratio	PET aggregate (%)	Split tensile strength (MPa)	Modulus of elasticity (10 ³ MPa)
53	0	3.27	23.5
	25	2.65	23.0
	50	2.25	21.2
	75	2.04	18.5
49	0	3.27	23.3
	25	2.76	22.8
	50	2.35	18.1
	75	1.94	16.7
45	0	3.32	25.5
	25	2.80	18.7
	50	2.55	17.3
	75	2.04	15.6

Frigione (2010) reported that the composite concrete having PET had high splitting tensile strength when a reduction will happen for the w/c ratio. Kou et al (2009) observed a reduction of the splitting tensile strength with an increase in PVC content in a manner similar to that found for the compressive strength. According to them, the splitting tensile strength of concrete is influenced by the properties of the interfacial transition zone (ITZ); therefore, the smooth surface of PVC particles and the free water accumulated at the surface of PVC granules could cause a weaker bonding between the PVC particles and the cement paste. Albano et al (2009) fix as the main reasons of the decrease in splitting tensile strength, the increased porosity of concrete caused by the incorporation of PET aggregate as well as the increase in w/c ratio. Kan and Demirbog (2009) also reported that the increasing of heat-treated expanded polystyrene (MEPS) aggregate in concrete would generate the decreasing of its splitting tensile strength. This behaviour is due to the generation of more porosity because of the incorporation of MEPS. Saikia and de Brito (2014) also arrived to find lower 28-day tensile strength for concrete containing three differently shaped PET aggregates by reference to the concrete containing natural aggregates. The authors also observed that the concrete cylinders having flakier PET aggregate did not split into two fractions after determination of tensile strength, which is generally the case for cylinders containing natural and pellet plastic aggregates, since the flaky-shaped plastic aggregate can act as a bridge between the two split pieces.

Kou et al (2009) found an excellent correlation between the 28-day splitting tensile and compressive strength for concrete containing PVC aggregate as replacement of fine natural aggregate. The correlation shown in the Figure 3.8 follows a linear relationship. Choi et al (2005) also found the following expression, $f_{st} = 0.23 \cdot f_c^{(1/3)}$ as the relationship between the 28-day compressive strength and the splitting tensile strength for concrete containing PET aggregate; and $f_{st} = 1.40 \cdot (f_c/10)^{(1/3)}$ as similar relationship for conventional concrete. Figure 3.9 below shows the details graphs for the two relationships.

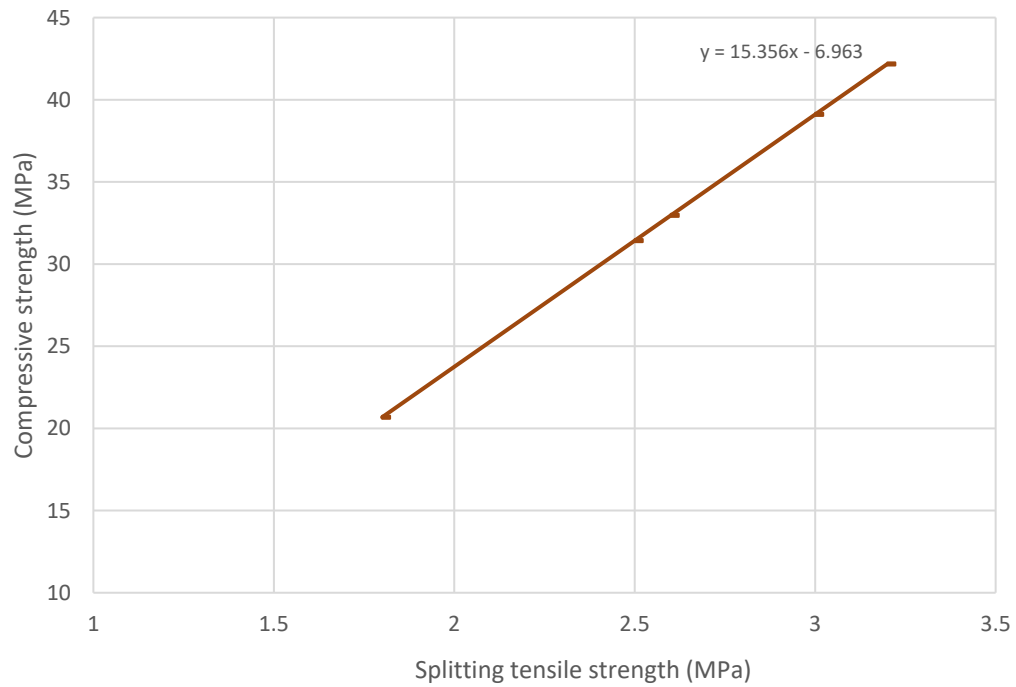


Figure 3-8: Relationship between the compressive strength and the splitting tensile strength of concrete containing PVC aggregate (adapted from Kou et al. 2009).

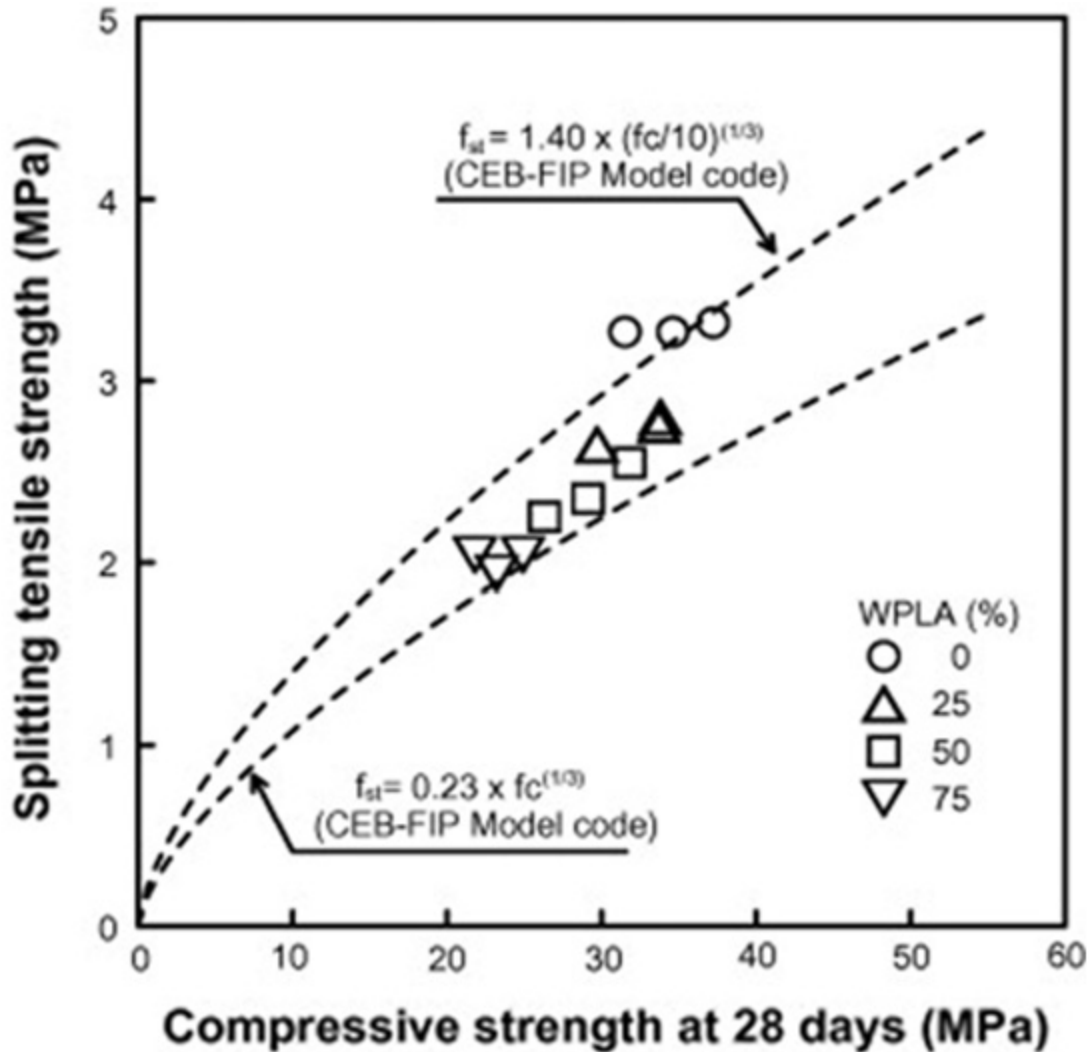


Figure 3-9: Relationship between the compressive strength and the splitting tensile strength of concrete containing PET aggregate (Choi et al. 2005).

3.2.2.3 Modulus of elasticity

Al-Manaseer and Dalal (1997) reported the effects of plastic aggregates on the modulus of elasticity of concrete. Figure 3.10 shows the details results of the modulus of elasticity for concrete with different percentages of plastic aggregates. They have been able to derive the following remarks: (i) Modulus of elasticity decreased with the increase in plastic aggregate content. (ii) Depending on the w/c value, modulus of elasticity varied between 24.3 GPa for concrete without plastic aggregates (w/c = 0.28) to 8.6 GPa for concrete containing 50% of plastic aggregates (w/c = 0.50). (iii) Usually, the increasing of w/c ratio in concrete corresponded to the decreasing of the modulus of elasticity.

Choi et al. (2005) investigated the effect of polyethylene terephthalate (PET) bottles lightweight aggregate (WPLA) on the modulus of elasticity of concrete. Mixture proportions of concrete have

been done in order to get the water–cement ratios values of 45%, 49%, and 53%, and the replacement ratios of WPLA were 0%, 25%, 50%, and 75% by volume of fine aggregate. They arrived to the conclusion that the modulus of elasticity of concrete mixtures decreased with the increase in PET aggregates.

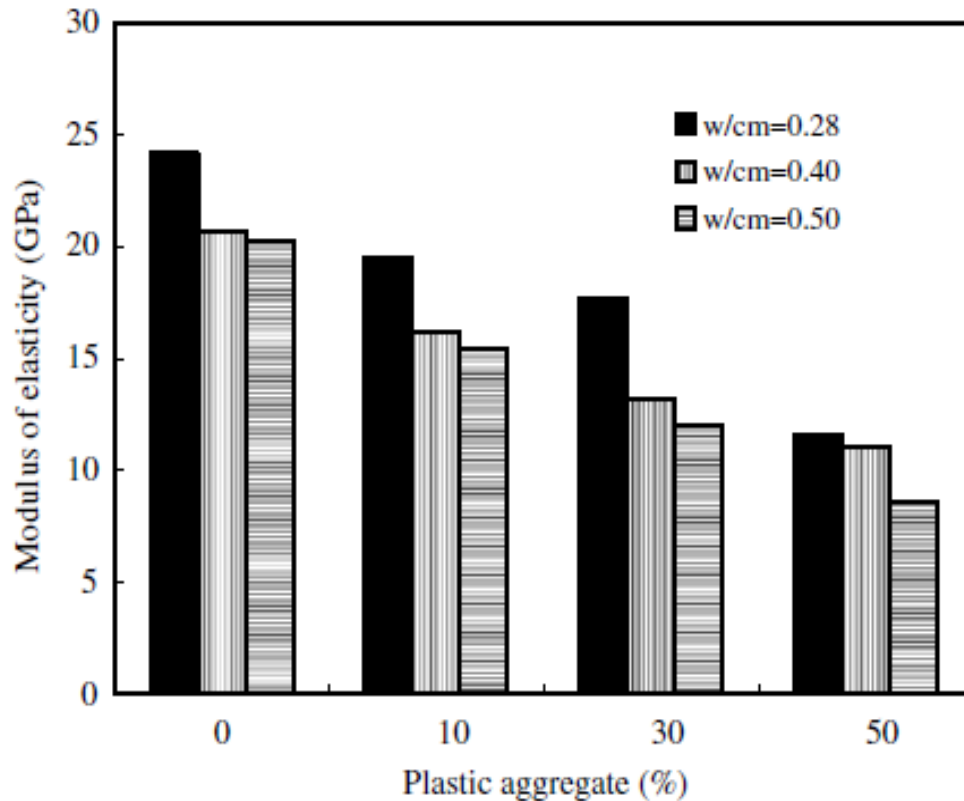


Figure 3-10: Modulus of elasticity versus plastic fiber percentage (Al-Manaseer and Dalal, 1997).

Albano et al (2009) used three fractions of PET waste aggregate to prepare the concrete with two different w/c ratios and two natural fine aggregate replacement levels. They arrived to the following conclusions: (1) higher elasticity modulus was observed for concrete having 10% of PET comparatively to 20% when dealing with fixed plastic particle size. This behaviour can be explained by the fact that, PET is less resistant than natural sand and would deform less when an equivalent stress is applied. (2) For the same quantity of PET, the particle size did not have strong effect on the elasticity modulus of the concrete. (3) For various w/c values, the trends obtained were similar for given plastic particle size and various PET contents. (4) Because of the greater porosity in the concrete prepared at higher w/c value, higher modulus of elasticity was observed for concrete prepared at w/c of 0.50 followed by the one with w/c ratio of 0.60.

Laukaitis et al (2005) determined the elastic modulus of composites prepared by using three types of polystyrene waste beads. Their results indicated that the modulus of elasticity depended on the density of composite and the type of beads.

Saikia and de Brito (2014) also found lower the elasticity for concrete containing three differently shaped PET waste aggregates comparatively to the concrete containing natural aggregate. According to them, this behaviour caused by the incorporation of PET aggregates is due to the lower modulus of elasticity of PET aggregate than that of the natural aggregate and the generation of higher porosity due to the higher w/c value.

The increasing of PVC aggregate in the concrete will reduce its elastic modulus (Kou et al. 2009). The replacement rates of 5%, 15%, 30% and 45% of fine aggregates by PVC granules was observed to reduce the elastic modulus by 6.1%, 13.8%, 18.9% and 60.2%, respectively, when compared to the control concrete with natural aggregates. According to the authors, the major causes of this reduction were (1) elasticity modulus of PVC granules was found to be lower than that of the cement paste; (2) also compressive strength of the concrete containing PVC was lower than that of the normal concrete.

3.2.2.4 Abrasion resistance

Abrasion resistance is the ability of a fabric (concrete, mortar, pavement, etc.) to resist surface wear caused by flat rubbing contact with another material. The procedures of ASTM C944/C944M-12, which is similar to Procedure B of ASTM C779/C779M provides the standard guidelines for abrasion resistance of concrete or mortar surfaces by the rotating-cutter method.

Soroushian et al. (2003) investigated the effect of recycled plastic on the abrasion resistance of concrete; details of their results are shown in the following Figure 3.11. The authors found a reduction of the abrasion resistance of concrete due to the incorporation of plastic waste fiber in concrete. However, other authors arrived to the conclusion that the incorporation of the commercial plastic aggregate in concrete improved the abrasion resistance of the resulting concrete (Nasvik, 1991; Saikia, and de Brito, 2014). They arrived to the conclusion that the abrasion resistance of concrete containing pellet PET aggregate increased with the increasing of plastic content. On the other hand, for the mixes containing two types of flaky aggregates the best results were obtained for 10% substitution level.

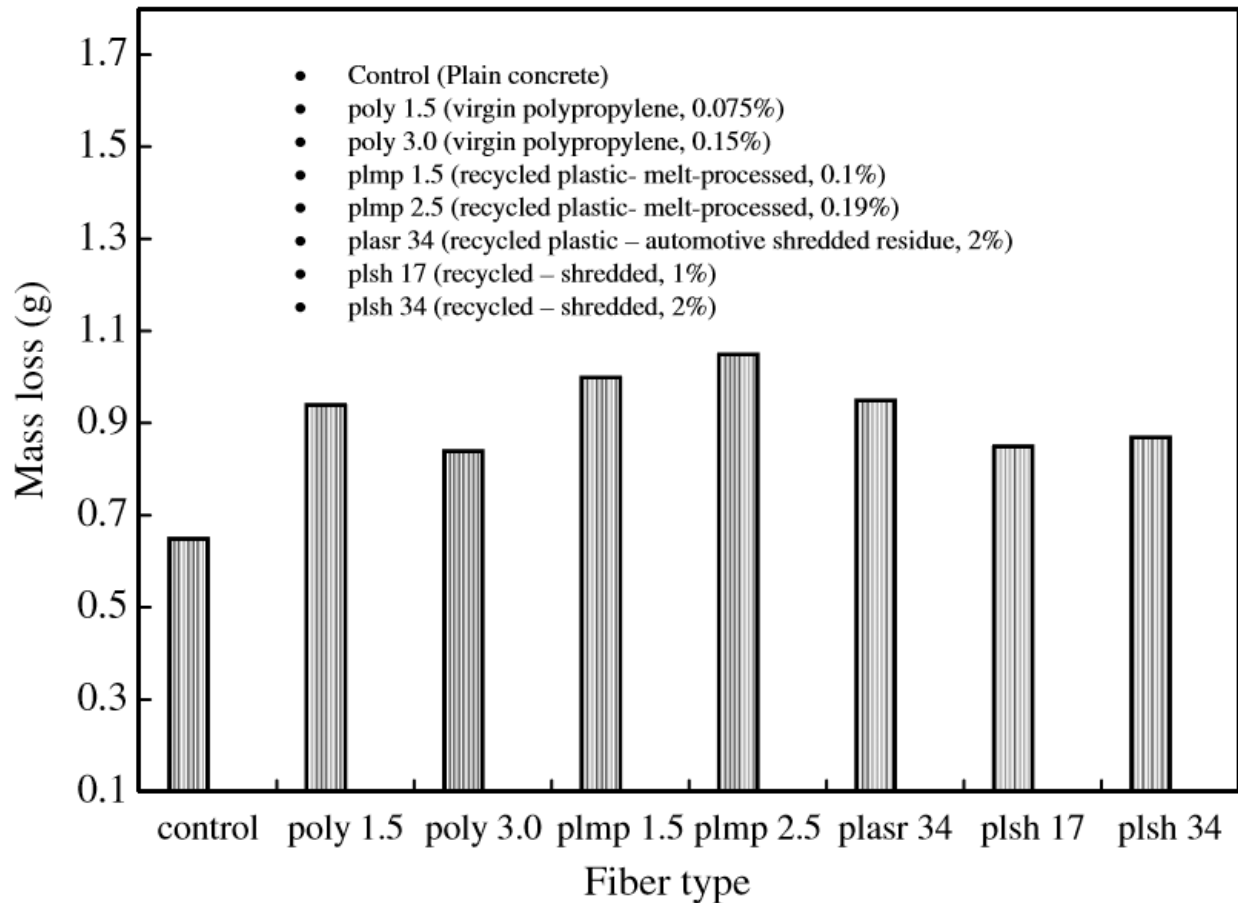


Figure 3-11: Abrasion resistance versus fiber type (Soroushian et al. 2003).

3.2.2.5 Durability and permeability properties

By against to the mechanical behaviour, there is less information about the durability and permeability performance of concrete or mortar containing plastic as aggregate. Some factors like water absorption and sorptivity, shrinkage, carbonation resistance, chloride ion permeation and resistance against freezing and thawing are evaluated in the sense to have clear idea about durability and permeability behaviour of concrete containing plastic aggregate.

From Bayasi and Zeng (1993) research results about the effect of recycled plastic on the permeability of composite concrete, it was observed a significant increasing of the concrete permeability with an inconsistent effect on the volume fraction of permeable voids for 19-mm polypropylene fibers. While 12.7-mm long fibers somewhat increased the permeability of concrete and tend to decrease the volume of permeable voids. More details about the results for permeability and permeable voids volume from their tests are given in the following Table 3-8.

Table 3-8: Hardened concrete properties of polypropylene fiber reinforced concrete adapted from (Bayasi and Zeng, 1993; Siddique et al, 2008).

Mix No.	Fiber length (mm)	Fiber Volume fraction (%)	Permeability, coulombs	Permeable voids (%)
1	-	0	3678	15.3
2	12.7	0.1	6770	15.0
3	12.7	0.3	4830	14.4
4	12.7	0.5	6796	13.0
5	19.0	0.1	8614	14.4
6	19.0	0.3	11905	17.1
7	19.0	0.5	8332	12.1

Albano et al (2009) reported higher water absorption for concrete containing PET aggregate than the concrete made using only natural aggregate. The water absorption was found to increase when the PET aggregate rate and/or size increase in the concrete, also the increase in w/c ratio was found to lead to the same result.

Marzouk et al (2007) observed that the volumetric substitutions of plastic aggregate lower than 100% decreased the rate of water adsorption with respect to the reference mortar without plastic aggregate. The sorptivity was found to further decrease when the rate of plastic aggregate replacement increased up to 50%. At the conclusion of their works, they revealed that the concrete containing plastic aggregate is stronger than the reference sample without plastic in term of durability performance when they are exposed to aggressive solutions.

Choi et al (2005) by measuring the sorptivity coefficient at 28-days cured cement mortars having sand powdered coated PET aggregate, indicated that the sorptivity of cement mortar containing PET aggregate at 25% replacement level was lower than the control mortar without plastic and for 50% and 75% replacement level it was higher than the control mortar. According to them, at 50% and 75% replacement level, the size changing of the fine aggregate mixture contributed to increase the inside porosity of mortar and thus increased its sorptivity.

At 3% of replacement level of the sand by PET or PC waste aggregate, Hannawi et al (2010) did not observed influence either on water absorption or on apparent porosity of the composites in comparison with the control mortar. However, water absorption and apparent porosity were found to increase with the increase in plastic content.

Kan and Demirboga (2009) reported the freeze and thaw resistance of concrete containing modified expanded polystyrene foam (MEPS) as partial or full substitution of fine and coarse natural aggregates. The following remarks were made: (1) by increasing the MEPS aggregate ratio in the mixtures, the concrete is expected to exhibit a higher frost resistance and have a higher durability; (2) coarse lightweight MEPS aggregate is more susceptible to the freeze–thaw cycles when compared to the fine lightweight aggregate.

3.2.2.6 Influence of time and temperature

According to Rebeiz (1995), the compressive strength of composite concrete was found to increase with the age and to decrease with the increase in temperature when recycled polyethylene terephthalate (PET) was used. Figure 3.12 provides more information about the effect of time dependency on the compressive strength of polymer concrete (P-C). Polymer concrete (P-C) achieved more than 80% of its final strength in one day. Conversely, normal cement concrete usually achieves about 20% of its final strength in one day (Rebeiz, 1995; Rebeiz and Craft, 1995). The early strength gain is important for precast applications because it permits the structures to resist large early stresses due to transportation and erection operations. The good compressive strength of P-C allows the use of thinner sections in precast components, thus contribute to reduce dead loads in structures at the same time minimizing transportation and erection costs. The effect of temperature on the compressive strength of P-C is shown in Figure 3.13. It is evident from the figure that an increase in temperature resulted in strength loss. This behaviour can be explained by the fact that resin binder decreases in strength with an increase in temperature; also the synthetic viscoelastic resin binder used in producing P-C is more temperature-sensitive than the inorganic cement binder used for producing normal cement concrete (Rebeiz, 1995).

Byung-Wan et al. (2006) studied the mechanical properties such as the compressive strength, the splitting tensile strength and the flexural strength of polymer concrete using an unsaturated polyester resin based on recycled PET. At 7 days, they concluded that the polymer concrete using resin based on recycled PET achieved compressive strength of 73.7 MPa, with the flexural strength of 22.4 MPa, the splitting tensile strength of 7.85 MPa, and an elastic modulus of 27.9 GPa. Some relationships have been developed between the compressive strength of polymer concrete and other properties such as elastic modulus, flexural strength, and splitting tensile strength. The use of recycled PET in polymer concrete helps in reducing the cost of the material, saving energy from construction field and contribute in solving some solid waste related problems especially the concerns about plastics products.

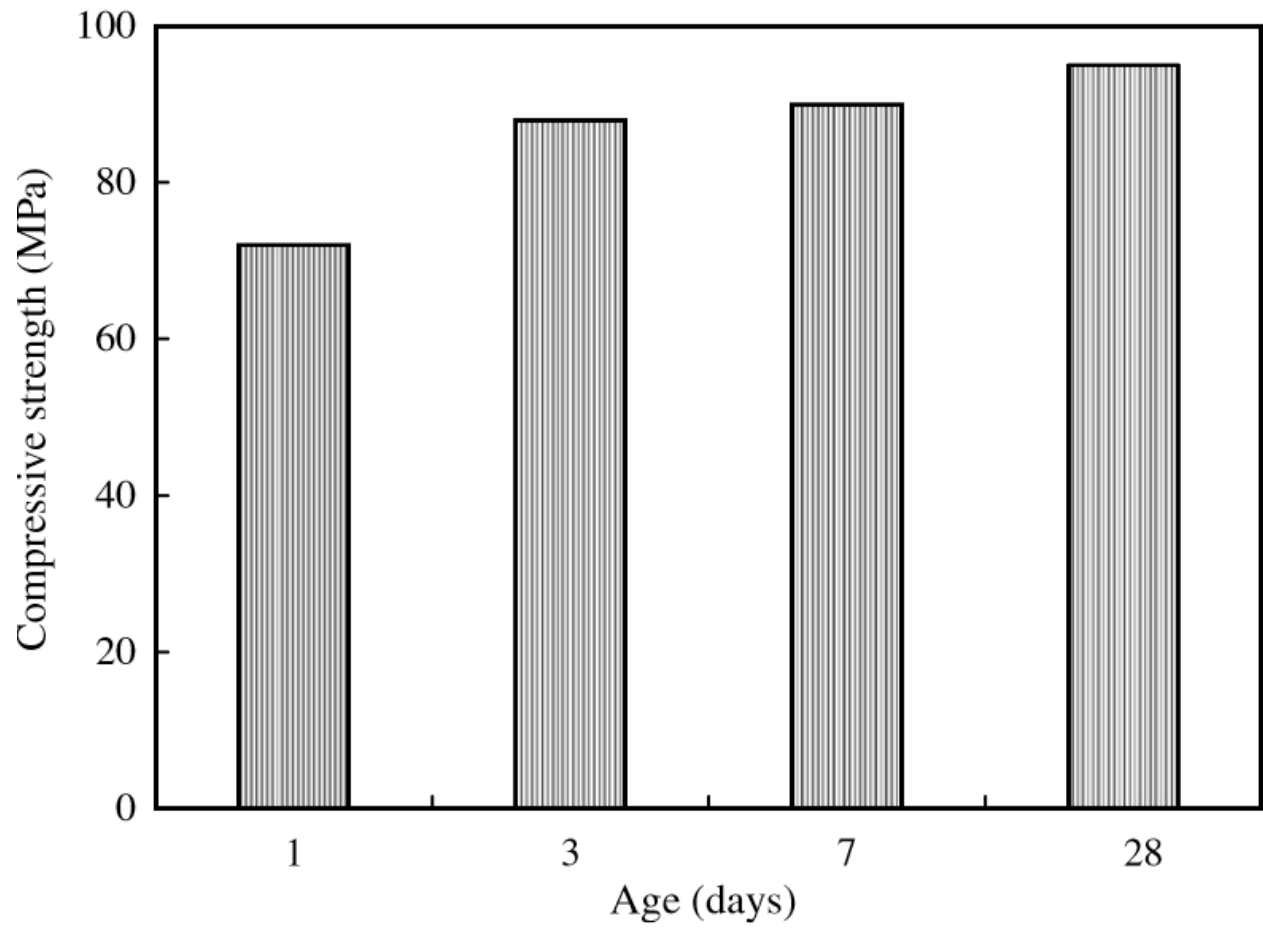


Figure 3-12: Compressive strength versus age of P-C (Rebeiz, 1995).

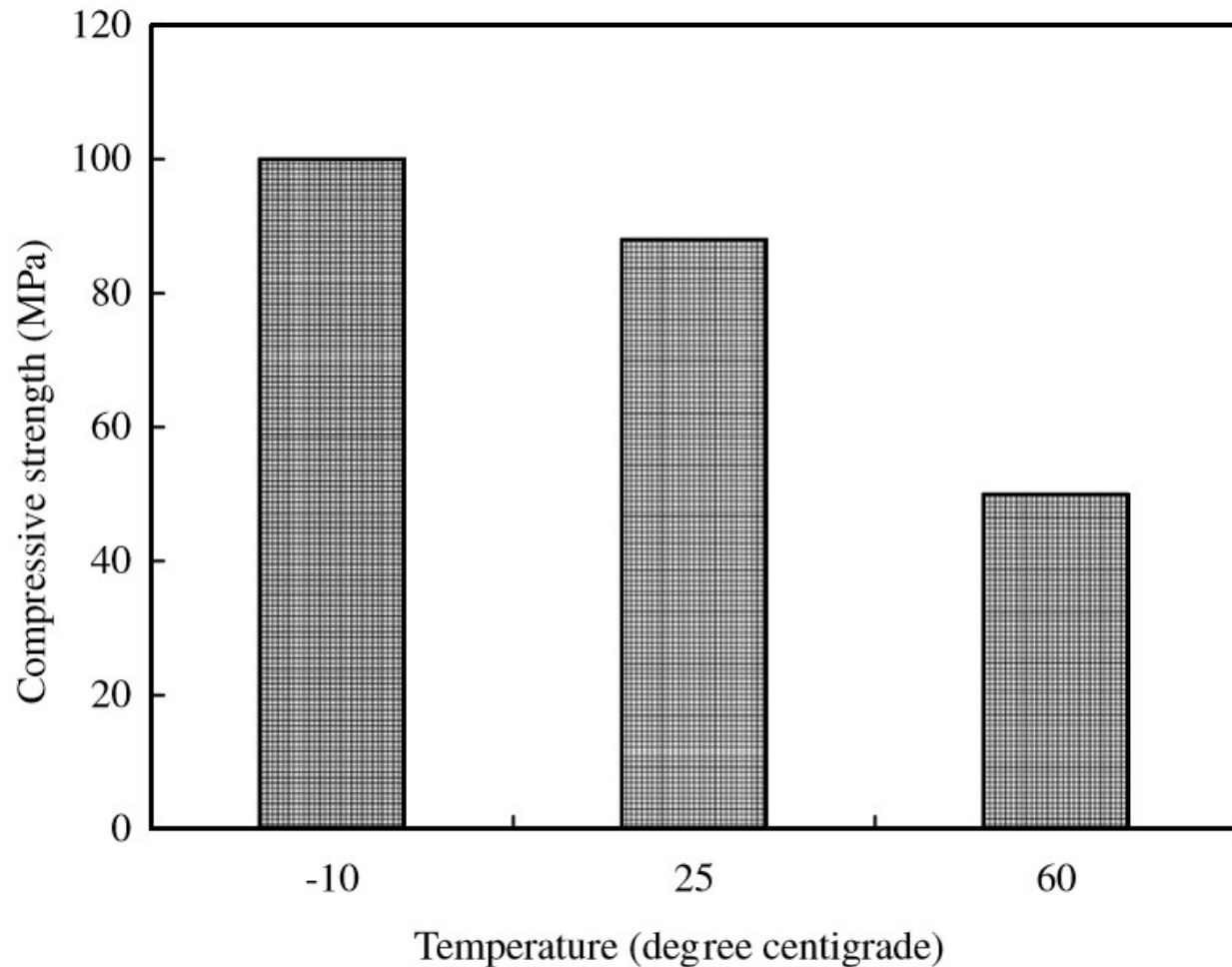


Figure 3-13: Temperature effect on compressive strength of P-C (Rebeiz, 1995).

3.2.3 Other properties of cementitious construction materials that contain plastics wastes

3.2.3.1 Fire behaviour and thermo-physical properties

Albano et al (2009) observed that at high w/c ratio the thermal stability of PET aggregate decreased due to the hydrolytic degradation of PET particles. Therefore, in presence of fire, this behaviour can lead to cracks in the concrete containing plastic aggregates and may cause some damages on the structure.

Mounanga et al (2008) observed significantly low thermal conductivity for concrete containing PUR foam aggregate that was used to partially replace the fine natural aggregate due to porous nature of PUR foam aggregate. These pores contain air whose thermal conductivity is much lower than the corresponding conductivity values for other components of the concrete. The decrease in thermal conductivity was prominent for concrete containing dry PUR foam aggregate compared to concrete containing saturated PUR foam aggregate.

3.2.3.2 Impact resistance

Bayasi and Zeng (1993) investigated the influence of polypropylene fibers on the impact resistance of concrete containing plastic aggregates; the results are summarized in the following Table 3.9. Based on the test results, they concluded that polypropylene fiber enhanced the impact resistance of concrete significantly. This was especially true for 12.7 mm long fibers. These fibers significantly increased the impact resistance of concrete for volumes that do not affect mix workability less than 0.5%), while, at higher volume contents, impact resistance may tend to decrease.

Table 3-9: Hardened concrete properties of polypropylene fiber reinforced concrete (adapted from (Bayasi and Zeng, 1993; Siddique et al., 2008)).

Mix No.	Fiber length (mm)	Fiber Volume fraction (%)	Impact strength (no. of blows)	
			At first crack	At failure
1	-	0	5	5
2	12.7	0.1	17	28
3	12.7	0.3	186	201
4	12.7	0.5	50	71
5	19.0	0.1	11	20
6	19.0	0.3	19	42
7	19.0	0.5	34	72

3.2.3.3 Toughness / Poisson's ratio

Ismail and Al-Hashmi (2007) showed during their works that the incorporation of plastic waste as aggregate in the concrete, contributes to arrest the propagation of micro cracks in it. In addition, they evaluated the toughness indices for concrete compositions containing plastic waste aggregates at the curing ages of 3, 7, 14, and 28 days as detailed in the Table 3.10. For all samples of various concrete compositions at 14 and 28 days curing ages, the toughness indices of those concrete containing plastic waste aggregates for all replacement levels were found to be desirable for many applications that require high toughness.

Kou et al (2009) observed an increasing Poisson's ratios with increasing contents of PVC waste aggregate in concrete. As the higher Poisson's ratios correspond to higher ductility, the incorporation of PVC improved the ductility of the resulting lightweight aggregate concrete, due to the elastic nature of PVC.

Table 3-10: Toughness indices for concrete containing various rates of plastic wastes aggregate (Ismail and Al-Hashmi 2007).

% of Plastic aggregate	Toughness indices at different curing ages											
	3-days			7-days			14-days			28-days		
	I ₅	I ₁₀	I ₅ : I ₁₀	I ₅	I ₁₀	I ₅ : I ₁₀	I ₅	I ₁₀	I ₅ : I ₁₀	I ₅	I ₁₀	I ₅ : I ₁₀
10	-	-	-	8.3	11.6	1.4	4.3	8.6	2.0	2.5	7.5	3.0
15	3.0	11.0	3.7	4.5	9.5	2.1	4.2	8.4	2.0	8.0	16.1	2.0
20	6.8	13.7	2.0	7.3	14.8	2.0	5.2	11.5	2.1	5.7	11.6	2.0

3.3 Use of plastic waste as binder

In contrast to the studies devoted to the incorporation of plastic waste in concrete as aggregates and additives, there is a scarcity of studies on the use of plastic as a binder in mortar or concrete materials. In recent years, some initiatives have been proposed to use melted plastic wastes to form different products such road signs, soil pavers, slabs for gutters and latrines (e.g., Doublier et al. 2009; Jnr et al. 2018; Agyeman et al. 2019; Vetrivel 2021). Doublier et al. (2009) proposed various examples of artisanal products (paving materials) that use plastic waste as the binding phase. Moreover, some previous studies (Mahdi et al. 2010; Vidales et al. 2014) assessed the use of an unsaturated polyester resin (derived from recycling PET by a glycolysis process) as the only binding material to develop concrete or mortar materials. The results obtained indicated a significant decrease in water absorption with increasing PET content as well as an increase in compressive strength with increasing resin content. A refinement of the pore structure or porosity reduction due to the use of resin was also observed. However, the high cost and high energy requirement related to the preparation of the unsaturated polyester resin have restricted the application of the aforementioned polyester resin concrete materials in building and construction practice. Moreover, the other types of plastic wastes (HDPE, LHPE) were ignored in the aforementioned studies. Thus, other researchers (Dalhat and Al-Abdul Wahhab 2016, Jnr et al. 2018; Agyeman et al. 2019; Vetrivel 2021) performed experimental studies to assess the potential use of recycled plastics (e.g., High density polyethylene (HDPE), Polypropylene (PP)) to make recycle plastic-only bounded cemented materials/structures such as pavers. They obtained encouraging results with respect to the mechanical performance of the proposed cement-less concrete. However, long curing time (>2.0 hrs) at high temperature is required in most of the previous studies to prepare the proposed recycle plastic-only bounded concrete. This high energy consumption associated with this curing time negatively impacts the cost of this product, thereby impeding its quick adoption in construction practice. So, there is a need to develop a less-energy intense method or technology to prepare plastic-only bounded concrete/mortar. Moreover, none of the aforementioned studies, to date, has examined the simultaneous use of melted (recycled) low density polyethylene (LDPE) and high density polyethylene (HDPE) as the only binder to develop mortar or concrete-like material, although LDPE is one of the most produced types of plastic waste and has a low recycling rate. This technology and research gap need to be addressed.

3.4 Concluding remarks

The environmental impacts of solid waste sector have becoming very important in the recent decades; several works have been done to reduce the negative effects of solid waste sector on human life and the environment. Several authors have been working on various aspects of plastics wastes and their uses in concrete/mortar, which have been summarized in the chapter 3 and some conclusions, can be drawn from their research as follow:

- a. The workability performance of concrete containing plastic aggregate depends on the size and shape of plastic aggregates. Porous as well as flaky plastic aggregates decrease the slump of fresh concrete mix while spherical shaped plastic aggregates increase it. The incorporation of plastic aggregates can reduce the density of resulting concrete and cement mortar; therefore, several studies have been done to prepare lightweight concrete using various types of plastic aggregates.
- b. Plastic waste aggregates can be utilized successfully and effectively to partially replace conventional aggregates. The concrete or mortar samples containing partial replacement of plastic aggregates meet several strength criteria for normal structural as well as lightweight concrete. Because of the very low binding strength between the surface of the plastic particles and the cement paste, incorporation of any type and/or quantity of plastic aggregates in concrete or mortar contributes to reduce the bulk density properties. Compared to the control mixtures, up to 72% reductions in compressive strength were observed for concrete prepared by replacing natural aggregate at the replacement level in the range of 10% to 50%. Compressive strength of concrete containing 10–50% recycled plastic aggregates ranged between 19 and 48 MPa. The bulk density was reduced by 2.5–13% for concrete containing plastic aggregates ranging from 10% to 50% of recycled plastic. Compressive strength decreased with the increase in recycled plastic content. About 16% of reductions in compressive strength of mortar prepared by replacing 50% in volume of sand were also reported. The changing behaviour in various strength properties are due to the difference of workability behaviour of concrete mix as well as the difference between the types of plastic wastes used, their size and shape.
- c. Splitting tensile strength and flexural strength of concrete made with post-consumer plastic aggregates was found to decrease when the percentage of plastic aggregates decreases, but relatively less prominent than the reduction in compressive strength. The reduction rate of 17% in splitting tensile strength was observed for concrete containing 10% of plastic aggregates. For a given plastic aggregate content, the splitting tensile strength was found to decrease when w/c ratio increased. However, this incorporation can considerably change the failure behaviour of the resulting concrete or mortar. The corresponding concrete will be more ductile than the conventional concrete and it can arrest the cracks generated during the mechanical failure.
- d. There are few studies related to the durability performance of concrete/mortar containing plastic aggregates. According to the authors, the incorporation of various types of plastic aggregates can improve the permeability behaviour of concrete, thus the concrete

containing plastic aggregates will be more durable and resist to various effects from aggressive chemical environment. However, concrete shrinkage is considerably increased due to the incorporation of various types of plastic aggregates.

- e. Concrete containing modified EPS aggregates exhibited higher frost resistance than conventional concrete. Similarly, the concrete containing PET-aggregates will have more strong fire behaviour than the conventional concrete. Concrete containing polyurethane foam as aggregates also exhibited lower thermal conductivity than the conventional concrete. However, more results are necessary to have a clear picture of these properties.
- f. Polymer concrete using an unsaturated polyester resin based on recycled PET is a feasible and effective material for precast applications. This material can achieve more than 80% of its ultimate strength in one day, a very significant advantage for many structural applications.
- g. Discrete reinforcement for concrete can be derived from shredded mixed plastic, milled mixed plastic particles and melt-processed plastic fibers. These actions will result in significant gains in resistance of concrete to impact and shrinkage cracking, also enhanced the impermeability and deicer salt scaling resistance. However, there was reduction in the abrasion resistance of concrete with the addition of recycled plastic.
- h. Polypropylene fibers had an adverse effect on the air content of concrete. With the inclusion of 0.5% polypropylene fibers, air content of concrete was increased whereas workability was reduced. Polypropylene fibers significantly enhanced the impact resistance of concrete.
- i. Recycled plastics can be used in transportation related components, in the repair and overlay of damaged cement concrete surfaces in pavements, bridges, floors, and dams.
- j. Use of plastic wastes in concrete can improve its toughness behaviour and therefore this type of concrete can absorb high amounts of energy, which has several practical implications. Considering the improvement of concrete toughness with the lightweight nature of plastic aggregate-based concrete, it can be envisaged to develop in the future some lightweight plastic based concrete or composites for earthquake resistance building construction.
- k. Plastic waste aggregates has significantly lower thermal conductivity than the natural aggregates used in concrete preparation. Thus, the concrete containing plastic aggregates will have better thermal insulation properties than conventional concrete, which can be used to control heat loss from building during winter and heat gain during summer.
- l. However, for practical applications of plastic wastes in concrete preparation, some other important aspects such as Life Cycle Analysis and Life Cycle Cost analysis of the products and recycling options at the end of the service life need to be evaluated. Therefore, future studies should be implemented to obtain durable and improved products but cost-effective plastic waste-based concrete products.

- m. Promising strength and fire resistance results were found for different construction products using melted plastic wastes as binding materials. More research is needed to explore deeper on the properties of these new products.
- n. Finally, the literature review presented above have shown some initiatives using melted plastic wastes to develop construction materials. However, no studies using only the mix of melted HDPE and LDPE plastic wastes as a binder to develop mortar- or concrete-like materials have been published in the scientific/technical literature. Moreover, the energy demand or cost of the methods used in the previous studies to make cemented materials with plastic waste as the only binding phase is relatively high, which has have restricted the application of the aforementioned cement-less materials in building and construction practice. This identified research gap is addressed in the present PhD research as presented in the following chapters.

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Chapter 4. Mortar with melted plastic waste as the only binding material: Development and Engineering Properties

4.1 Introduction

This chapter deals with the development and experimental investigation of the performance properties of the proposed new mortar with melted plastic binder (MPB). The results of the study are presented in two research papers (technical papers I and II). The Mechanical, physical and microstructural properties of a mortar with melted plastic waste binder will be studied and discussed in the technical paper I, whereas the impacts of physical factors and curing conditions on the performance properties of the MPB will be addressed in the technical paper II.

4.2 Technical Paper 1: Mechanical, physical and microstructural properties of a mortar with melted plastic waste binder

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Abstract

The feasibility of using plastic waste as a binding material to develop a new construction material (mortar with plastic waste binder (MPB)) is presented in this paper. Two types of plastic: high density polyethylene (HDPE) and low density polyethylene (LDPE), are combined in three blend (weight) ratios (HDPE/ LDPE of 40/60, 50/50, 60/40) and mixed with sand in four plastic contents (45%, 50%, 60%, and 65%). First, the plastic material is melted in an oven. Then, sand and the melted plastic are thoroughly mixed under a controlled temperature into an homogenous mixture. The mixture is then poured into standardized molds and cured for different periods of time. Mechanical, physical and water absorption tests are performed on the MPB samples after different curing times to assess the influence of the change in the plastic content and the blend ratio (HDPE/LDPE or H/L) on their mechanical and physical properties. Moreover, microstructural analyses and tests are performed on some of the samples for a better understanding of the behavior of this MPB at its microstructure level. The results show that samples with plastic contents of 50% and 60% and a blend ratio of 50/50 have the highest unconfined compressive strength. The same range of plastic content is found to provide the MPB with the highest splitting tensile strength when the H/L blend ratio is equal to 40/60 or 60/40. A relationship between the splitting tensile strength (ft) and the compressive strength is proposed. It is also found that the MPB is more ductile with greater plasticity than conventional mortar materials that use Portland cement. The plastic content and H/L ratio have significant effects on the water absorption, density and microstructure of the mortar. The microstructure of the MPB plays an important role in the development of its strength. This new material has good potential for use as a construction material to recycle plastic waste and reduce the impact of plastic on the environment.

Keywords: Plastic waste; Recycling; Ecological mortar; Green materials; Cement

4.2.1 Introduction

The current material consumption habits globally have led to massive waste production in local regions (Saikia and De Brito, 2012). According to the estimations from the World Bank, 174 and 289 million tons of solid waste were produced in Sub-Saharan Africa and North America in 2016, respectively, which are projected to increase by 54.6% and 18.3% respectively by 2030 (World Bank, 2019).

Plastic, an invention of the 20th century that is widely used in consumer goods today, is contained in many waste products (Saikia and De Brito, 2012). After its useful lifetime, plastic can remain as intact waste for over 100 years without any degradation, thus causing substantial environmental, social, and health related problems (Le Siedmto, 2019). For instance, disposal of plastic waste in landfills can lead to soil and water pollution as well as blockage of the city's drainage systems,

which in turn, can result in proliferation of mosquitoes and other insects, thus contributing to the spread of diseases (Zuberi and Ali, 2015). Incineration of plastic waste leads to air pollution, increases the risk of the expansion of carcinogenic diseases, and contributes to the deterioration of air quality close to the incineration plants (Allsopp et al. 2001). Moreover, discarding plastic waste in aquatic environments greatly damages fauna and flora (Schwarz et al. 2019) with harmful consequences on biodiversity and fishery and potential risk to food security and human health (Barboza et al. 2018). About four to twelve million tons of plastic are disposed in the oceans annually (Boucher and Damien, 2017; Compa et al. 2019) with an estimate of 150 million tons of accumulated waste (Jambeck et al. 2015; Lebreton et al. 2017; UN 2018).

Considering the above issues and the need to find an ecological and sustainable solution to manage plastic waste and its related problems, some studies have been conducted in civil engineering to recycle plastic into a cementitious material, much like cement and mortar. Numerous experimental studies [(e.g., (Bayasi and Zeng, 1993; Al-Manaseer and Dalal, 1997; Soroushian et al. 2003; Ismail and Al-Hashmi, 2008; Le Siedmto, 2019) have been carried out to evaluate the properties of fresh and/or hardened cementitious materials (concrete and mortar) that contain different types of plastic wastes for use as aggregate, filler or fiber with some success. For example, Bayasi and Zeng (1993) reported that the air entrainment in fresh concrete increases with the inclusion of polypropylene fibers with a fiber volume over 0.3%. Furthermore, independent of the size, type (polystyrene, polyvinyl chloride (PVC), polyethylene terephthalate (PET), polycarbonate (PC), fine plastic aggregates, etc.) and quantity of plastic as a substitute aggregate, several authors have arrived at the conclusion that the introduction of plastic aggregates in concrete would generally reduce its fresh and dry densities (Al-Manaseer and Dalal, 1997; Choi et al. 2005; Marzouk et al. 2007; Ismail and Al-Hashmi, 2008; Kou et al. 2009; Hannawi et al. 2010). The density of the concrete is less than 2000 kg/m³, which is considered to be the minimum dry density required for structural lightweight concrete according to the RILEM LC2 classification (RILEM, 1978). Other studies (e.g., Batayneh et al. 2007; Ismail and Al-Hashmi, 2008; Kou et al. 2009; Frigione, 2010). show that the slump of fresh concrete that contains several types of plastic aggregates is lower than that of conventional concrete mix. Moreover, most of the studies on the strength of concrete and mortar with plastic aggregates (Rebeiz, 1995; Al-Manaseer and Dalal, 1997; Batayneh et al. 2007; Ismail and Al-Hashmi, 2008; Choi et al. 2009; Kou et al. 2009; Saikia and De Brito, 2012; Gesoglu et al. 2017; Babafemi et al. 2018) find a reduction in the compressive strength due to the addition of plastic waste as a partial substitute of fine aggregates. For example, Ismail and Al-Hashmi (2008) reported that the compressive strength of the concrete with 10%, 15% and 20% of fine natural aggregates substituted with PET aggregates are lower than the compressive strength of concrete that contains only the natural aggregates but higher than the minimum compressive strength required for structural concrete, which is 17.24 MPa (Ismail and Al-Hashmi, 2008). However, with 5% and 20% of plastic aggregates, the compressive strength shows a sharp decrease of 23% and up to 72% of the original strength respectively (Batayneh et al. 2007). Similar reduction, but with a smaller effect, is found in both the splitting tensile and flexural strengths of plastic aggregate samples (Batayneh et al. 2007). However, the splitting failure of the concrete samples is more ductile with more plastic aggregates and does not exhibit the typical brittle failure observed in conventional concrete with natural aggregates. Choi et al. (2005) investigated the effects of PET bottles as waste plastic lightweight aggregate (WPLA) on the modulus of elasticity

of concrete. Water–cement ratios of 45%, 49%, and 53% with WPLA contents of 0%, 25%, 50%, and 75% by volume of fine aggregates were studied. The modulus of elasticity of the concrete is found to decrease with an increase in the amount of PET aggregates. In addition, Marzouk et al. (2007) observed that substituting conventional aggregates with plastic aggregate decreases the rate of water absorption. The sorptivity, that is, the ability of concrete to absorb water, is found to further decrease with 50% of plastic aggregate. In conclusion, they showed that concrete with plastic aggregates is more durable when exposed to aggressive solutions.

From this literature review, it is obvious that there is a lack of studies that use plastic wastes as the only binding agent. In addition, most of the previous research studies have not explored the use of low-density polyethylene bags or plastic films because they are difficult to recycle. It is also challenging to find an equivalent grain size that corresponds to the grain sizes of sand or gravel (Coppola et al. 2016). This research work will address the knowledge gap in this area.

In this paper, the experimental program and results of a multiple year research project on recycling plastic for use in construction material are presented with the following objectives: (i) to create a new construction material called mortar with melted plastic waste binder (MPB) by mixing sand with melted plastic as the only binding material; (ii) to assess the strength of MPB made with two types of plastics (low density polyethylene (LDPE) and high density polyethylene (HDPE)) with different blend (weight) ratios (H/L) and different amounts of plastic; (iii) to study the deformation (stress-strain) behavior of the MPB; and (iv) to investigate the microstructural and physical properties of MPB.

4.2.2 Experimental Program

4.2.2.1 Materials used

4.2.2.1.1 Sand material

Natural sand (Figure 4.1) from Niger River collected from the banks of Kalaban-coro in Bamako, Mali, is used in this study. A sieve analysis was carried out on the sand in accordance with ASTM C136 / C136M standards to determine the grain size distribution. The results of the sieve analysis indicate that the grain size distribution of the sand can be described as follows: d_{10} (effective diameter) = 0.25 mm, d_{30} = 0.32 mm, d_{60} = 0.85 mm, C_u (coefficient of uniformity) = 3.4 and C_c (coefficient of curvature) = 0.5.



Figure 4-1: (a) Sampling site of the sand in Kalaban - Coro on the banks of the Niger River in Bamako, Mali and (b) image of the sand sample used in the experiments

4.2.2.1.2 Plastic materials

Two types of plastic wastes were used, HDPE and LDPE. The plastic was collected from the Medina-Coura waste transit depot in Bamako, Mali. Figure 4.2 shows samples of the plastic waste used. HDPE and LDPE represent the most frequent types of polyethylene. The latter is one of the most extensively used thermoplastics in the world. This type of plastic can be found in almost everything from grocery bags to shampoo bottles.



Figure 4-2: Samples of (a) HDPE and (b) LDPE plastics wastes used in testing program

4.2.2.2 Sample preparation and curing

4.2.2.2.1 Mortar with melted plastic

Natural river sand, as the only aggregate, was mixed with different proportions of molten HDPE and LDPE plastic for the preparation of the MPB. The sand was oven dried at 105°C and passed through a 2 mm sieve. The plastic was cut in small pieces (less than 6 cm in length) to fit into the oven. Different proportions (by weight ratio) of HDPE and LDPE plastics were melted in the oven at an average temperature of approximately 250°C; see Table 4.1. The melting time took 20 to 45 minutes depending on the type and amount of plastic. Then, the melted plastic, which constitutes the plastic paste binding material, was thoroughly mixed into a homogenous liquid paste and the required amount of sand was added to the melted plastic in a concrete mixer at a temperature of about 100°C. Mixing continued until a homogeneous mixture was obtained. The average mixing time was 15 min. The temperature change of the hot MPB during mixing was insignificant. Subsequently, the hot liquid MPB was poured into metallic cylinders of 10 cm in diameter and 20 cm in height, or 5 cm in diameter and 10 cm in height. Note that prior to pouring the liquid (fresh) mortar, the inner surface of the cylindrical molds was coated with lubricant to facilitate extraction of the sample. When the molds were filled, a manual hand press was used to compact the fresh mortar in the mold and keep it under pressure to limit sagging of the sample. Finally, the samples were extracted after half an hour. Figure 4.3 shows the MPB samples before and after extraction from the mold. The samples were then cured at room temperature for periods of 1, 3, 7, and 28 days.



Figure 4-3: Samples of MPB before and after extraction from the mold.

The mix proportions of the MPB and curing times are shown in Table 4.1. The rationale for the recipe or mix proportions considered is based on preliminary tests conducted to assess the MPB performance. The preliminary tests used equal amounts of HDPE and LDPE plastics. The

percentage of the plastic varied from 10% to 100% of the mass of dry sand. In the preliminary test, some procedures in making the samples are optimized, including the timing to introduce different types of plastics and sand. Another important parameter that is established in the preliminary test is the melting and casting temperature. At an ambient air temperature between 24°C and 30°C, the average melting temperature in the oven is found to be 250°C. The results of the preliminary test indicate that, for a plastic content less than 40%, the mortar will be very heterogeneous and some of the sand particles are not covered by the plastic binder. On the other hand, the mortar is found to be too fluid or liquid with more than 70% plastic, thus allowing rapid settlement of the sand grains, and leading to segregation and a heterogeneous sample during casting. In addition, flowing of the MPB in a liquid or fluid state does not allow proper casting of the sample, which affects hardening of the material.

Considering the results from the preliminary tests, the plastic contents vary between 45% and 65% of the initial mass of dry sand. Four proportions of plastic contents are chosen (45%, 50%, 60% and 65%) in this study with three HDPE/LDPE ratios (40/60, 50/50 and 60/40); see Table 4.1. The combination of parameters here will cover the practical range of values in making a workable mortar.

Table 4-1: Mix proportion and curing time of the MPB with melted HDPE and LDPE plastics

Sample Designation	Plastic Binder	Plastic Content (%)	HDPE / LDPE	Granular material	Curing time (days)
45% P – H/L 50/50	HDPE - LDPE	45	50/50	Sand	1, 3, 7, 28
50% P – H/L 60/40	HDPE - LDPE	50	60/40	Sand	1, 3, 7, 28
50% P – H/L 50/50	HDPE - LDPE	50	50/50	Sand	1, 3, 7, 28
50% P – H/L 40/60	HDPE - LDPE	50	40/60	Sand	1, 3, 7, 28
60% P – H/L 60/40	HDPE - LDPE	50	60/40	Sand	1, 3, 7, 28
60% P – H/L 50/50	HDPE - LDPE	50	50/50	Sand	1, 3, 7, 28
60% P – H/L 40/60	HDPE - LDPE	50	40/60	Sand	1, 3, 7, 28
65% P – H/L 50/50	HDPE - LDPE	65	50/50	Sand	1, 3, 7, 28

P: plastic content in percentage (%) of dry mass of sand, H/L mass ratio of HDPE to LDPE.

4.2.2.2 Conventional mortar with cement paste

Since “conventional” or “normal” mortar made of sand, cement and water is one of the most widely used construction materials in civil engineering worldwide, some conventional mortar samples were prepared to compare and identify or understand how the MPB differs from conventional mortar. It should be noted that the goal of this exercise is not to compare the performance of these materials, but rather to gain a better understanding of the properties or behavior of the MPB. Therefore, several samples of conventional mortar with a water to cement ratio (W/C) of 0.5, and sand to cement (S/C) ratio of 3 were prepared. Type I Portland cement and tap water were used to prepare the samples. The ingredients were mixed in a concrete mixer for about 7 minutes, and then poured into metallic cylinders of 5 cm in diameter and 10 cm in height. The cylinders were then sealed (to avoid evaporation) and cured at room temperature. Moreover, cement paste (CP) samples for a microstructural analysis were also prepared by using the same procedures. The W/C

ratio of all of the CP specimens was constant and equal to 0.5. After the required curing times, the samples were subjected to various tests and analyses as described below.

4.2.2.3 Tests

4.2.2.3.1 Uniaxial compression strength and splitting tensile tests

Mechanical properties, such as (compressive, tensile) strength and stress-strain behavior, are very important for mortar with regard to its capacity to withstand load and cracking potential when forces are applied to the mortar. Consequently, these properties enable to establish the service life that can be expected for a given construction material. Thus, compression and splitting tests were performed on prepared the MPB samples.

Compression tests were conducted in accordance with ASTM C39 / C39M – 18 to determine the uniaxial compressive strength of the MPB. In these tests, a computer-controlled mechanical press was used. The load was applied at a slow rate (1 mm/min). The axial deformations were recorded with a data acquisition system. Each uniaxial compression strength test was repeated at least 3 times to ensure the repeatability of the results.

Splitting tensile tests, which are commonly known as the "Brazilian test", were conducted on cylindrical samples that were 5 cm in diameter and 10 cm in height to determine the splitting tensile strength of the material. The splitting tensile tests were performed in accordance with ASTM C496 / C496M – 17. Each test was repeated at least three times.

4.2.2.3.2 Hardened density test

The density of a hardened cemented material is a parameter that can affect its strength and permeability. Therefore, the density of the hardened MPB was determined by following ASTM C 138 / C138M - 17a. Each density test was performed at least three times to verify the repeatability

4.2.2.3.3 Absorption test

Water absorption by immersion and capillarity tests were conducted on the MPB and conventional mortar samples. The immersion test was conducted in accordance with ASTM C97 / C97M – 18. The cylindrical samples (5 cm in diameter, 10 cm in height) were first dried in a ventilated oven at 60°C for 2 days. After drying, the samples were cooled in a temperature-controlled room ($23 \pm 2^\circ\text{C}$) for around 30 min. Immediately after cooling, the samples were completely immersed in distilled water in a temperature-controlled room ($23 \pm 2^\circ\text{C}$) for 48 hrs. At the end of the immersion, water on the surface of the sample was wiped off with a cloth, and the samples were weighed to calculate the water absorption by immersion. The absorption of water, expressed in percentage (%), is equal to the difference in weight before and after immersion for 48 hours over the initial weight. Each test was repeated two times and the average was calculated for a given plastic content and H/L ratio.

Capillary tests were carried out in accordance with ASTM C1585 – 13 on the MPB and conventional mortars. Before performing the capillary tests, the samples were oven-dried at 50°C until they reached a constant mass. Then, the sides of the sample were covered with plastic tape for a unidirectional flow of water. The specimen was then placed in a pan with water and a cover was used to avoid direct evaporation of the water from the pan. The water level was kept at 3 mm

from the bottom of the specimens throughout the experiment. The experiment was conducted under a controlled temperature of $23 \pm 2^\circ\text{C}$ and tap water was used for the test. The weight of the sample was determined at about 5-minute time intervals at the beginning of the test and increased accordingly as the test progressed. The capillary absorption (I) is calculated using the following formula:

$$I = \frac{\Delta m}{A \cdot d} \quad \text{Equation 4-1}$$

Where Δm is the difference between the mass after immersion at time t from the initial mass of the sample, A is the exposed area of the specimen, and d is the density of water, which is assumed to be 1 g/cm^3 .

By plotting the capillary absorption against the square root of time, the graph has two parts with different slopes, which are called the rate of absorption or sorptivity. The initial sorptivity or initial rate of absorption is considered to be the slope of the curve in the first 6 h, while secondary sorptivity is the slope of the curve between 1 and 7 days, as described in ASTM standard C1585-20. However, for the purpose of this research, the change in the slope is observed after 10 h. Therefore, the initial sorptivity will be calculated based on the slope of the capillary absorption curve up to 10 h.

It should be noted the determination of the water vapour permeability of the proposed material was out of the scope of this study. Future investigations should address it since this parameter is important in assessing potential of water condensation.

4.2.2.3.4 Microstructural analyses

To understand the microstructure of the MPB and the conventional mortar and how it affects the mechanical properties of the material, several microstructural testing techniques were used to evaluate the microstructure of some of the samples (Kumar and Bhattacharjee, 2003). These tests or analyses include mercury intrusion porosimeter (MIP) tests, scanning electron microscopy (SEM) and thermogravimetric analyses (TGA). Samples for the microstructural analyses were oven dried at 45°C . Drying at this temperature does not cause cracking of the specimens (Kumar and Bhattacharjee, 2003; Fall et al. 2010).

For examination under a scanning electron microscope, approximate square samples were cut and carbon coated for the SEM by using the Joel JSM-6610LV scanning electron microscope. SEM examinations with different magnifications were used to analyze the adhesion/cohesion between various elements of the MPB, its morphology and texture, for a clear view on its porosity microscopically.

The MIP tests were carried out to evaluate the pore size distribution or the total porosity of the specimens (MPB, conventional mortar). The tests were performed by using a Micrometrics Auto Pore III 9420 mercury porosimeter in accordance with ASTM D4404-10.

The thermogravimetric analysis (TG-DTG tests) was performed with a thermal analyzer (TGA Q5000 V3.15 Build 263). Less than 40 mg from each material, plastic wastes, MPB, and conventional mortar, were placed on an alumina pan and heated under a nitrogen atmosphere from

10°C to 1000°C at a heating rate of 10°C / min and a flow rate of 10 mL/min to assess the thermal degradation. For analysis purposes, the change in weight is recorded as a function of the temperature increment for the samples.

4.2.3 Results and discussion

4.2.3.1 Compressive strength of the MPB

Figure 4.4 shows the time-dependent development of the compressive strength of the MPB with different plastic (P) contents for a constant H/L ratio (50/50). Regardless of the plastic content, the compressive strength is found to increase with time. It is observed that several hours after casting the sample, the sample does not take its final shape, thus indicating a slow transition (solidification) of the material from the liquid to solid state which has an impact on the compressive strength of the material. When the MPB is poured into the mold after melting the plastics, the samples exposed to an ambient temperature (24°C to 30°C) exhibit accelerated solidification, which leads to a rapid gain in strength. The change in strength is dependent on the polymer and the type of polymer, which can even increase after recycling (Braun, 2002; Sun et al. 2018). LDPE and HDPE are both semicrystalline polymers but the degree of crystallinity is higher in HDPE, due to the different number of polymer branches (da Silva and Wiebeck, 2017). The changes in strength can be linked to the changes in thermal properties, melting temperature, crystallization, etc., and the physical/surface properties of the mix after processing (Ragaert et al. 2017). Volk et al. (2015) observed a similar behaviour on the improvement in the tensile strength of linear low-density polyethylene with surface treated cellulose nano-fibers. Therefore, further understanding of the strength of the MPB can be gained by examining the material microscopically. Furthermore, melted plastic behaves differently when interacting with granular materials. At high temperatures during the initial stage of cooling after casting, weak spots develop at the interfacial transition zone (ITZ) between the plastic paste and the aggregates. With time, the interface (ITZ) becomes stronger during the solidification phase, which binds the constituent elements of MPB together to act as one unit and contributes to higher compactness and elasticity (due to increase in degree of crystallinity of the plastic as its solidification progresses) of the material (Inai et al. 2018). Thus, part of the strength improvement can be linked to the high elastic modulus and better adhesion in the MPB. From Figure 4.4, it can be seen that the compressive strength of the MPB specimens reached around 60% to 80% of their final values just after one day of curing. This increase in the early age strength for MPB is much higher than conventional mortar, which typically reaches less than 40% of its final strength after 1 day of curing (Yang et al. 2021).

Figure 4.5 illustrates the effect of plastic content with an H/L ratio of 50/50 on the compressive strength of the MPB for various curing times. From Figures 4.4 and 4.5, it is obvious that not only the curing time, but also the plastic content, significantly affects the compressive strength of the MPB. The samples with 50% and 60% of plastic and H/L of 50/50 show the highest rate of gain in strength as well as the ultimate strength, whereas the samples with 45% plastic and H/L of 50/50 show the slowest rate of gain in strength and the lowest ultimate strength. These results suggest an optimal plastic content from 50% to 60% with respect to the highest compressive strength. Lower or higher than this optimal plastic content means that, the strength curves for different ages tend

to decrease. This behavior can be attributed to two main factors. First, at a low plastic content, or less than 45%, there is not enough melted plastic paste to cover all of the sand grains to solidly bind all the particles together. That leads to the creation of weak spots in the MPB with low inter-particle bonding, which reduces the compressive strength. On the other hand, when the plastic content is higher than 65%, plastic then constitutes a significant portion of the material with less sand. Although this contributes to an increase in the amount of plastic as a binding material, the decrease in sand content will lead to a decrease in dry density which affects the strength of the material. Therefore, the compressive strength of the MPB is decreased at a plastic content higher than the optimal values (Kou et al. 2009; Hannawi et al. 2010).

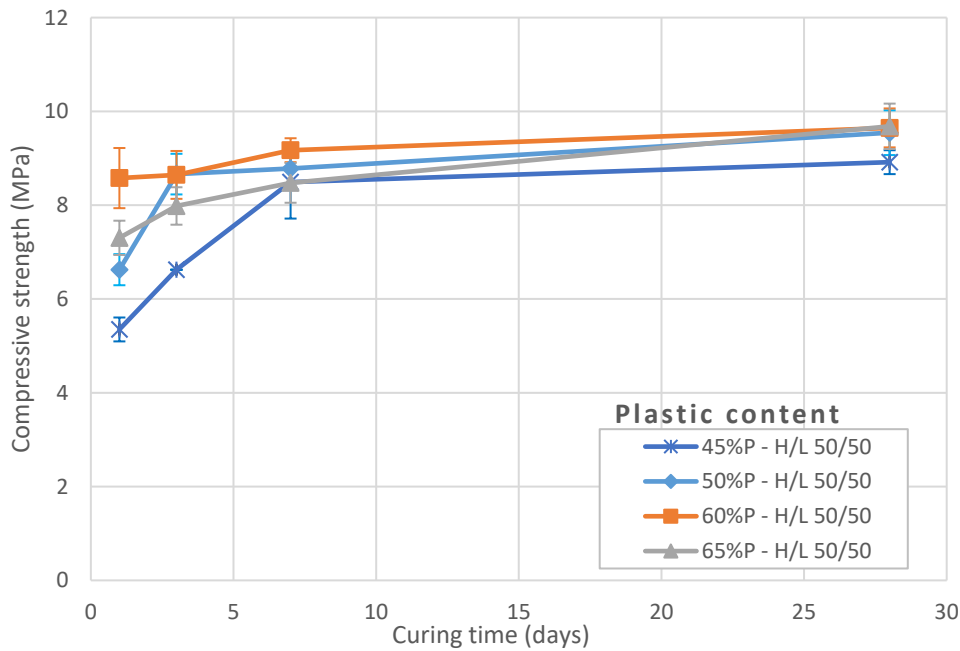


Figure 4-4: Compressive strength development vs time of the MPB with different percentages of plastic waste (sand particle size < 2 mm, H/L of 50/50).

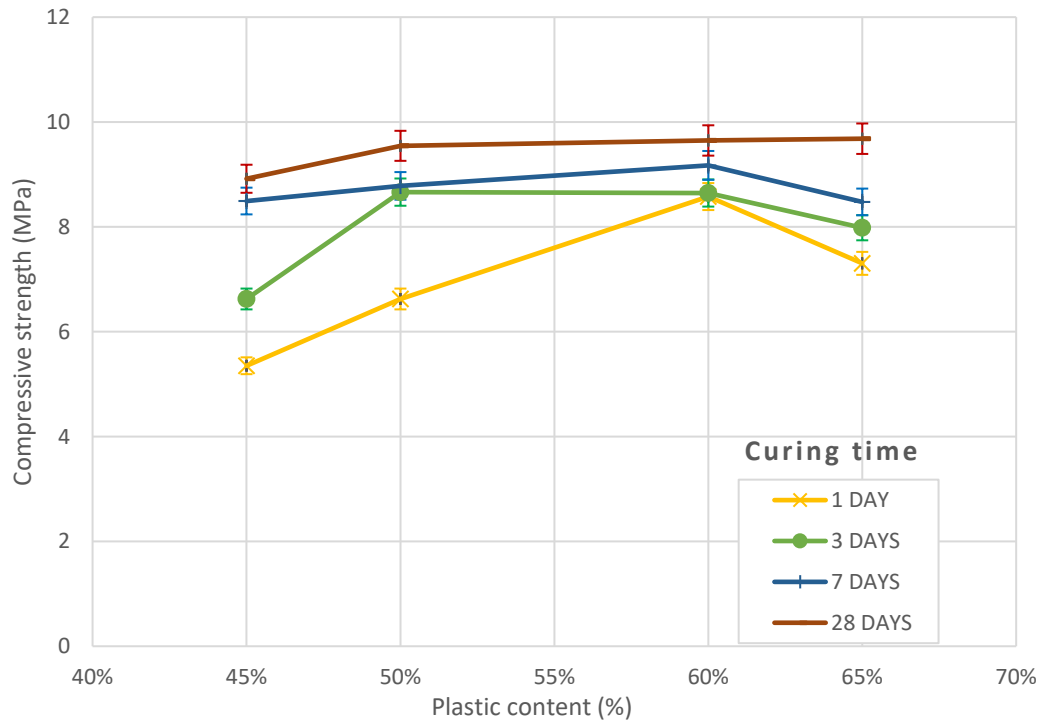


Figure 4-5: Effects of plastic content on the compressive strength for different ages of the MPB with H/L = 50/50

Figures 4.6 and 4.7, show the change in compressive strength with time for MPB with 50% and 60% of plastic, respectively, and H/L ratio of 40/60, 50/50 and 60/40. The results show clear increase in compressive strength with more HDPE. A H/L ratio of 50/50 gives the lowest strength, while a ratio of 60/40 provides the highest strength regardless of the curing time and plastic contents. This behaviour can be related to the physico-chemical transformation of the plastic during melting, casting and curing (Braun, 2002; Volk and Magniez, 2015; Ragaert et al. 2017), as well as the lower porosity of the MPB with H/L= 60/40. Further discussion on this point will be provided in the sections below related to the microstructural analysis and absorption tests.

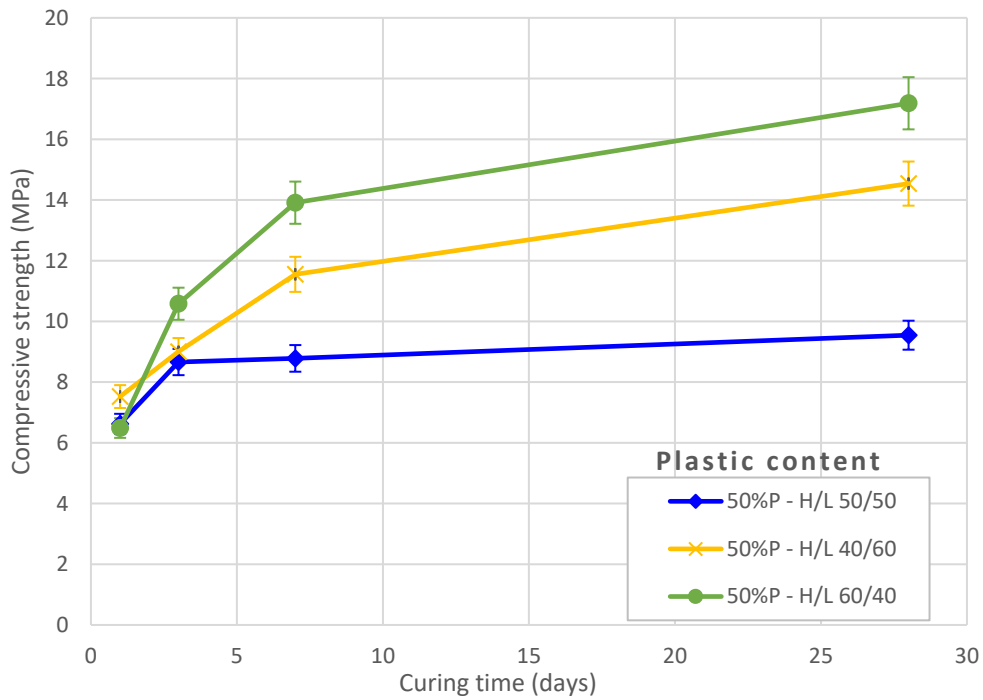


Figure 4-6: Unconfined compressive strength vs time of the MPB for different H/L ratios with plastic content (P) of 50%.

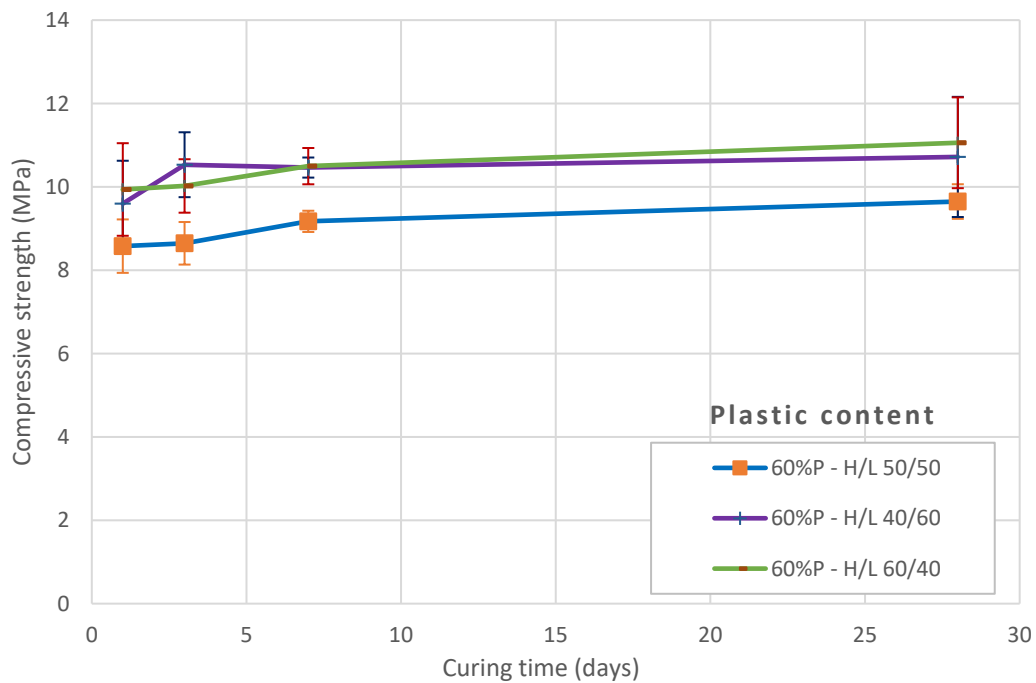


Figure 4-7: Compressive strength development vs time of MPB for various H/L ratio with plastic content (P) of 60%

4.2.3.2 Split tensile strength of the MPB

Typical results of the splitting tensile tests on the MPB are presented in Figures 4.8 and 4.9. Similar to the compressive strength test results, the splitting tensile strength of the MPB is found to increase with time for different H/L ratios. The compressive strength lies between 1.5 and 4.6 MPa. Moreover, the splitting tensile strength is shown to be a function of the H/L ratio and plastic content. It is believed that the mechanisms responsible for these changes are the same as those for the compressive strength. Moreover, the splitting tensile strength appears to be very sensitive to the cracking of the material (Fall et al. 2010), since different plastic contents and manufacturing processes can affect the porosity of the mortar, cohesion between particles, and the adhesion between plastic and sand particles in the mortar. These parameters will affect the tensile strength of the materials.

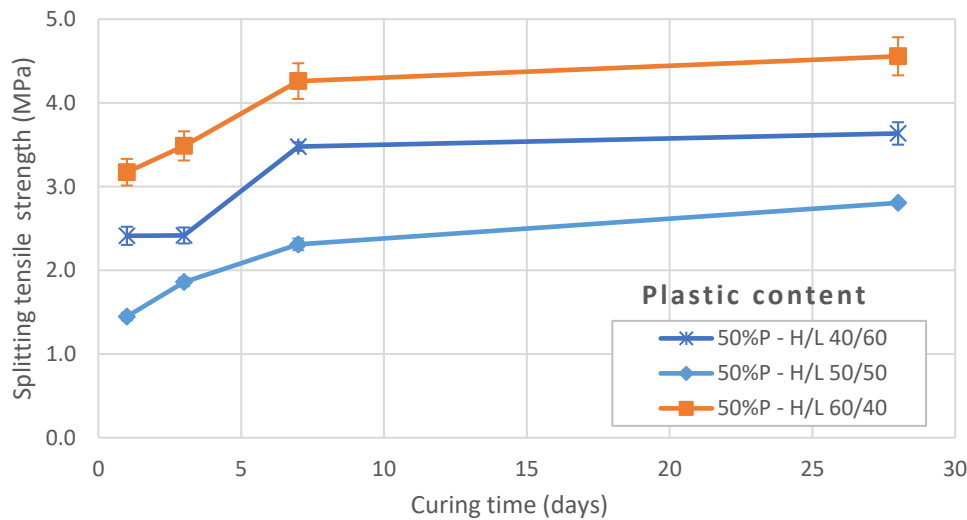


Figure 4-8: Splitting tensile strength vs time of the MPB with different H/L ratio and plastic content (P) of 50%.

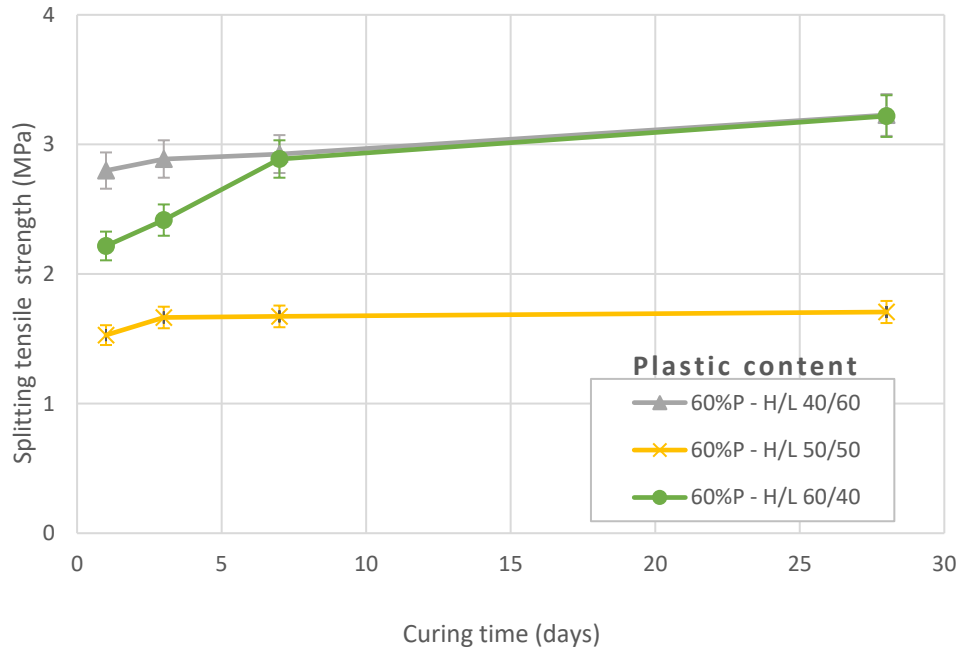


Figure 4-9: Splitting tensile strength vs time of the MPB with different H/L ratio and plastic content (P) of 60%

In practice, only the compressive strength is usually measured for quality control and assessment of the performance of many construction materials, particularly cemented materials. When needed, the tensile strength can be determined by using empirical correlation or predetermined relationships. Measurements of the compressive strength and splitting tensile strength make it possible to determine if there is a relationship between them as shown in Figure 4.10. Using a regression analysis, a linear relationship is found between the splitting tensile strength (f_t) and the compressive strength (f_c) which can be expressed by:

$$f_t = 0.1432 * f_c + 1.8129 \quad (\text{in MPa}) \quad \text{Equation 4-2}$$

(This equation 4.2 is only valid for compressive strength values between 5 MPa and 20 MPa)

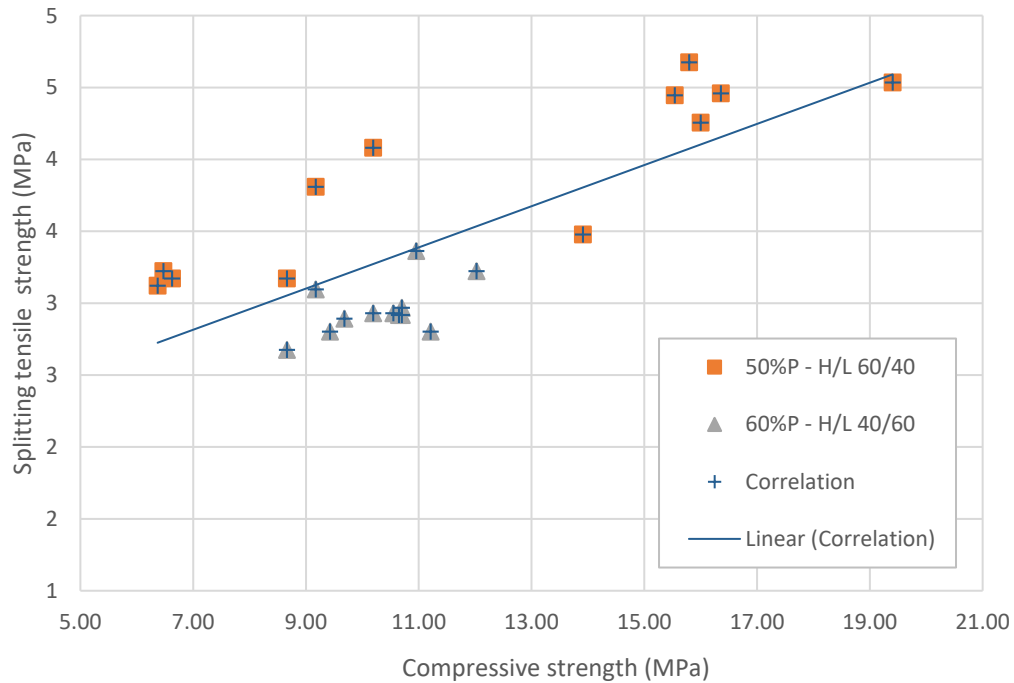


Figure 4-10: Splitting tensile strength vs compressive strength of the MPB with 50% plastic and H/L of 60/40 and 60% plastic with H/L of 40/60

4.2.3.3 Stress-strain behaviour of the MPB

Figures 4.11 shows typical stress-strain curves of the MPB under compressive and tensile stresses. The stress-strain behaviour is similar under compression and tension. In the first part of the test, the increase in stress leads to a small increase in strain under compressive or tensile stresses until reaching the peak values. At the peak, failure occurs, and the material continues to deform with a reduction in stress and continual increase in strain. This mechanism continues until full disintegration of the material.

The MPB appears to have a similar stress-strain behaviour as the conventional mortar up to the peak strength. After the peak stress, the conventional mortar tends to show brittle failure/fractures, see Figure 4.12, which is not shown in the MPB. In other words, the MPB undergoes more plastic deformation, whereas with the conventional mortar is more brittle with sudden failure (Hannawi et al. 2010).

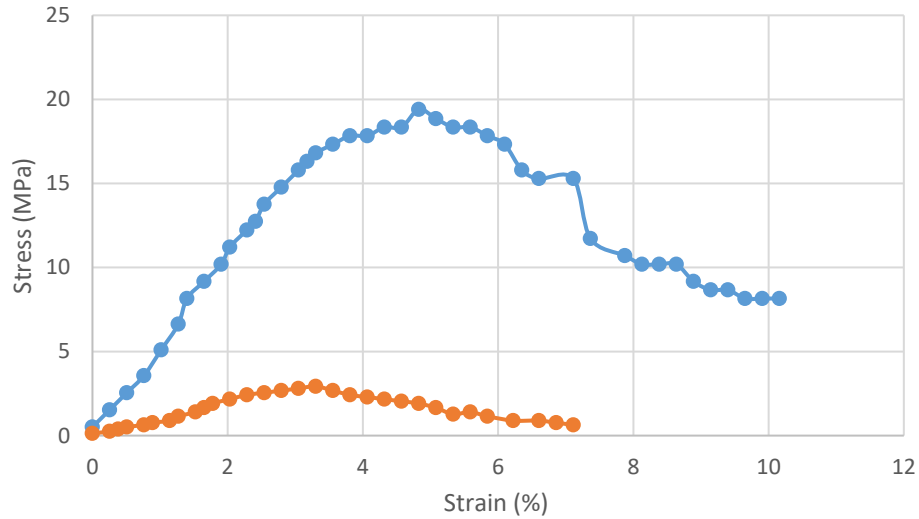


Figure 4-11: Compressive stress-strain curve of the MPB with 50% plastic and H/L of 60/40

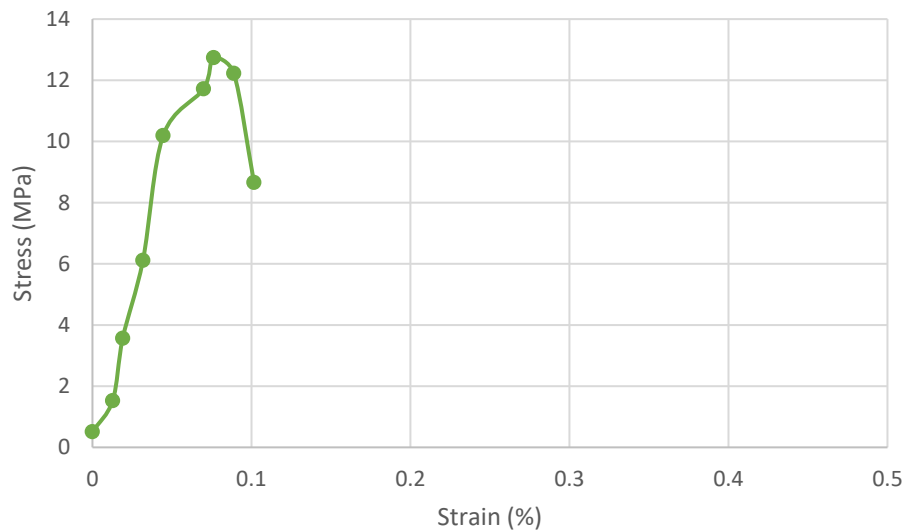


Figure 4-12: Compressive stress-strain curve of conventional mortar after 28 days

Figures 4.13 and 4.14 present the photographs that show typical failure modes of the MPB and the conventional mortar under compression. Under compression, different types of failure modes are observed for the MPB. Some samples split on the longitudinal side while others show localized fractures in specific parts of the samples or failure into the formation of a cone, see Figure 4.13(a). Despite the fractures, as shown in Figure 4.11, the MPB tends to always maintain a connection between its different broken parts, which allow it to continue to support the applied loads even after failure without total disintegration under both compression or tension. This new material undergoes extended straining before its peak with a change in slope of the deformation curve (Figure 4.11). After the peak, different parts of the sample tend to connect together for a short

period of time before completely disintegrating, thus indicating that this material is more ductile than conventional mortar. Several researchers have found similar properties for construction materials that contain plastic aggregates (Jansen et al. 2001; Malloy et al. 2001; Alqahtani et al. 2017). They all observe that concrete that contains plastic aggregates continue to deform after the peak load before complete disintegration due to the ductile behaviour of the plastic component (Jansen et al. 2001; Hannawi et al. 2010; Alqahtani et al. 2017). This finding will be of great interest for future applications especially when evaluating cracking, durability and loading capacity during the lifetime of pavements that use the MPB.



a) 50%P – H/L 50/50 samples after compressive strength tests



b) 50%P – H/L 60/40 specimen after compression

Figure 4-13: Images of typical failure behaviors observed in compressive strength tests on various MPB samples.



Figure 4-14: Images of typical failure behaviors observed in compressive strength tests on conventional mortar samples

4.2.3.4 Water absorption of the MPB

The purpose of the water absorption tests is to acquire a good understanding of immersion and the capillary absorption behavior of the MPB to gain more insight into its porosity and pore structure, and subsequently link this pore structure to some of the key engineering properties (e.g., strength, density, permeability, and durability) of the MPB, similar to previous studies (Fall and Sam, 2008; Azhdarpour et al. 2016; Kurad et al. 2017). Figure 4.15 presents the rate of absorption by immersion vs time for up to 48 hours for conventional mortar and the MPB samples. The MPB samples with the highest and lowest compressive strength were selected for the test. A higher rate of absorption, which ranges from 4% to 5%, can be observed in the conventional mortar with Portland cement. For the MPB, as expected, the absorption is higher for the sample with a plastic content of 45% and H/L of 50/50, which has the lowest compressive strength in comparison to the samples with 50% plastic and H/L of 50/50 and 60% plastic and H/L of 50/50 which correspond to a higher compressive strength. This means that the sample with 45% plastic has more interconnected pores and higher void ratio or porosity than samples with 50% and 60% plastic. This larger porosity will obviously result in a less dense structure and less resistant material (Li et al. 2020; Abukhattala and Fall, 2020; Fang and Fall, 2020). This finding agrees with the compressive strength results.

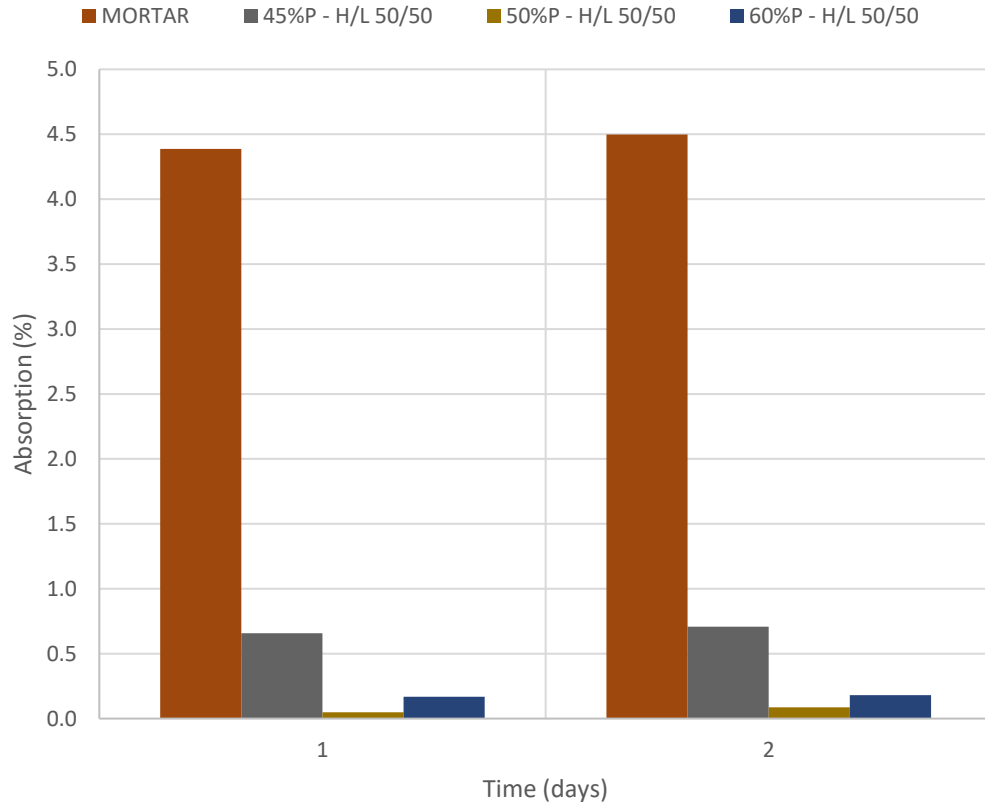


Figure 4-15: Water absorption by immersion vs time for MPB and conventional mortar samples

Figure 4.16 shows the initial and secondary absorption rates of the conventional mortar and different MPB samples with the highest compressive strength. The capillary absorption is found to increase with time for all of the samples and reaches a constant value after 7 days. The capillary absorption graphs for both the MPB and the conventional mortar show similar behavior as predicted by Halls' function (Hall, 1989) with two stages as described in ASTM standard C1585 – 20. In the first hour of immersion, there is not much difference between the absorption values for all the samples. After two hours of immersion, a clear difference can be observed between the two materials. The maximum absorption values are 5.02 mm and 2.88 mm for the 50%P - H/L 50/50 and 60%P – H/L 40/60 samples, respectively. However, the peak absorption value of the conventional mortar is 7.00 mm, which is higher than that of the MPB samples. This difference clearly reveals the effect of the pore structure because water used in making the cement paste is the major source of creating porosity in the cement mortar after the hydration process (Kurda et al. 2019). In addition, the MPB contains only melted plastic paste as the binding material, which if compacted enough, will contribute to limit water absorption.

According to previous studies, initial and secondary sorptivities can be used to evaluate the connectivity of the pore network (Yang, 2004; Kurda et al. 2019). No study has been carried out on the water absorption of mortar with HDPE and LDPE plastics. However, there are a number of relevant works on the water absorption of concrete/mortar with plastic aggregates. In general, these

studies have shown that the increase in plastic aggregates in concrete or mortar contributes to the increase of the capillary absorption (Abukhettala and Fall, 2020; Fang and Fall, 2020; Li et al. 2020). This increase is due to the creation of more pores during pouring, casting and curing. The presence of pores can be caused by the particle configuration at the ITZs between natural aggregates (sand, gravel) and plastic. However, MPB made with melted plastic is very different from cement paste. In this case, the porosity and strength will not depend on the shapes of the plastic aggregates but tied to the compactness when pouring liquid plastic in forming the MPB and the interfacial behaviour of the transition zone between plastic and sand. In addition, since the MPB samples are prepared and poured at a high temperature, over 100°C, there is greater chance of forming micro cracks and weak compaction points in the material. These cracks are formed due to thermal gradients which cause expansion and/or contraction (Henkensiefken et al. 2009) at certain depths while the MPB is in a liquid state or during manual compaction. This will affect the various properties of the MPB such as the initial and secondary rates of capillary absorption. On the other hand, the absorption values (both immersion and capillarity) of the MPB with optimal plastic contents are lower than the ones with 45% plastic and H/L of 50/50 which appears to have higher porosity than the other samples. Thus, the variation in plastic content and H/L has an impact on the absorption values of the MPB which leads to changes in strength due to the configuration at the ITZ and the degree of compaction. Moreover, loss of surface material due to flaking of conventional mortar is observed. This is not observed in the MPB during the absorption tests which is advantageous for practical use of the material in situations when the material will be in contact with running or flowing water or under high concentrations of aggressive chemicals.

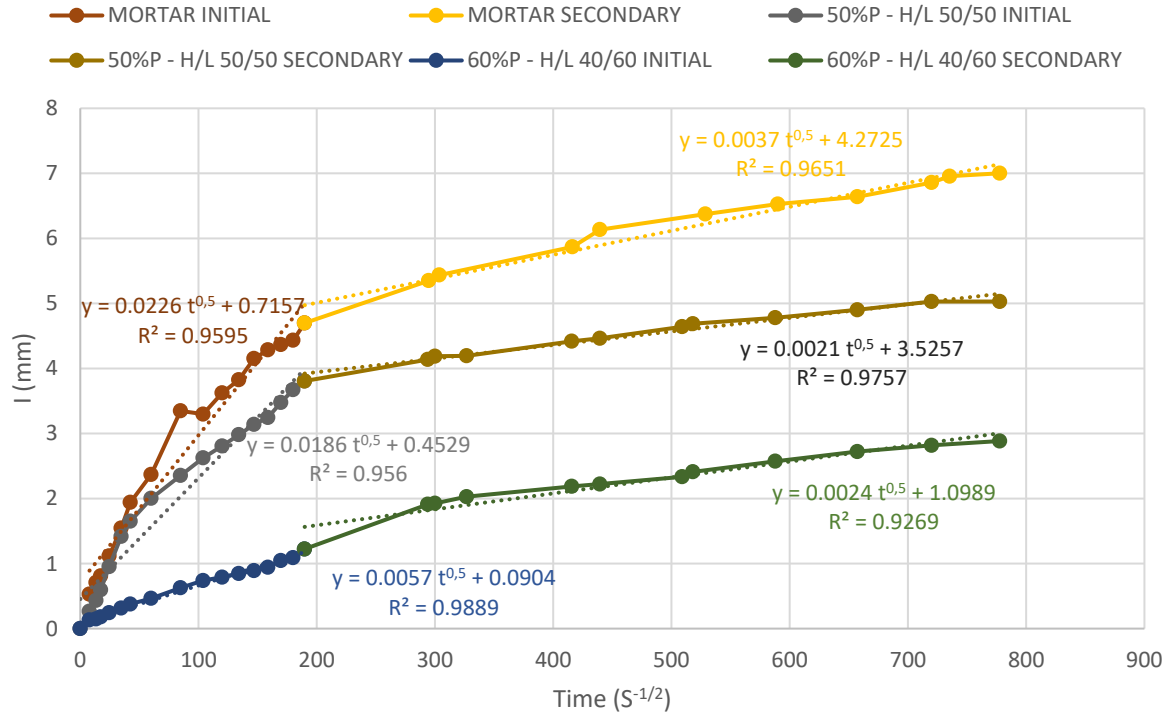


Figure 4-16: Water absorption by capillarity (I) vs square root of time showing the initial and secondary rates of absorption for conventional and MPB samples (50%P – H/L 50/50 and 60%P – H/L 40/60).

4.2.3.5 Density of the MPB

Figure 4.17 presents the density of the MPB with time for different plastic contents with an H/L ratio of 50/50. Depending on the composition of the MPB, the density is found to vary with time. The test results show that the average density of the MPB lies between 1.7 and 2.3 g / cm³. An average density of 2 g/cm³ is considered by the RILEM LC2 classification to be the minimum density for lightweight concrete (RILEM, 1978 ; Saikia and De Brito, 2012). The 28-day density of the conventional mortar is found to be 2.24 g / cm³. Therefore, the MPB listed in Table 4.1 is lighter than conventional mortar. This lightness can be explained by the fact that the density of plastic is low, 0.915-0.940 g cm⁻³ for LDPE and 0.940-0.965 g cm⁻³ for HDPE (Al-Manaseer and Dalal, 1997; Choi et al. 2005; Ismail and Al-Hashmi, 2008; HDPE, 2019; LDPE, 2019). For the conventional mortar, the binding component is cement paste and the cement itself is denser (2.8 g.cm⁻³) than the plastics. Therefore, the cement paste that bonds the granular materials will have a higher density than the virgin cement, which supports the fact that MPB is lighter than conventional mortar (NRMCA - CIP36).

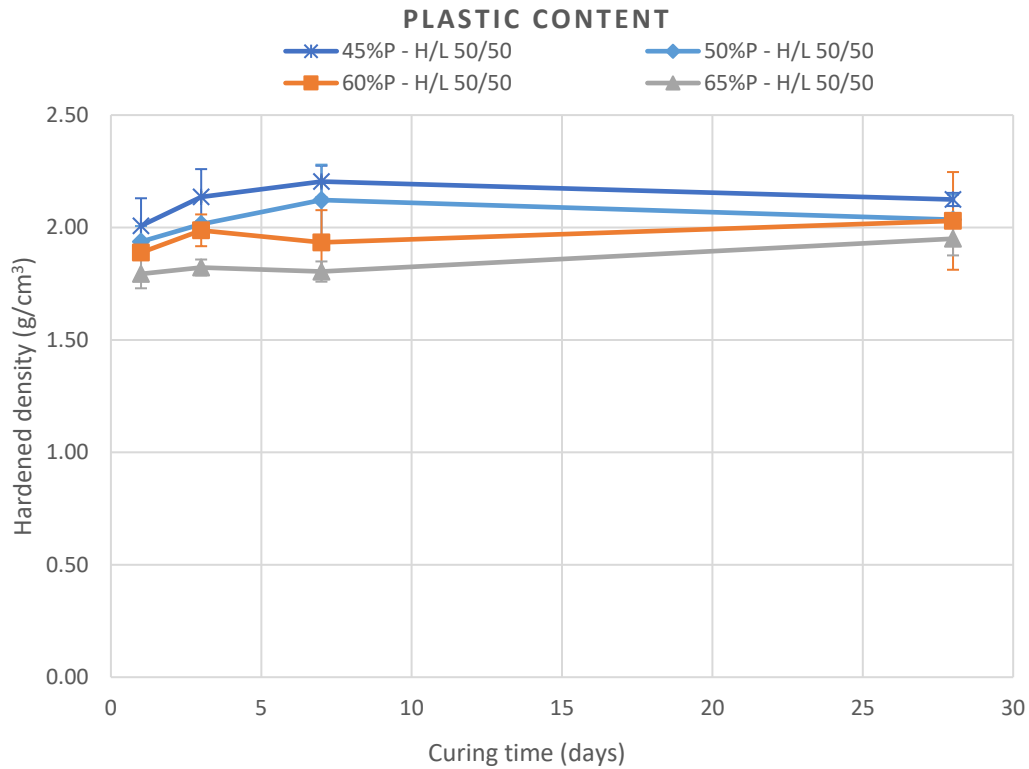


Figure 4-17: Density of MPB samples vs curing time with H/L of 50/50

Figure 4.18 shows a slight decrease of the density of the MPB samples with increased plastic content. This is related to the fact that MPB with less plastic has more sand per unit volume, which translates into a higher overall density. Bartolomeo et al. (2016) came to a similar conclusion in their study of lightweight mortars with plastic aggregates.

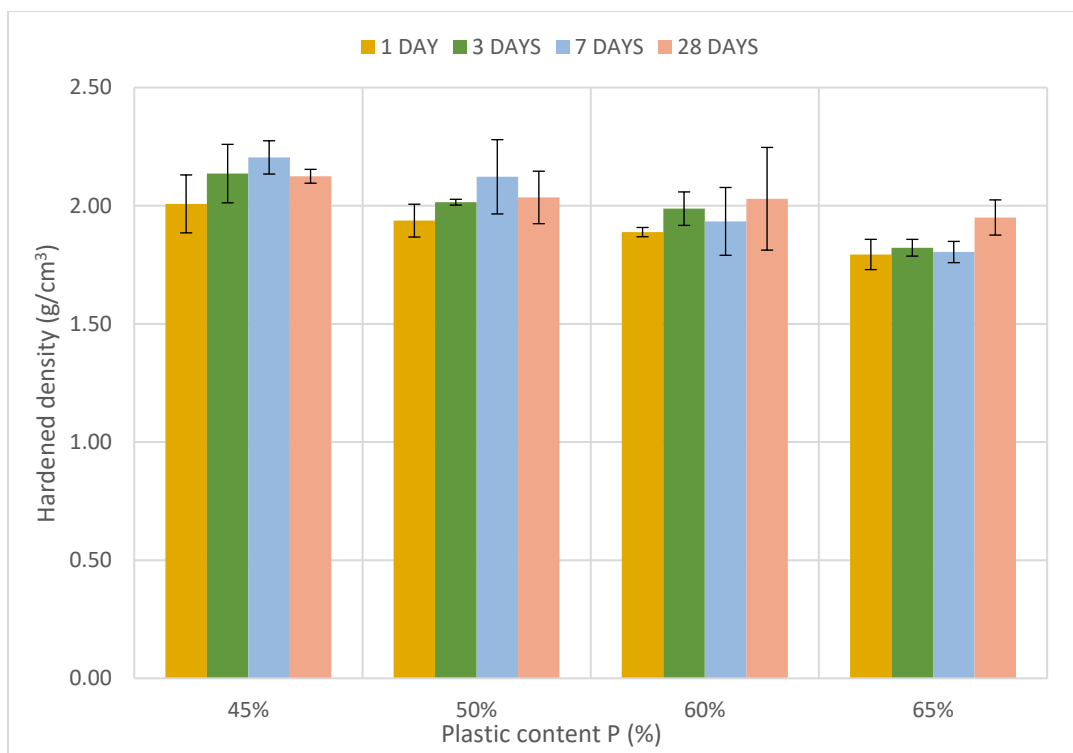


Figure 4-18: Effect of plastic content on the density of MPB with H/L of 50/50.

4.2.3.6 Microstructural properties of the MPB

4.2.3.6.1 Thermal analysis results

Figure 4.19 presents the TG/DTG results of the MPB samples that show the thermal decomposition temperature ranges for various phases of the material as well as the corresponding weight loss associated with decomposition. In general, there is little change in mass (or mass loss) below 200°C for the MPB as indicated by the TG graphs. This is because the product does not contain any water and very few impurities are present in the MPB. At a temperature above 250°C, as expected based on plastic thermal degradation, the MPB begins to show a drastic decrease in mass. For the 60%P – H/L 50/50 sample, the maximum rate of change in mass of 0.295% (compared to its initial weight) per °C is observed between 325°C and 475°C, see Figure 4.19. The sample with the least amount of plastic, 45%P – H/L 50/50, has a peak rate of loss of mass of 0.28% per °C between 400°C and 500°C. After 700°C, no mass loss can be observed in both the TG and DTG tests and the mass tends to reach a constant value. This is because the mass of the solid residue of sand in the samples no longer changes which requires a very high temperature (> 1000°C) for its decomposition. The melting temperature ranges are slightly different for these two samples, which is due to the differences in plastic content. The 45%P – H/L 50/50 sample has less plastic content than the 60%P – H/L 50/50 sample. Therefore, the latter will lose more material with more sand residue than the former in the TG/DTG tests. Similar findings have been reported by Tondl et al. (2018) for marine plastics.

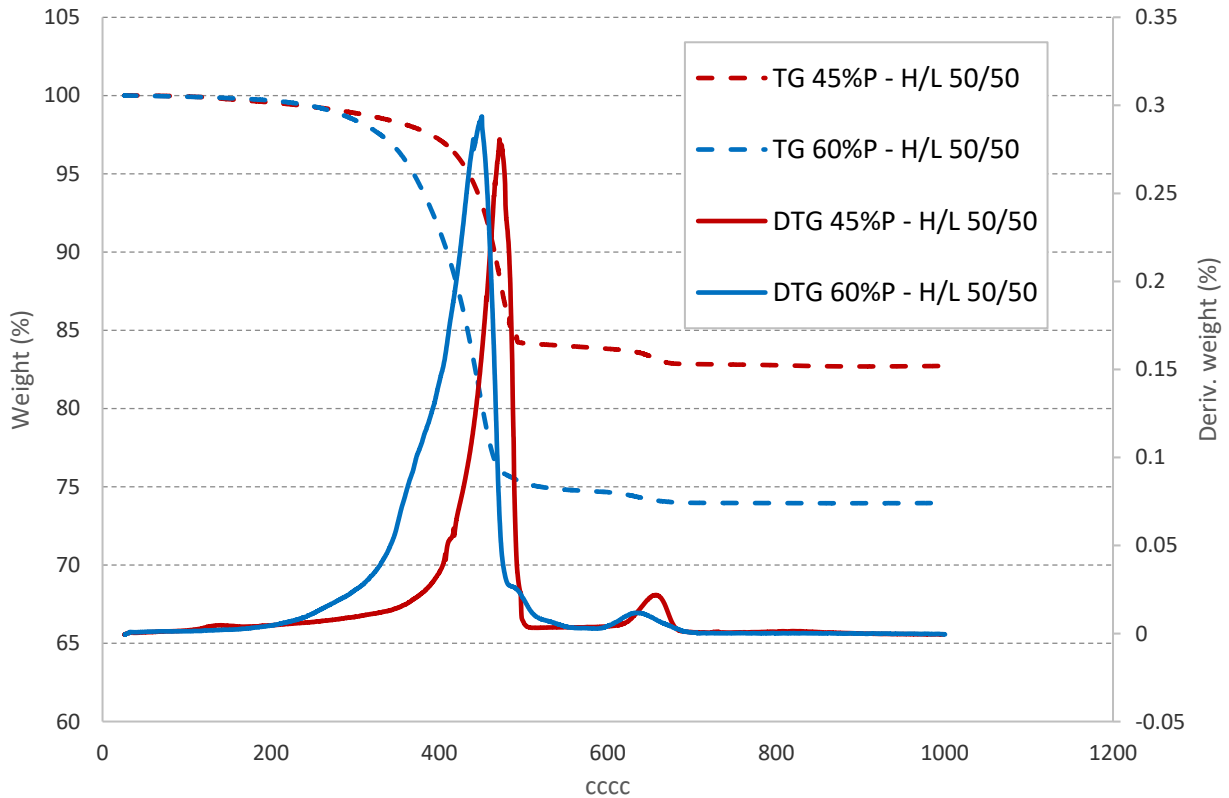


Figure 4-19: TG and DTG curves for 60%P – H/L 50/50 and 45%P – H/L 50/50 MPB samples.

To obtain more information on the thermo-gravimetric behaviour of MPB, two additional samples in the range of the optimal plastic content with different H/Ls were tested. Figure 4.20 shows the TG/DTG results for the 60%P – H/L 40/60 and 50%P – H/L 60/40 MPB samples. The results show an initial drop in the mass at 200°C similar to the previous samples (Figure 4.19). The MPB sample with 60% plastic and H/L of 40/60 has the peak mass loss at a temperature between 350°C and 525°C with a peak rate of loss of mass of 0.155% per °C (Figure 4.20). The samples with 50% plastic and H/L of 60/40 has a peak rate of loss of mass of 0.1575% per °C between 400°C to 500°C, see Figure 4.20.

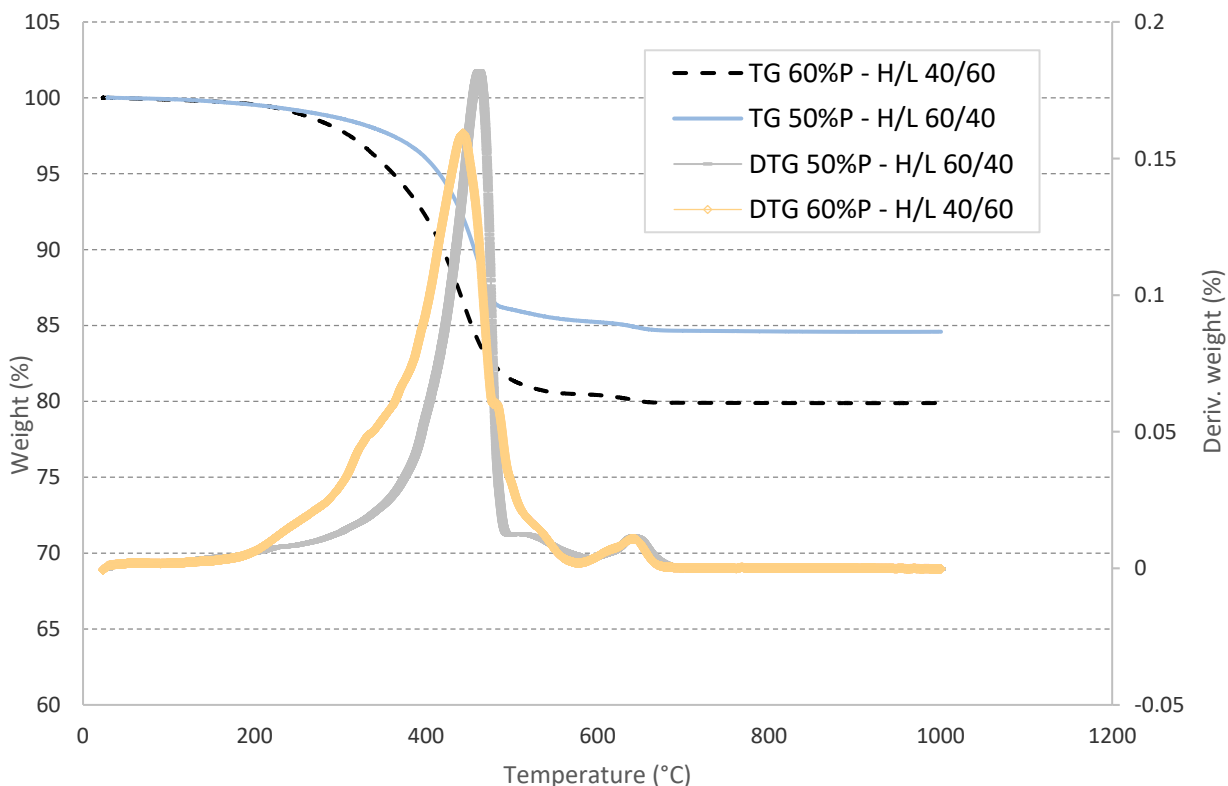


Figure 4-20: TG and DTG curves of 60%P - H/L 40/60 and 50%P - H/L 60/40 MPB samples

A similar trend has been observed for pure plastic wastes used in making the MPB samples. Figure 4.21 presents the results of the TG/DTG tests on pure HDPE and LDPE. HDPE has a peak rate of loss of mass of 0.155% per °C for a temperature range between 325°C and 450°C and the LDPE has a peak rate of loss of mass of 0.225% per °C based on the TGA curve for a temperature range between 425°C and 500°C. Tondl et al. (2018) observed similar behavior for marine plastic waste.

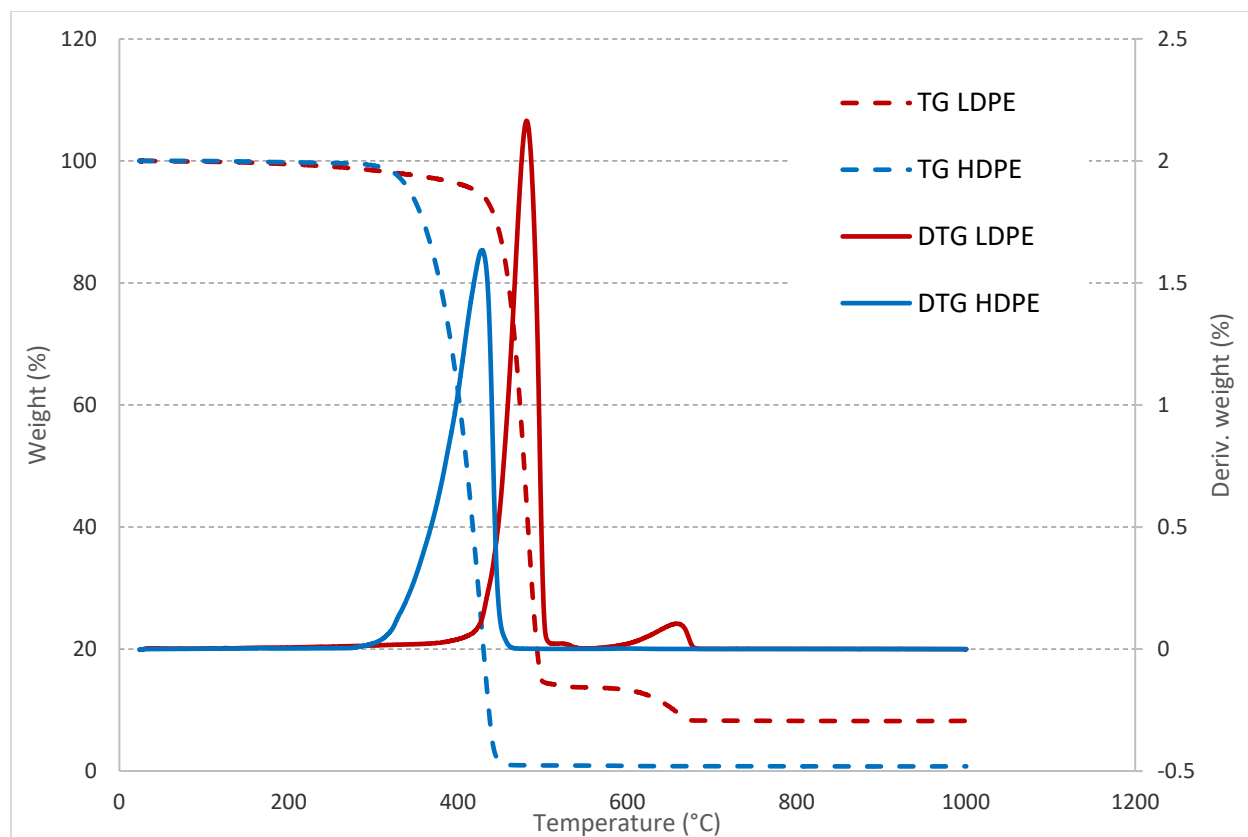


Figure 4-21: TG and DTG curves for virgin (or pure) HDPE and LDPE plastic wastes

Very different TG/DTG behavior has been observed for conventional mortar that contains Portland cement in comparison with the MPB. Figure 4.22 shows the TG/DTG results for the conventional mortar. There are apparently more than three (3) peak rates of loss of mass and the loss in mass starts before reaching a temperature of 100°C due to the presence of water in the conventional mortar. The conventional mortar with Portland cement shows three major peaks induced by various phase changes and weight losses during the experiment as observed in previous studies (Fall et al. 2010). The first peak, which appears at a temperature between 70°C and 160°C, results from the loss of capillary water and/or the decomposition of some of the elements, such as ettringite, gypsum and calcium-silicate-hydrate (C-S-H) (Zhou and Glasser, 2001; Fall et al. 2010). The second peak occurs in the temperature interval between 400 and 500°C, which is associated with the dehydroxylation or decomposition of calcium hydroxide (CH). The third peak between 550 and 750°C is due to the disintegration or decomposition of calcite (Zhou and Glasser, 2001; Fall et al. 2010).

The conventional mortar has a peak rate of loss of mass of 0.035% per °C followed by regular mass change up to the maximum peak rate of loss of mass of 0.225% per °C between 400°C and 500°C, and finish with a series of smaller peaks after 550°C, see Figure 4.22. By comparing Figures 4.20 and 4.22, it can be observed that the temperature at the peak rate of loss of mass is generally higher for conventional mortar than the MPB. In addition, the residual mass after the disintegration process is 92.5% of the initial mass for the conventional mortar while the residual

masses are 1–5% and 72.5% - 83% for the HDPE and LDPE plastics respectively. When exposed to higher temperature, conventional mortar materials seem to be more resistant to heat, but the MPB can only withstand temperatures of up to 400°C before disintegrating. Considering the observations, it can be seen that thermal degradation of material is not governed by a single element in the mixture or compound, but entails a series of processes in which all of the elements have different contributions (Murty et al. 1996; Tondl et al. 2018). Therefore, in the analysis of MPB, it should be seen as a collection of particles instead of considering the behavior of each plastic component acting individually.

Furthermore, the TG/DTG results also revealed that the decomposition temperature to achieve 50% of mass loss falls between 425°C and 475°C for the pure HDPE and LDPE plastics, which is close to the results obtained by Rajasekaran and Maji (2018) for plastic wastes with polymer (ethylene-co-methacrylic acid) and copolymer for which the temperature that corresponds to 50% of the mass loss lies between 442°C and 445°C. The MPB has, in general, more than 50% residue before the mass becomes constant due to the presence of sand. The decomposition temperature at 90% of mass loss for various types of MPB is found to lie between 450°C and 475°C, which is higher than the 90% degradation temperature of pure HDPE and LDPE plastics. This signifies the improvement in the thermal stability of plastic due to melting and/or interaction with inorganic material (Verdolotti et al. 2011; Liguori et al. 2014).

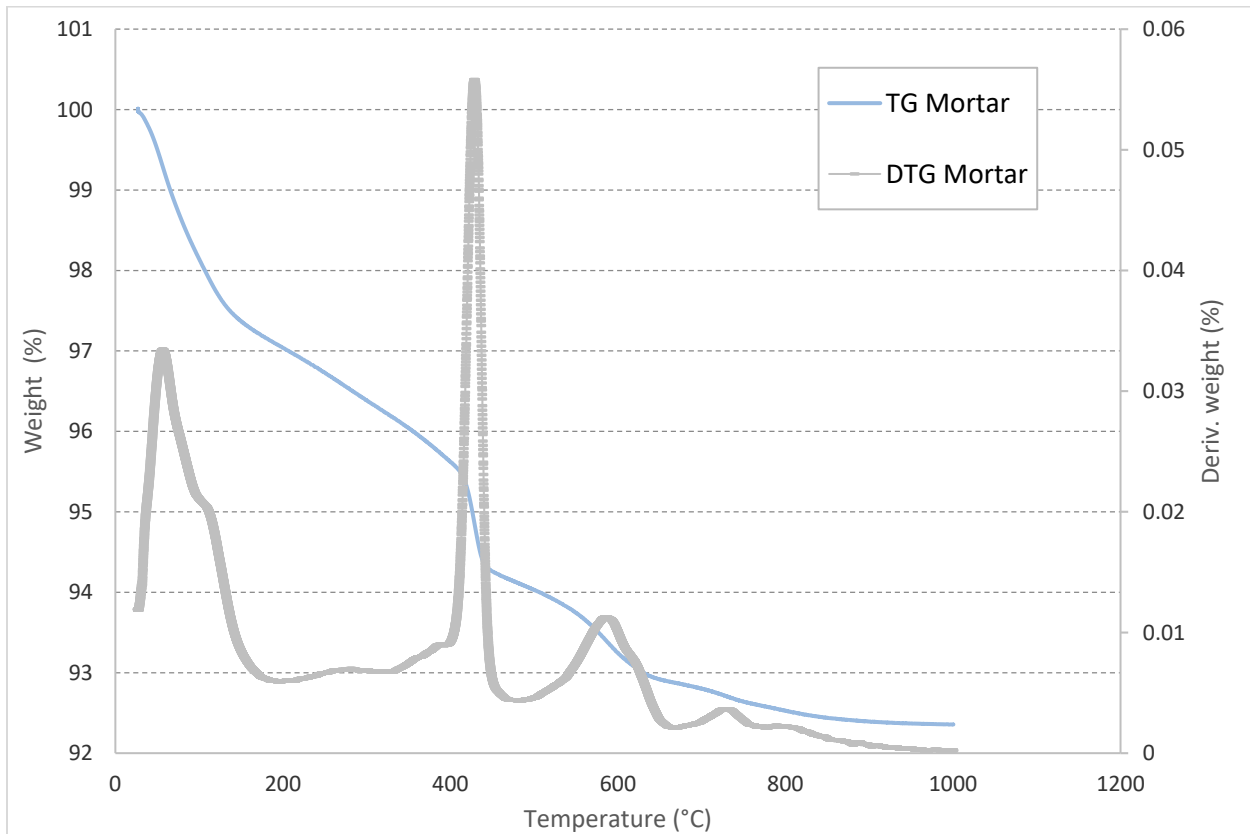


Figure 4-22: TGA and DTG curves for conventional mortar

4.2.3.6.2 Mercury Intrusion porosimetry tests results:

To understand and facilitate the interpretation of the MIP results, a description or definition of the MIP characteristics or parameters is first given in Figure 4.23, which represents a typical MIP curve for hardened cement pastes (hcps) (Ouellet et al. 2007; Zhang et al. 2019).

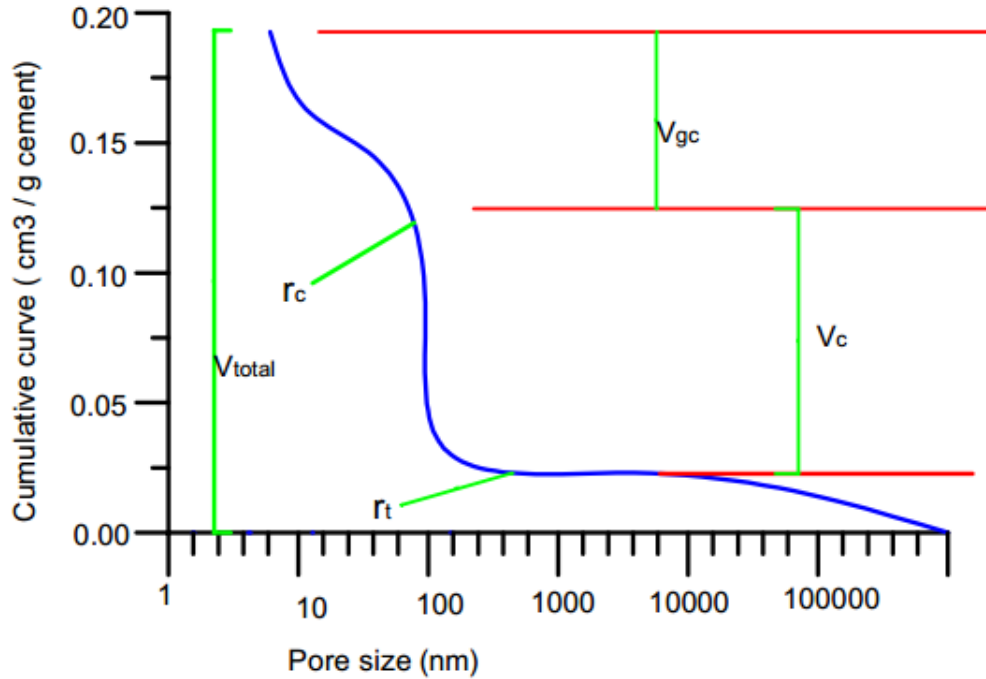
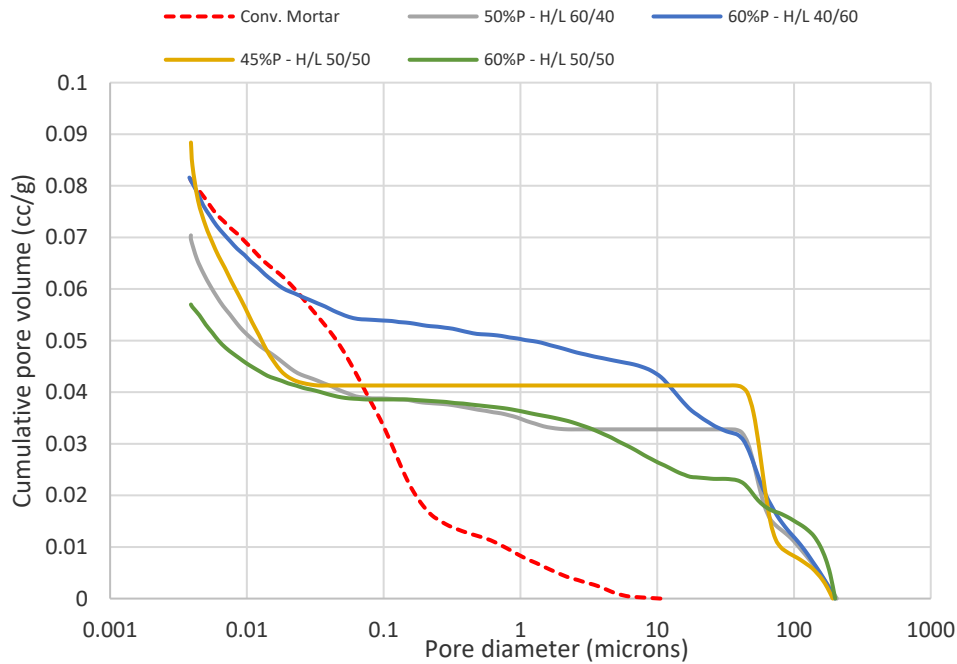


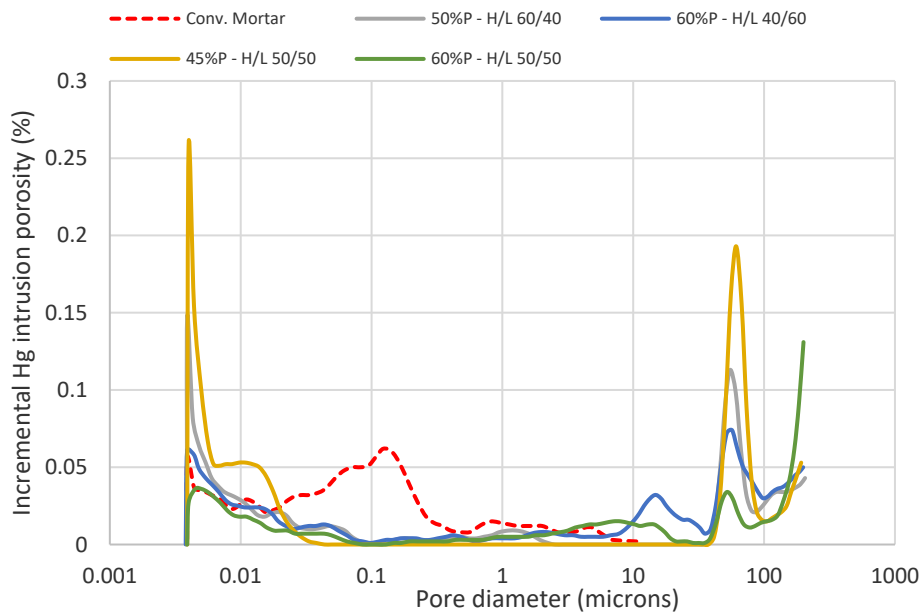
Figure 4-23: Characteristics of typical mercury intrusion curve, adapted from Zhang et al. (2019).

In Figure 4.23, r_t is the threshold radius that corresponds to the pore size under which mercury intrusion percolation occurs which is a measure of the connectivity of the pore structure, r_c is the aperture of the inflection point on the cumulative porosity curve which represents the critical radius between phases with different densities, V_{total} is the total pore volume per unit mass of the original sample, V_c represents the volume of larger capillary pores and V_{gc} represents the volume of the gel pores and smaller capillary pores.

In this paper, the MIP analysis is based on the total pore volume, threshold diameter (TD or r_t) and aperture of the inflection point (r_c). These parameters are used to calculate the volume of the capillary pores, V_c , and its percentage of the total pore volume. Capillary pores are defined as pores with a width larger than 0.3 microns and interconnected to the main network of capillary porosity (Powers, 1958). The results of the MIP tests are shown in Figure 4.24. The results of analyzing the MIP tests are summarised in Table 4.2. Figure 4.24(a) shows the cumulative pore volume and Figure 4.24(b) shows the pore size distribution of the conventional mortar and MPB with different plastic contents (45%, 50% and 60%) and H/L (60/40, 50/50, 40/60). Table 4.2 provides the MIP characteristic parameters determined from the cumulative porosity curves of the specimens (Figure 4.24).



a- MIP Cumulative pore volume vs pore diameter of different MPB and conventional mortar samples



b- MIP pore size distribution of different MPB and conventional mortar samples

Figure 4-24: MIP results of different MPB and conventional mortar samples (Conv.: conventional)

Table 4-2: MIP characteristic parameters of pore structure of different MPB and conventional mortar samples

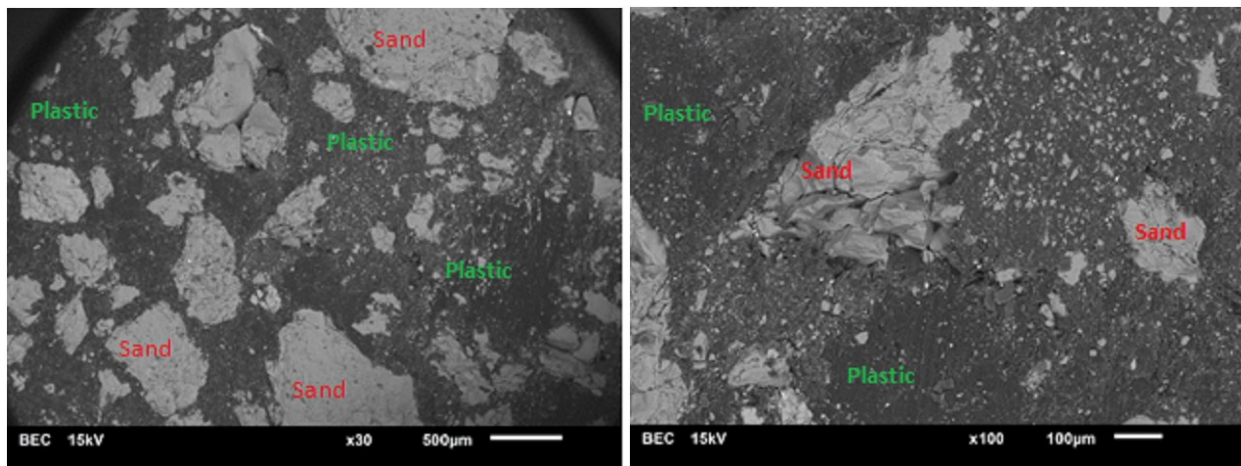
Sample	45%P - H/L 50/50	60%P - H/L 50/50	60%P - H/L 40/60	50%P - H/L 60/40	Conventional Mortar
Total pore volume, V_t (cm ³ /g)	0.0884	0.057	0.0816	0.0704	0.0815
TD or r_t , (μm)	0.0201	0.0338	0.0556	0.0474	0.0174
r_c , (μm)	80.4015	63.4965	42.9089	75.1677	1.2554
Capillary volume, V_c , (cm ³ /g)	0.0318	0.0225	0.0240	0.0243	0.0530
V_c / V_t (%)	35.97	39.47%	29.41	35.52	65.03

From the results in Table 4.2, it can be clearly seen that the total porosity and the capillary volumes that reflect larger pores in the 45%P – H/L 50/50 MPB are higher than those in the 60%P - H/L 50/50 MPB. Previous works by several authors (Odler and Rößler, 1985; Poon et al. 1997; Jiang and Guan, 1999; O'Farrell et al. 2001; Li and Aubertin, 2003) on the relationship between porosity and compressive strength for cementitious materials conclude that the increase in total porosity leads to a decrease in compressive strength. The compressive strength test results shown in Figures 4.5 – 4.7 are related to the MIP results shown in Figure 4.24 in the same fashion. The MPB with plastic content in the optimal range of 50% to 60% has higher strength and lower porosity than the 45%P – H/L 50/50 sample. A higher compressive strength can be obtained by varying the H/L within the optimum range of plastic contents based on the MIP results, see Table 4.3. The results in Table 4.3 confirm that samples with 50% plastic and H/L of 60/40 have a lower total porosity than the 60%P - H/L 40/60 sample. Therefore, from the compressive strength results, the 50%P - H/L 60/40 sample has the highest compressive strength followed by the 60%P - H/L 40/60 sample with compressive strength higher than the 45%P – H/L 50/50 MPB sample. On the contrary, the 45%P – H/L 50/50 sample has largest porosity from the MIP tests as opposed to the 60%P - H/L 40/60 sample followed by the 50%P - H/L 60/40 sample. This correlation between the compressive strength and porosity of the MPB is in agreement with the results from previous works on cementitious materials (Odler and Rößler, 1985; Poon et al. 1997; Jiang and Guan, 1999; O'Farrell et al. 2001; Li and Aubertin, 2003).

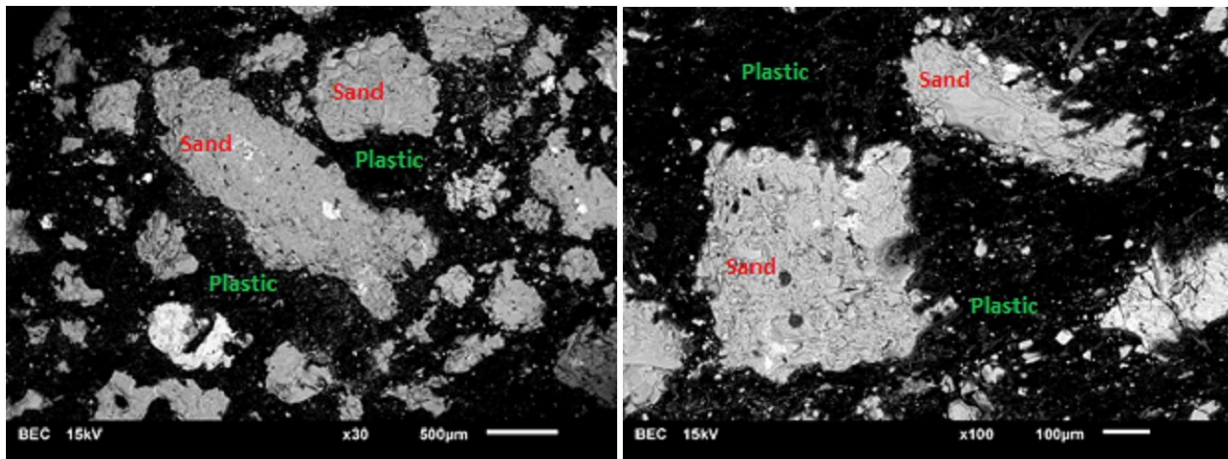
Moreover, Figures 4.24(a) and 4.24(b) compare the MIP results for the MPB samples (50%P – H/L 60/40 and 60%P H/L 40/60), in the optimal range of plastic content with the conventional mortar. Based on the data in Table 4.3, the average total porosity of the MPB samples is lower than that of the conventional mortar. Even though the pore diameter of the conventional mortar is less than 30 microns, the ratio of the capillary volume to the total porosity is about 20 – 25% higher than that of the MPB samples. This is a beneficial property of the MPB when the material is exposed to fluid intrusion or absorption, by capillary or immersion (Yang, 2004; Neithalath, 2006; Castro et al. 2011), especially in cold or sub-zero environments, by limiting the infiltration rate in the MPB, which may have an impact on its resistance to frost damage.

4.2.3.6.3 Scanning Electron Microscope results

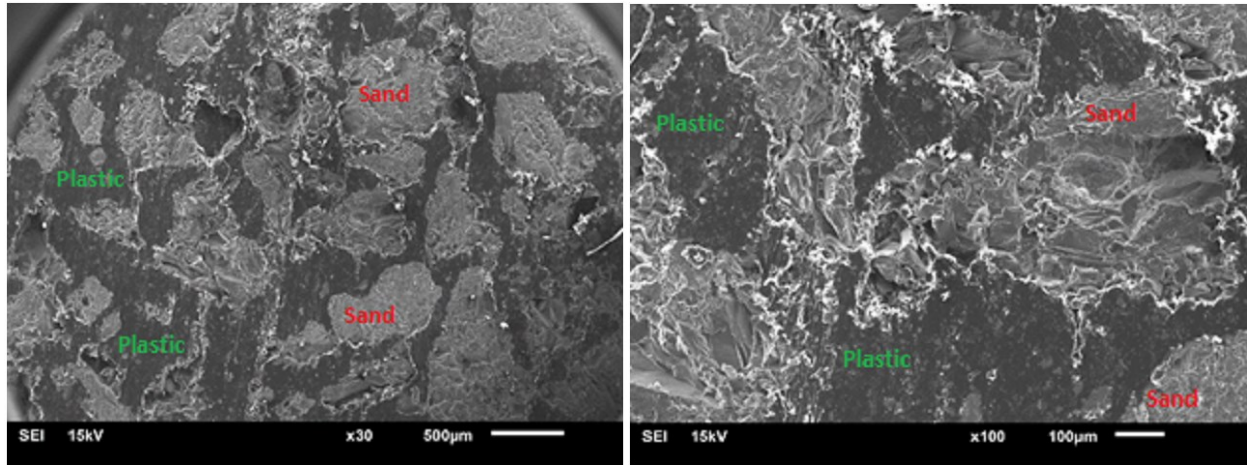
Figure 4.25 shows the SEM images (backscattered electron composition (BEC) and topographical secondary electron imaging (SEI)) of the MPB samples with different plastic contents and H/L. The MPB has mainly two components, the melted plastic binder shown in dark color and the sand shown in white color in the pictures in Figures 4.25(a) to 4.25(d). Figures 4.25(a) and 4.25(b) show the BEC at a given point of the 45%P – H/L 50/50 and 60%P H/L 40/60 samples magnified 30 and 100 times, while Figures 4.25(c) and 4.25(d) are the corresponding secondary electron images magnified 30 and 100 times. The images in Figures 4.25(a) and 4.25(b) depict the nature of the adhesion points between plastic paste and sand. The analysis of Figures 4.25(c) and 4.25(d) indicates that the porosity of the 45%P – H/L 50/50 sample is higher than that of the 60%P – H/L 40/60 sample, thus confirming the higher rate of absorption of the former compared to the latter. These results are in agreement with the findings on porosity from the MIP tests.



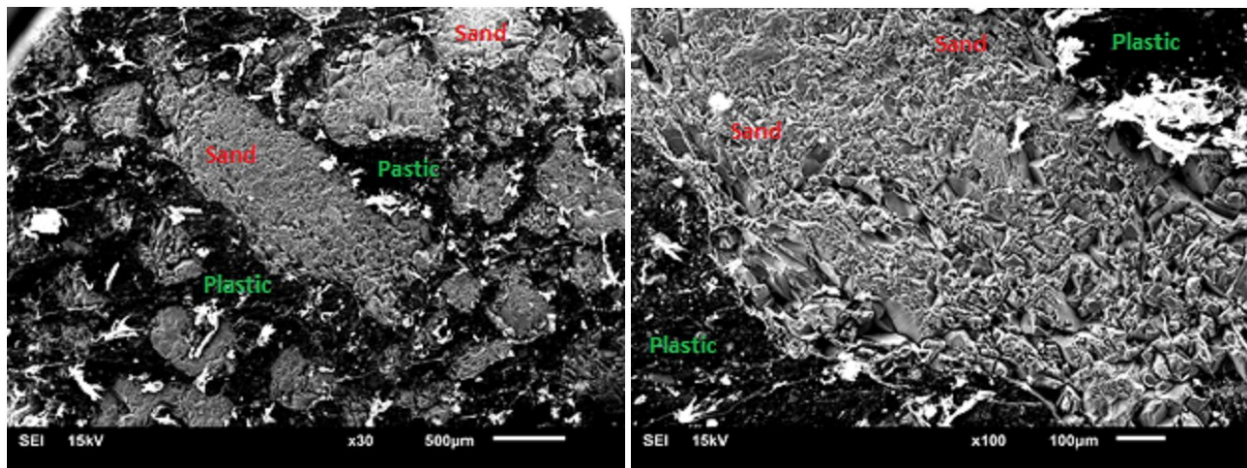
a) SEM images (magnified 30x and 100x) showing the composition (BEC) of the 45%P – H/L 50/50 sample



b) SEM images (magnified 30x and 100x) showing the composition (BEC) of the 60%P H/L 40/60 sample



c) SEM images (magnified 30x and 100x) showing the topography (SEI) of the 45%P – H/L 50/50 sample



d) SEM images (magnified 30x and 100x) showing the topography of the 60%P H/L 40/60 sample

Figure 4-25: SEM topography (SEI) and composition (BEC) images of the MPB samples

4.2.4 Summary and conclusions

This research work presents the experimental results on a study of the mechanical, physical and microstructural properties of a new ecological building mortar made with melted plastic waste as the only binder material. The findings and conclusions are as follows:

- The compressive strength of the proposed new material is found to be between 5 and 18 MPa, regardless of age and plastic content, while its splitting tensile strength varies between 1 and 5 MPa. A linear relationship is developed between the tensile strength (F_t) and the compressive strength (F_c) of the material. The splitting tensile strength appears to be very sensitive to cracking, which is linked to the porosity of MPB.

- Irrespective of the plastic content, the strengths are found to increase with time due to the solidification of the plastic binder. The highest compressive strength values are obtained for samples with plastic contents of 50% and 60% and an H/L ratio of 50/50, whereas the plastic contents of the 50%P - H/L 60/40 and 60%P - H/L 40/60 samples show the highest splitting tensile strengths. The MPB samples with an optimum plastic content (50% to 60%) has lower porosity and stronger inter-particle bonding than the others, thereby leading to higher strengths.
- The MPB reaches around 60 to 80% of its final strength after just one day of curing, much higher than the conventional mortar which typically reaches less than 40% of its ultimate strength in one day.
- During the initial stage of curing, the ITZ between the plastic paste and the sand particles has some weak points. With time, these weak points strengthen and become stronger during solidification and increase the compactness of the MPB with an increase in the elasticity of the material. Therefore, a high elastic modulus and better adhesion in the MPB will lead to an improvement in its strength with time.
- The MPB is more ductile with a higher degree of plasticity than the conventional mortar with Portland cement. Even after failure at the peak strength, the MPB is able to sustain further straining before complete disintegration. Failure cones, longitudinal cracking and localized disintegration are the common failure modes of the MPB samples.
- The initial and secondary sorptivities, and total water absorption by immersion and capillarity are found to be lower for the MPB samples at any given time in comparison with the conventional mortar.
- The decomposition temperature at 90% of mass loss for different MPB samples is found to be between 450°C and 475°C, which is higher than the 90% decomposition temperature of pure plastics. That means that there is an improvement in the thermal stability of plastic due to melting and/or interaction with inorganic materials.
- The total porosity and the capillary volumes reflect larger pores in the 45%P H/L 50/50 mortar than the 60%P – H/L 50/50 mortar. The average total porosity of the MPB is found to be lower than that of the conventional mortar. The ratio of the capillary volume to the total porosity of the conventional mortar is found to be 20 – 25% higher than that of the MPB samples. From the SEM images, the conventional mortar appears to be more porous than the MPB.
- This new material has good potential for use as a construction material to recycle plastic waste and reduce the impact of plastic on the environment.
- Despite the promising results obtained in this study, it is also clear that life cycle assessment should be conducted to gain a deeper insight into the ecological or environmental impacts or benefits associated with all the stages of the life cycle of this new construction material.

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- ASTM C138/C138M - 17a Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete
- ASTM C496/C496M - 17 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens
- ASTM C1585 - 20 Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes
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4.3 Technical Paper 2: Properties of a mortar with plastic waste binder (MPB): Impact of granular material size and curing conditions

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Abstract

There has been a growing interest in the potentials of incorporating plastic waste in concrete and other construction materials for economic and environmental benefits. This research study aims at evaluating the effect of the size of the granular material (sand) and curing conditions on different properties of the mortar with plastic waste binder (MPB).

Granular material size and curing conditions were found to have impact on the mechanical strength of the MPB materials, however, curing conditions were found to not have adverse effect on the MPB density. Regardless of age, plastic content and H/L ratio, the MPB samples subjected to thermal shock in water showed lower strength (compressive and tensile) than the specimens cured at ambient temperature under controlled laboratory conditions, while adding coarse granular materials helped to improve these strength properties. A relative decrease from 10% to 143% (0.22 to 1.99 MPa) was observed in tensile strength when the MPB curing conditions moved from air-dry to thermal shock curing in water. A linear correlation was found between the compressive strength and splitting tensile strength of MPB independent to the curing regime.

The absorption values were higher for MPB subjected to thermal shock in water, confirming its higher porosity, pores interconnectivity and subsequently lower strength compared to the specimen cured at ambient temperature in controlled laboratory conditions. Moreover, independent to the curing conditions, the absorption of MPB was found to be lower than the ones obtained for the conventional mortar made of sand and cement. In general, the mortars with plastic binder were found to be light materials based on their density and able to withstand heavy loads without undergoing sudden/brittle failures like the conventional cement-based mortar.

Keywords: Plastic waste; granular materials, curing conditions, recycling; MPB; construction materials; cement

4.3.1 Introduction

The global demand for plastics was nearly 212 million tons in 2013 and was expected to reach 304 million tons by 2020 (GVR, 2015). Most of these plastics end up in the landfills and ocean, contributing to the pollution of the environment and endanger aquatic animals. By considering wastes as resources instead of a problem to be solved, some researchers come up with alternatives providing social, environmental and economic benefits. Among these, is the use of plastics wastes (melted or not) to develop construction materials. With the recent attention being given to environment protection, new ways are emerging towards developing more environmentally friendly concrete and mortar using various types of wastes as substitute/additive.

Indeed, several researchers (e.g., Rebeiz 1996, Soroushian et al. 1999, Sam and Tam 2002, Choi et al. 2005, Batayneh et al. 2007, Marzouk et al. 2007, Kou et al. 2009) showed the possibility of using plastic waste aggregates as substitute of sand/gravel in concrete/mortar. With the density and compressive strength ranging between 1000-2000 kg/m³ and 5-60 MPa, respectively, they come to the conclusion that the compressive strength decreases with an increase of plastic aggregate proportion in the given concrete/mortar when the replacement ratio is higher than 0.5%, and the corresponding material is more resistant to cracks than the conventional concrete. Al-Manaseer and Dalal (1997) observed ductile behaviour for concrete containing car bumpers plastic as aggregate, which contribute to reduce cracks in the corresponding concrete. Marzouk et al. (2007) found that using plastic aggregates in concrete can lead to an attractive low-cost material, which can be an alternative to conventional concrete and contribute in solving solid wastes related problem, especially its high pollution. Soloaga et al. (2014) observed lower emission (footprint) for 1 m³ of concrete mix containing 20% of plastic waste aggregates compared to the same amount of conventional concrete with natural aggregates. In another study, polyester resins were added to sand and gravel to prepare polymer concrete and it was observed to reach 80% of its final strength at one day (Rebeiz, 1996). Same material was found to be resistant under compression and tension in comparison to conventional cement concrete (Sam and Tam, 2002).

With the international interest about climate change (environment) and its adaptation methods, various eco-friendly materials were developed in recent years. Recycling plastic wastes material for making useful construction material is one of the options contributing to attend some sustainable development goals. With this aim in mind, Thiam and Fall (2020) developed a mortar with melted plastic wastes (HDPE and LDPE) as the only binder (MPB). The potential benefits of this alternative construction material are significant, however a fundamental understanding of the effect of key influencing factors on the engineering properties of MPB is still far from complete. Many fundamental questions about the mechanical and physical response of MPB to various curing conditions or granular material composition have been left unanswered. For example, what is the effect of curing conditions on key mechanical and physical properties of MPB? How much would the grain size distribution of granular materials affect the mechanical and physical properties of MPB? No previous research has studied the effect of samples curing conditions (on air and thermal shock in water) on the mechanical and physical properties of MPB using melted plastics (HDPE and LDPE) as the only binder. This paper reports on the investigations performed to understand the effect of samples curing conditions as well as the grain size distribution of granular materials on the physical (density, water absorption) and mechanical (e.g., compressive strength, splitting tensile strength, deformation behaviour) properties of the MPB. The findings will contribute to a better understanding of the engineering properties and performance of MPB under various environments.

4.3.2 Experimental Program

4.3.2.1 Materials and methods

4.3.2.1.1 Materials

High-density polyethylene (HDPE) and Low-density polyethylene (LDPE) plastic wastes (Figure 4-26), collected from wastes transit stations in Bamako (Mali), washed and cut to the corresponding sizes for experiment purposes, were used to prepare the MPB specimens. Moreover, natural sand from Niger River in Bamako (Mali), whose characteristics are displayed in Figure 4-27, was used as natural aggregates for preparing the MPB and conventional mortar samples.

The grain size distribution of the sand, determined according to ASTM C136 / C136M, is shown in Figure 4-28. Since the original granular material from the river is composed of sand and gravel, it has been first sampled (Figure 4-28). The sampled sand was used to obtain the appropriate amounts and dimensions of fine sand S (< 2 mm) and GS granular material (composed of 70% of fine sand (< 2 mm) and 30% of coarse material between 2 mm and 4.75 mm) for various formulations of the MPB specimen (Figure 28).

Tap water and Portland cement type I were employed for the conventional cemented mortar preparation, which was used to gain more ideas on the MPB specimen. Manual oven with its appropriate heat system and metallic cylindrical molds (5cm in diameter – 10 cm in height) were used for the preparation of MPB using melted plastics (HDPE and LDPE) as the only binder.



Figure 4-26: Samples of a) HDPE and b) LDPE plastic wastes used during the experiments.



Figure 4-27: The location and sample of the sand used during the experiments

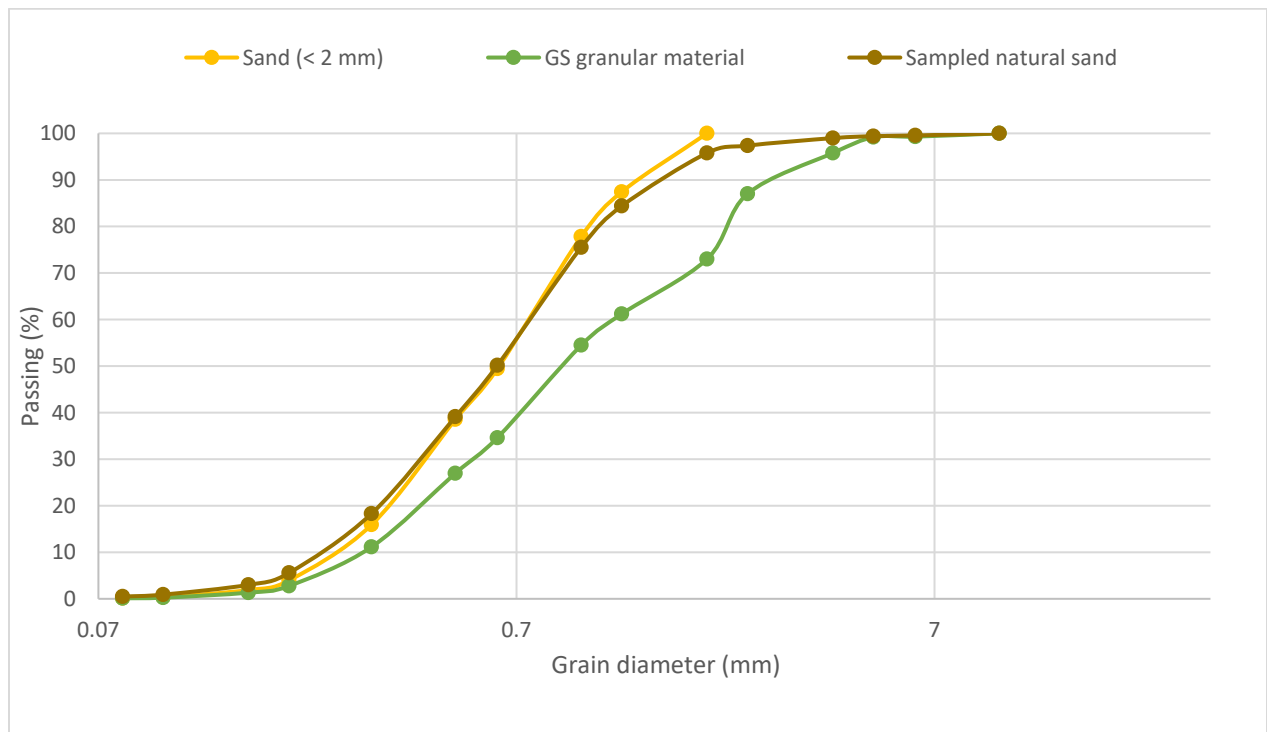


Figure 4-28: The particle size distribution of the sampled sand and used granular materials for MPB preparation.

4.3.2.1.2 Sample preparation and curing methods

Conventional mortar (with sand to cement ratio of 3 and water to cement ratio of 0.5) was used as the reference material. It was prepared by mixing the dry mass of sand and cement for 3 minutes, after which water was added and mixed for 7 min. It should be underlined that the goal of using

conventional mortar in this research is not to compare the performance of these two materials, but rather to gain a deeper insight into the properties of the MPB.

Natural river sand and gravel, as the only aggregates, were mixed with different proportions of molten HDPE and LDPE using the optimal plastic contents for mortar with plastic binder determined by Thiam and Fall (2020). Plastic materials in small pieces (less than 6 cm in length) and dried granular materials (sand and gravel) passed to the corresponding sieves were employed to prepare MPB samples with various plastic contents and H/L ratios.

Two plastic contents, 50% and 60% of total dry mass of sand and three HDPE to LDPE ratios (H/L of 40/60, 50/50 and 60/40) were employed and melted in the oven. The mix design compositions of various MPB samples are presented in Table 4-3. The melting time took 20 to 45 minutes depending on the type and amount of plastic. The coarser granular material, called GS, contains of 70% of finer sand (< 2 mm) and 30% of sand and gravel ($2 \text{ mm} < \text{size} < 4.75 \text{ mm}$), whereas the finer granular material (S) consists of 100% of finer sand (< 2 mm) (Table 4-3, Figure 28). Cylindrical samples (5 cm in diameter and 10 cm in height) were prepared and cured under different conditions for the purpose of the experiments (Figure 29). Prior to pouring the liquid MPB, the inner surface of the cylindrical molds was coated with lubricant to facilitate extraction. The plastic melting temperature was found to be around 250°C for an initial ambient temperature between 24 to 30°C . Once sand was added to the melted plastic and mixed, the obtained homogeneous MPB paste is poured into the molds and kept under pressure using manual press to ensure proper compaction and limit sagging. Half an hour later the various MPB specimens were demolded and cured for 1, 3, 7 and 28 days.

The size of the granular material was varied to understand the effect of the aggregate fineness or coarseness on the mechanical strength of the MPB.

After casting, fresh MPB and conventional mortars were allowed to cure under laboratory-controlled ambient temperature conditions (about 27°C). Another set of hot MPB samples were subjected to thermal shock through rapid curing. This was done by putting the specimens in water right after pouring them in the molds and kept in for a period of time before the test. These samples have the same nomenclature as the ones in the Table 4-3, with the letter “W” appended at the end of the sample name. The MPB and conventional mortars samples were tested to determine various properties, such as density, absorption, compressive and splitting tensile strengths at different curing ages.



Figure 4-29: Samples of MPB with melted plastic wastes as binder before and after demolding.

Table 4-3: Mix composition and curing time of the MPB using melted HDPE and LDPE plastic wastes as the only binder

Mortar with plastic binder sample*	Plastic binder type	Plastic binder content (%)	HDPE / LDPE	Granular material	Curing time (days)
S 50% P – H/L 60/40	HDPE – LDPE	50	60/40	Sand	1, 3, 7, 28
S 50% P – H/L 50/50	HDPE – LDPE	50	50/50	Sand	1, 3, 7, 28
S 50% P – H/L 40/60	HDPE – LDPE	50	40/60	Sand	1, 3, 7, 28
S 60% P – H/L 60/40	HDPE – LDPE	50	60/40	Sand	1, 3, 7, 28
S 60% P – H/L 50/50	HDPE – LDPE	50	50/50	Sand	1, 3, 7, 28
S 60% P – H/L 40/60	HDPE – LDPE	50	40/60	Sand	1, 3, 7, 28
GS60% P – H/L 50/50	HDPE – LDPE	60	50/50	Gravel-Sand	1, 3, 7, 28
GS50% P – H/L 50/50	HDPE – LDPE	50	50/50	Gravel-Sand	1, 3, 7, 28

P: plastic content in in (wt %) by reference to the dry mass of sand, H/L ratio of HDPE to LDPE. * The letters S at the beginning of the sample names refer to MPB, which has only fine sand smaller than 2 mm in their composition. The samples commencing with GS correspond to MPB samples prepared using 70% of sand (smaller than 2 mm) and 30% of sand and gravel (which sizes are between 2 to 4.75 mm).

4.3.2.2 Testing of the specimens

The dimensions and weight of the specimens were measured to determine their densities following ASTM C 138 / C138M - 17a. For each formulation, the test was repeated at least three times to ensure the repeatability.

ASTM C39 / C39M – 18 and ASTM C496 / C496M – 17 instructions were followed for the determination of the compressive and splitting tensile strengths. The tests were performed at a rate of 1 mm/min to record the deformations under variable applied force until reaching the failure and/or full disintegration. From the obtained strength results for MPB, a linear correlation between compressive and splitting tensile strengths was derived as well as the stress- strain curve for various formulations of the MPB.

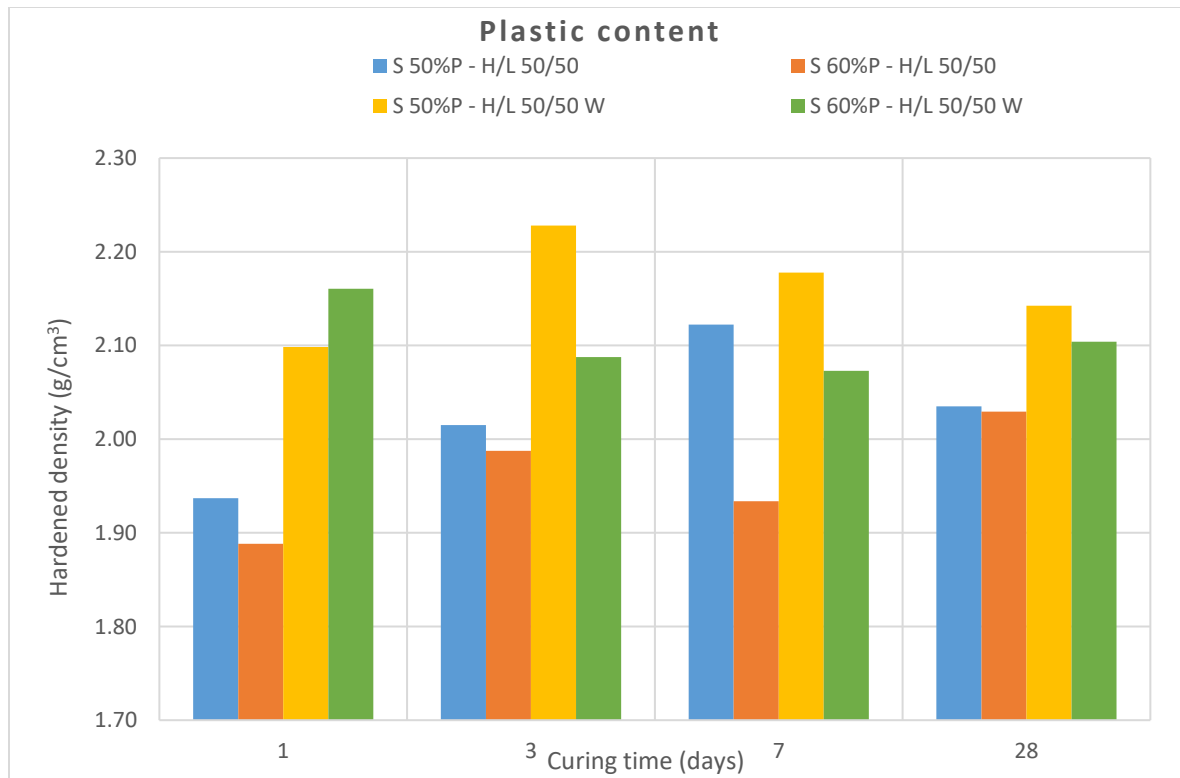
The samples for water absorption test were dried in the oven at 60°C for two days to eliminate of any water they might contain. Then, the samples were immersed in distilled water tanks for 48 hours to determine the immersion absorption in accordance to ASTM C97 / C97M – 18 specifications. The rate of absorption by immersion in percentage (%), is equal to the difference between the weight of the sample after 48 hours and the initial weight divided by the initial weight. The average is then calculated for each formulation with a given plastic content and a fixed HDPE-LDPE ratio.

4.3.3 Results and discussions

4.3.3.1 Impact of curing conditions on the MPB properties

4.3.3.1.1 Impact of curing conditions on the MPB density

Figure 4-30 presents the densities of MPB samples subjected to two curing regimes, namely at ambient room temperature and under sudden cooling in water with thermal shock caused by the temperature changes. Both curing conditions showed similar time-dependent behaviour, with the density varying with time and hardened conditions of the MPB specimens. The values of density were found to be between 1.9 and 2.3 g / cm³ and the thermal shock does not seem to have significant impact on the MPB density. This fact can be related to the hydrophobic behaviour of plastic paste and the absence of mass loss when the MPB samples are placed in water (Thiam and Fall, 2020). Moreover, independent to the curing conditions, the average density was found to be around 2 g/cm³, considered by RILEM classification as the structural lightweight material (RILEM LC2, 1978).

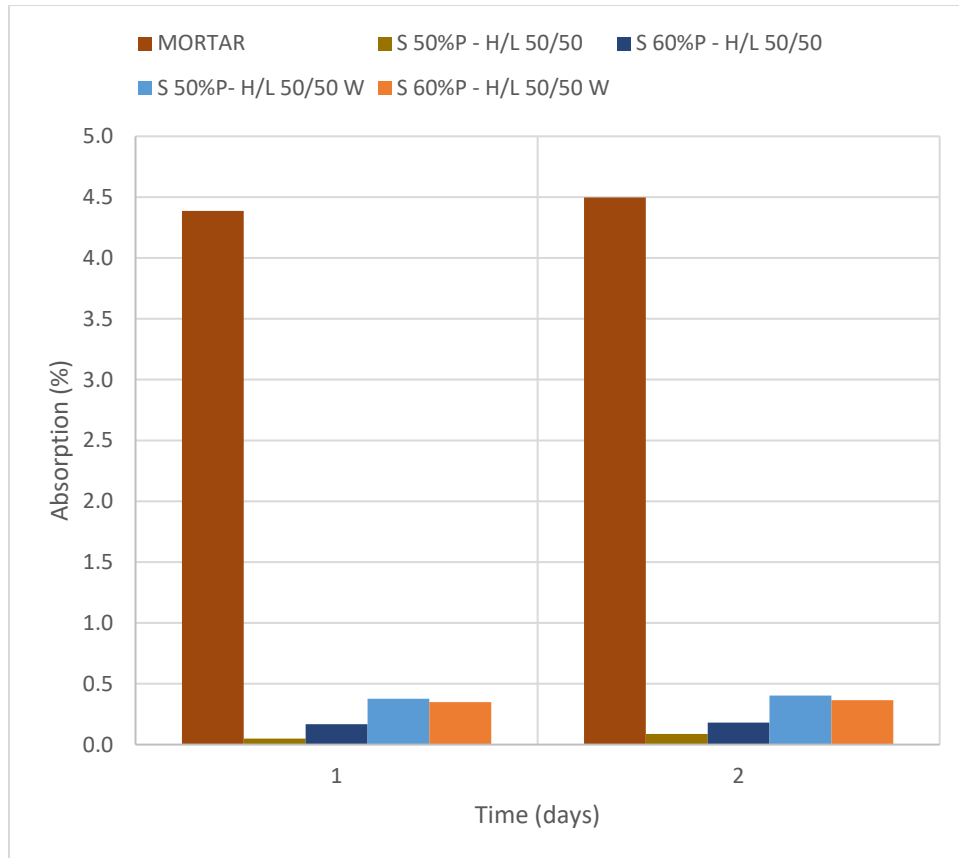


* The letters S at the beginning of the sample names refer to MPB with only fine sand smaller than 2 mm in their composition and the letter “W” appended at the end of the sample name means hot MPB samples subjected to thermal shock through rapid curing

Figure 4-30: Effect of curing conditions on the hardened density of MPB for various plastic contents (sand particle size < 2mm; HDPE/LDPE = 50/50).

4.3.3.1.2 Impact of curing conditions on immersion absorption of MPB

Figure 4-31 presents the influence of curing conditions on the immersion absorption behaviour up to 48 hours for MPBs containing 50% and 60% of plastic content with equal amount of HDPE and LPDE. The absorption values are higher for MPB that was subjected to thermal shock, confirming its higher porosity and pores interconnectivity. Indeed, the water (at 26 to 30°C) in contact with MPB specimens (at temperature higher than 100°C), will create a temperature difference of more than 70°C, impacting the internal pores structure and the ITZ within the MPB sample body (Braun 2002; Mehta and Monteiro 2006; Darquennes et al. 2011; Volk et al. 2015; Ragaert et al. 2017; Krishna et al. 2019; Duan et al. 2020). Moreover, independent to the curing conditions, the absorption of MPB was found to be lower than the ones obtained for the conventional mortar made of sand and cement. This is due to the hydrophobic behaviour of plastic paste in the MPB as well as the cracks induced by the water during the drying stage of the conventional mortar specimen (Kurda et al. 2019).

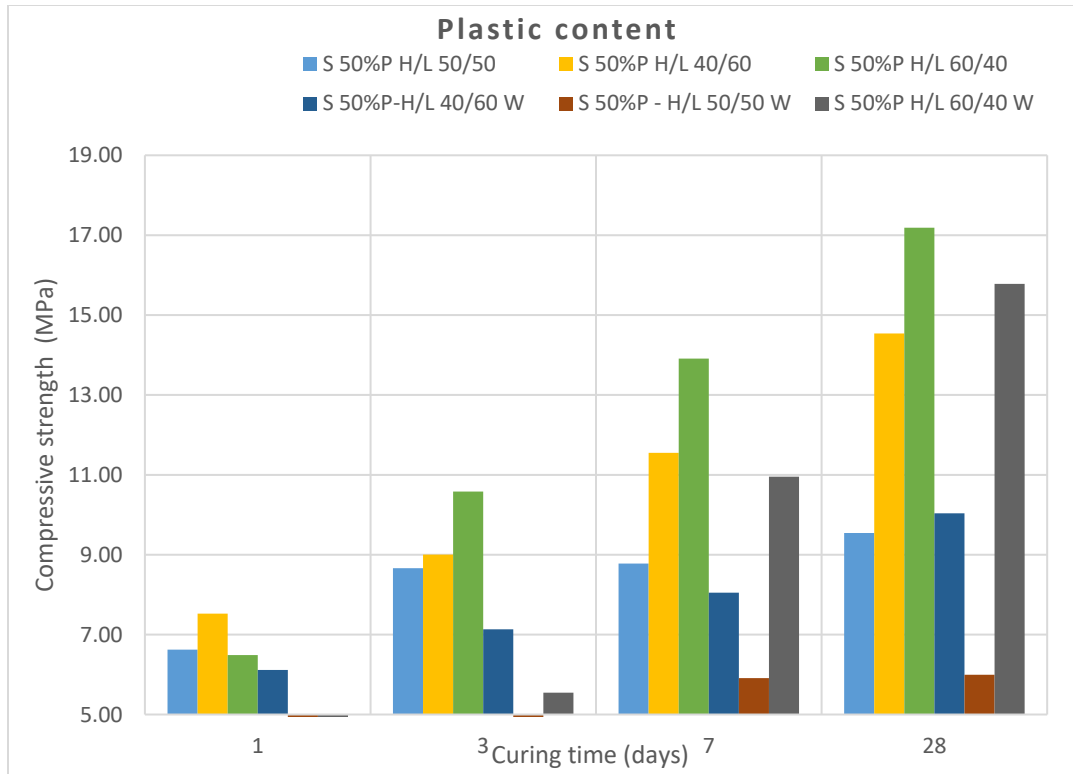


* The letters S at the beginning of the sample names refer to MPB with only fine sand smaller than 2 mm in their composition and the letter “W” appended at the end of the sample name means hot MPB samples subjected to thermal shock through rapid curing

Figure 4-31: Water absorption by immersion vs time for MPB and conventional mortars

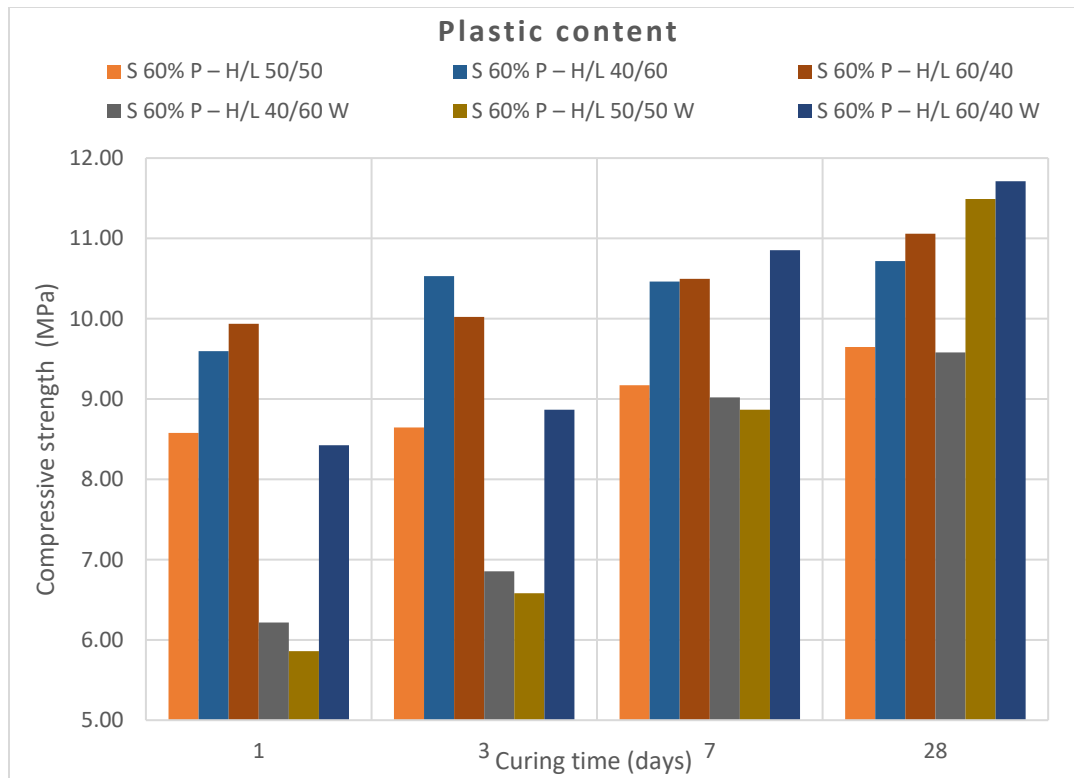
4.3.3.1.3 Impact of curing conditions on the compressive strength of the MPB

Figures 4-32 and 4-33 highlight the impact of curing conditions on the development of the compressive strength for various MPB samples containing 50% and 60% of plastic contents with different HDPE/LDPE ratios.



* The letters S at the beginning of the sample names refer to MPB with only fine sand smaller than 2 mm in their composition and the letter “W” appended at the end of the sample name means hot MPB samples subjected to thermal shock through rapid curing

Figure 4-32: Effect of curing conditions on the compressive strength development vs time of MPB for various HDPE/LDPE ratios (sand particle size < 2mm; Plastic content = 50%).



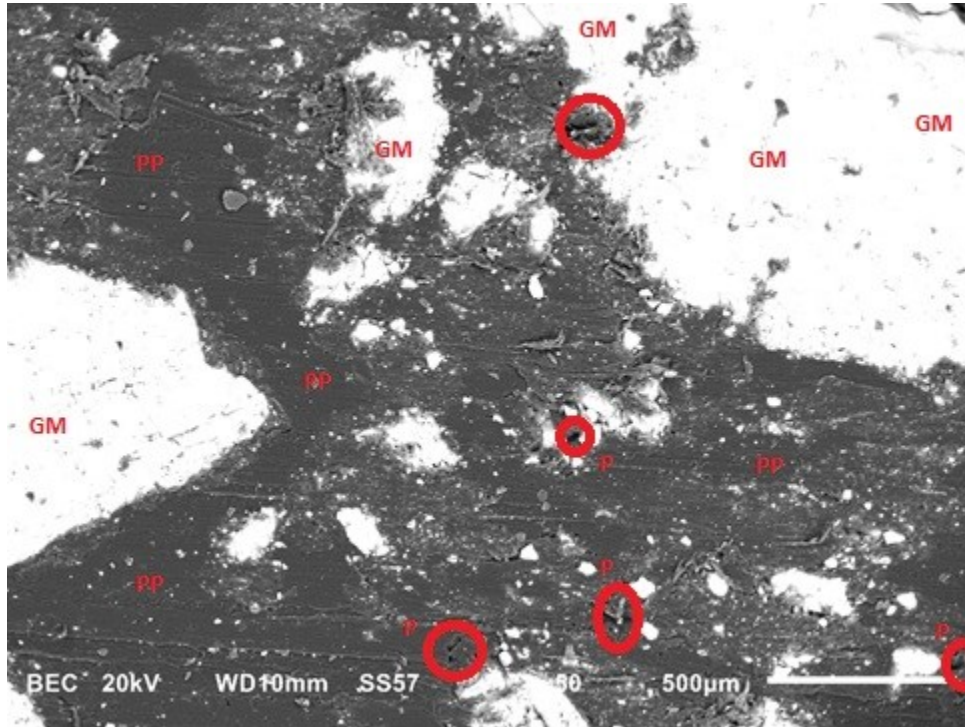
* The letters S at the beginning of the sample names refer to MPB with only fine sand smaller than 2 mm in their composition and the letter “W” appended at the end of the sample name means hot MPB samples subjected to thermal shock through rapid curing

Figure 4-33: Effect of curing conditions on the compressive strength development vs time of MPB for various HDPE/LDPE (sand particle size < 2mm; Plastic content = 60%)

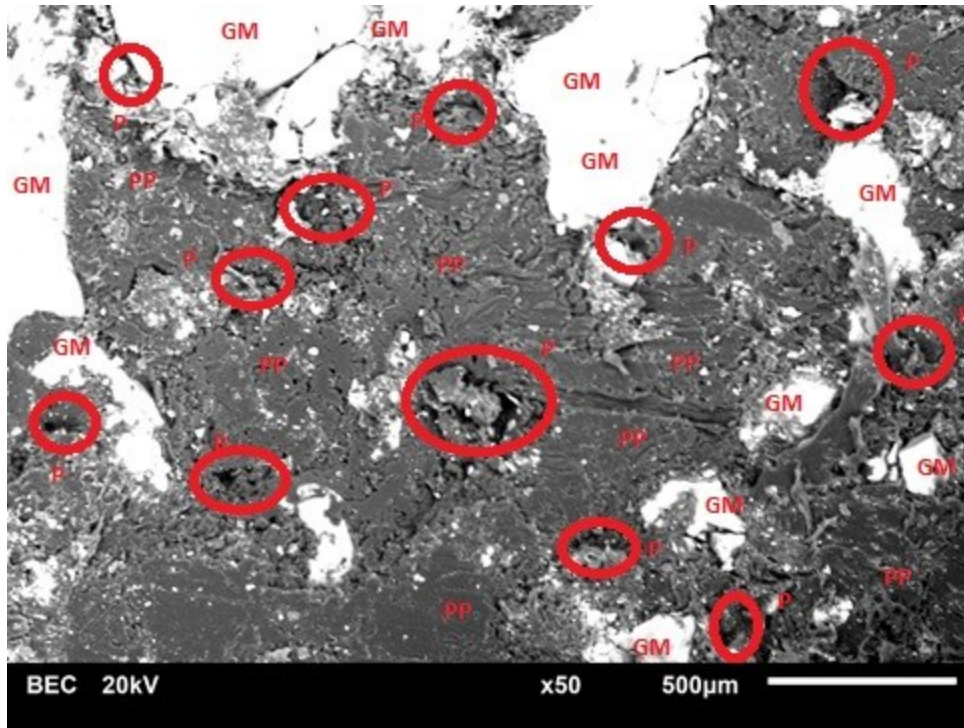
Regardless of age, plastic content and H/L ratio, the MPB samples subjected to thermal shock in water showed lower compressive strength than the specimens cured at ambient temperature under controlled laboratory conditions (Figures 4-32 and 4-33). This indicates that the curing conditions have an impact on the MPB compressive strength and the reasons for this can be related to the properties of the MPB products. Moreover, many factors such as binder type, the temperature or heating rate may affect the strength of the corresponding construction materials (mortar, concrete, etc.) when exposed at high temperature (Mehta and Monteiro 2006; Krishna et al. 2019). For the case of MPB poured in the molds at high temperature (more than 100°C), the heat transfer rate through the MPB induced by the sudden exposure to ambient temperature (26 to 30°C) will have impact on its proprieties. This heat transfer rate will be significantly increased when the MPB samples are introduced into the water tank with sudden thermal shock, thereby affecting the thermal, physical and mechanical properties of the corresponding MPB (Mehta and Monteiro 2006; Krishna et al. 2019).

Figure 4-34 present SEM images of MPBs cured at ambient temperature and other subjected to thermal shock in water. More voids/pores can be observed on the sample with thermal induced impact, which can be related to the sudden curing and the fact for all the MPB constituents do not have enough time to solidify and bind as it should be with required time (Braun 2002; Volk et al.

2015 ; da Silva and Wiebeck 2017; Ragaert et al. 2017; Inai et al. 2018). Thus, the higher temperature difference imposed to MPB will lead to the development of stress within the sample body, contributing to weakening the interfacial transition zone (ITZ) between different constituents' elements of the MPB, subsequently increasing its porosity and affect its strength properties (Türkel and Alabas, 2005; Duan et al. 2020). This temperature gradient or difference induced coarsening of the pore structure of MPB is consistent with the results of absorption tests on MPBs subjected to different curing conditions, which were discussed above (Figure 4-31).



a) BEC image of S 50%P – H/L 50/50 cured at ambient temperature

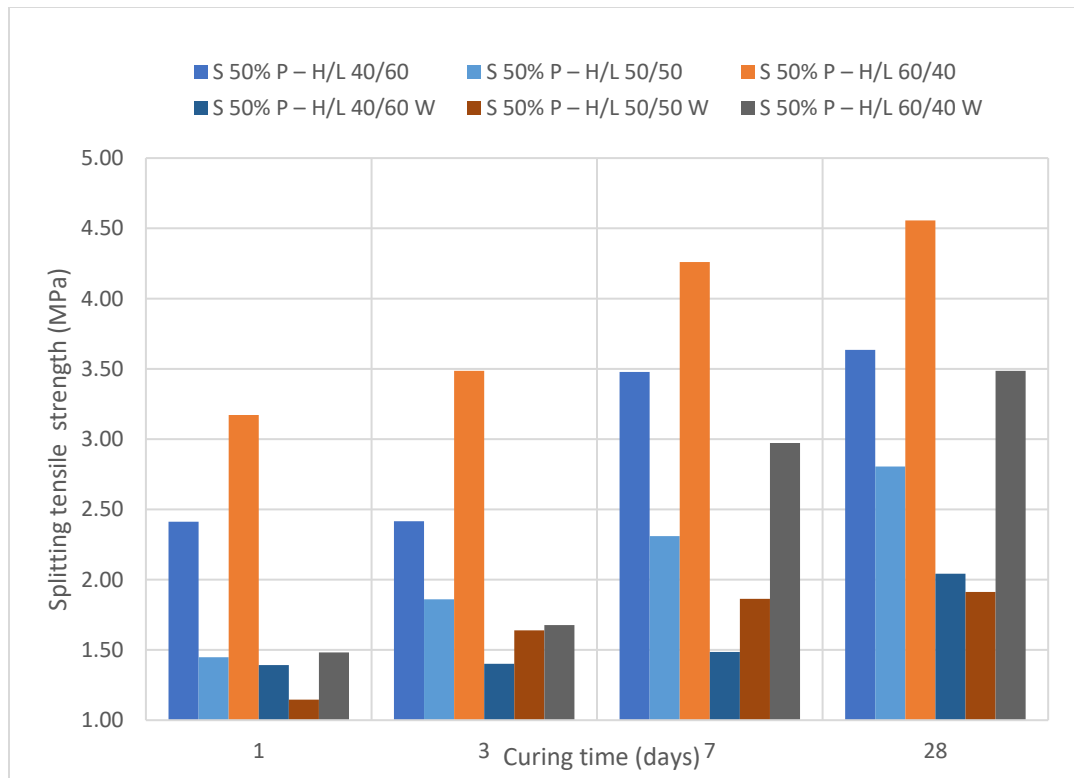


b) BEC image of S 50%P – H/L 50/50 W subjected to thermal shock in water

Figure 4-34: SEM (BEC) images magnified x50 showing the effect of curing conditions on the MPB for various HDPE/LDPE (sand particle size < 2mm; Plastic content = 50%) (GM: granular material, sand/gravel; PP: plastic paste; P: pore; SEI: Secondary Electron Images; BEC: Backscattered electron composition image).

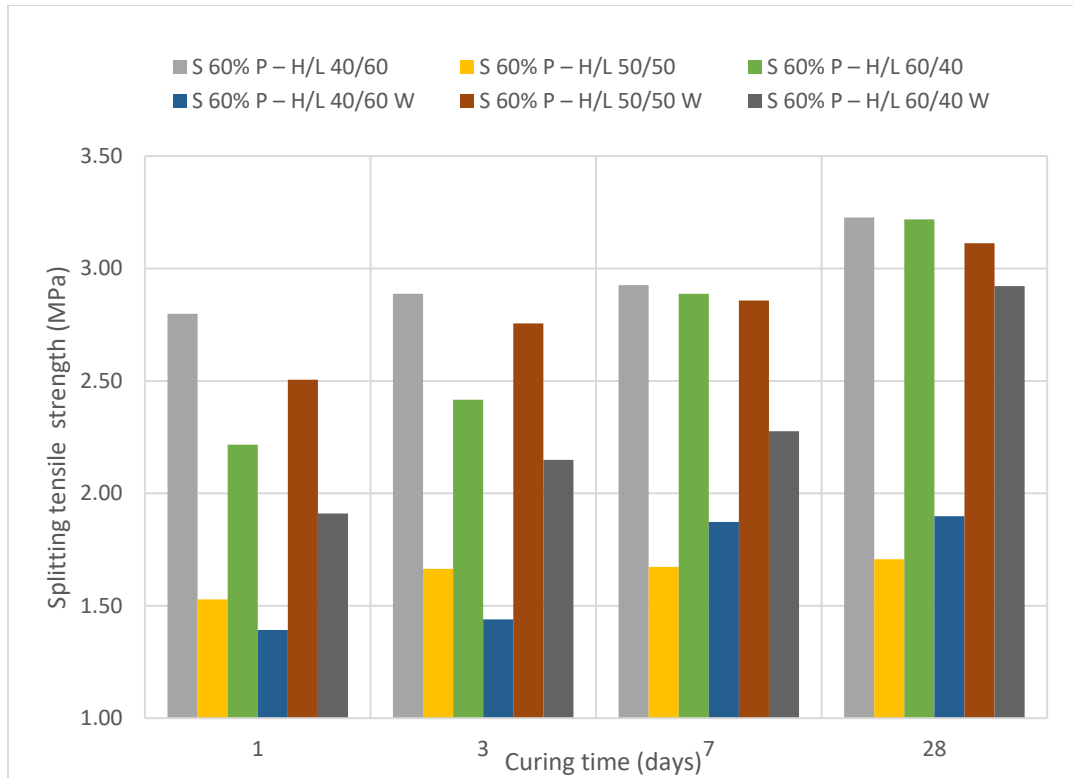
4.3.3.1.4 Impact of curing conditions on the splitting tensile strength of the MPB

Figures 4-35 and 4-36 show the variations of splitting tensile strength with time of MPBs with 50% and 60% plastic contents for various H/L ratios and subjected to different curing conditions.



* The letters S at the beginning of the sample names refer to MPB with only fine sand smaller than 2 mm in their composition and the letter “W” appended at the end of the sample name means hot MPB samples subjected to thermal shock through rapid curing

Figure 4-35: Effect of curing conditions on the splitting tensile strength development vs time of MPB for various HDPE/LDPE ratios (sand particle size < 2mm; Plastic content = 50%)



* The letters S at the beginning of the sample names refer to MPB with only fine sand smaller than 2 mm in their composition and the letter “W” appended at the end of the sample name means hot MPB samples subjected to thermal shock through rapid curing

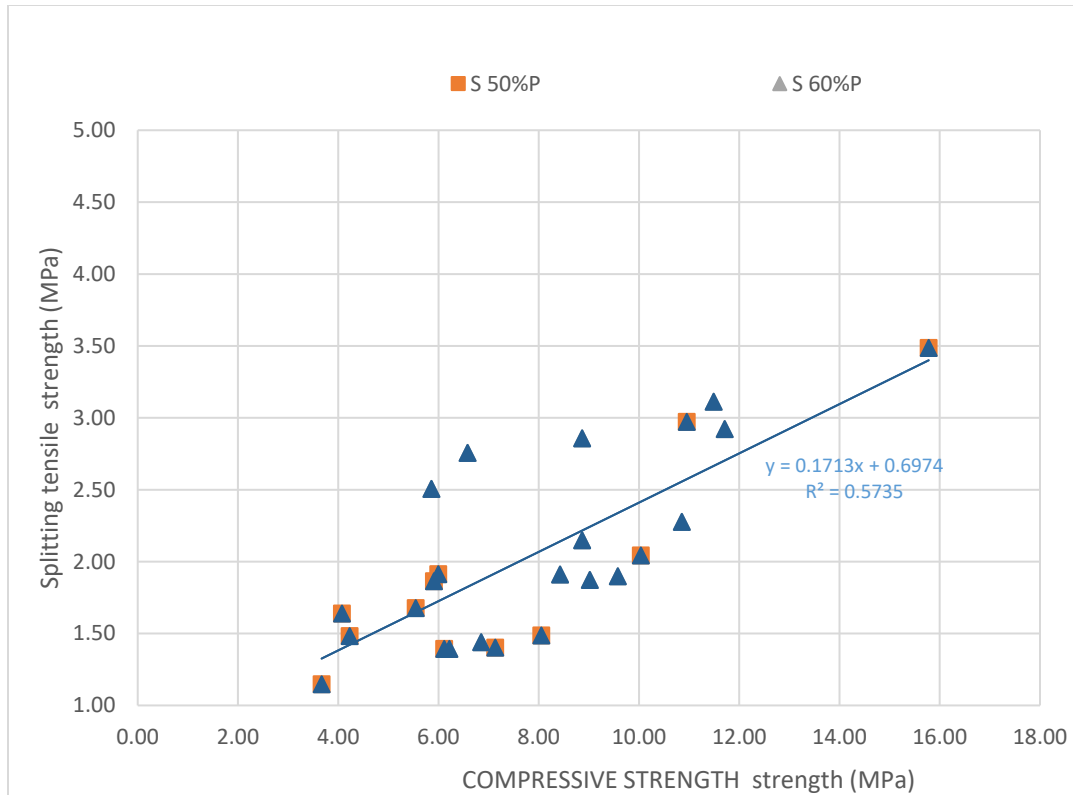
Figure 4-36: Effect of curing conditions on the splitting tensile strength development vs time of MPB for various HDPE/LDPE ratios (sand particle size < 2mm; Plastic content = 60%)

The tensile strength of MPB samples subjected to thermal shock was found to be lower than that of the samples cured at ambient temperature regardless of age, plastic content and H/L ratio. The magnitude of the decrease is in the range of 0.22 to 1.99 MPa in absolute values corresponding to the relative values from 10% to 143%. The reasons for that decrease are the same as pointed out for the compressive strength in the previous section. Moreover, the splitting tensile strength of MPB specimen after the thermal shocks in water was found to be between 1 and 4 MPa. These values were found to be similar to the ones in the literature for some construction materials containing plastic wastes (Al-Manaseer and Dalal, 1997; Choi et al., 2005; Siddique et al., 2008).

Linear relation has been deduced from the set of data obtained for splitting tensile strength (f_t) as a function of the compressive strength (f_c) for various formulations of MPB containing the optimal plastic contents (50% and 60%) and subjected to thermal shock (Figure 4-37). The linear relation is provided by (Equation 4-3), which could be used in practice to estimate one parameter if the other is known under the same conditions.

$$f_t = 0.1713 * f_c + 0.6974 \quad (\text{in MPa}) \quad \text{Equation 4-3}$$

(This equation 4.3 is only valid for compressive strength values between 5 MPa and 20 MPa)



* The letters S at the beginning of the sample names refer to MPB with only fine sand smaller than 2 mm in their composition

Figure 4-37: Splitting tensile strength vs compressive strength of MPB containing 50% and 60% of plastic content with various H/L ratios and subjected to thermal shock in water (sand particle size < 2mm)

4.3.3.2 Impact of fineness and proportion of granular materials on the MPB properties

The granular material displayed in Figure 4-28 were used for the preparation of S and GS mortars with plastic binder. Using fine sand material with grain size smaller than 2 mm, the optimum margin was determined for MPB. The granular material size and proportion were varied in order to understand their impact on the physical (density) and mechanical (strength) proprieties of the MPB. Thus, in this section 30% of fine sand (< 2mm) will be replaced by the same weight of granular 2 – 4.75 mm corresponding to GS samples.

Figures 4-38 to 4-40 present the impact of granular material size on the hardened density, compressive strength and splitting tensile strength of MPB samples containing 50% and 60% of plastic content with H/L ratio of 50/50, respectively.

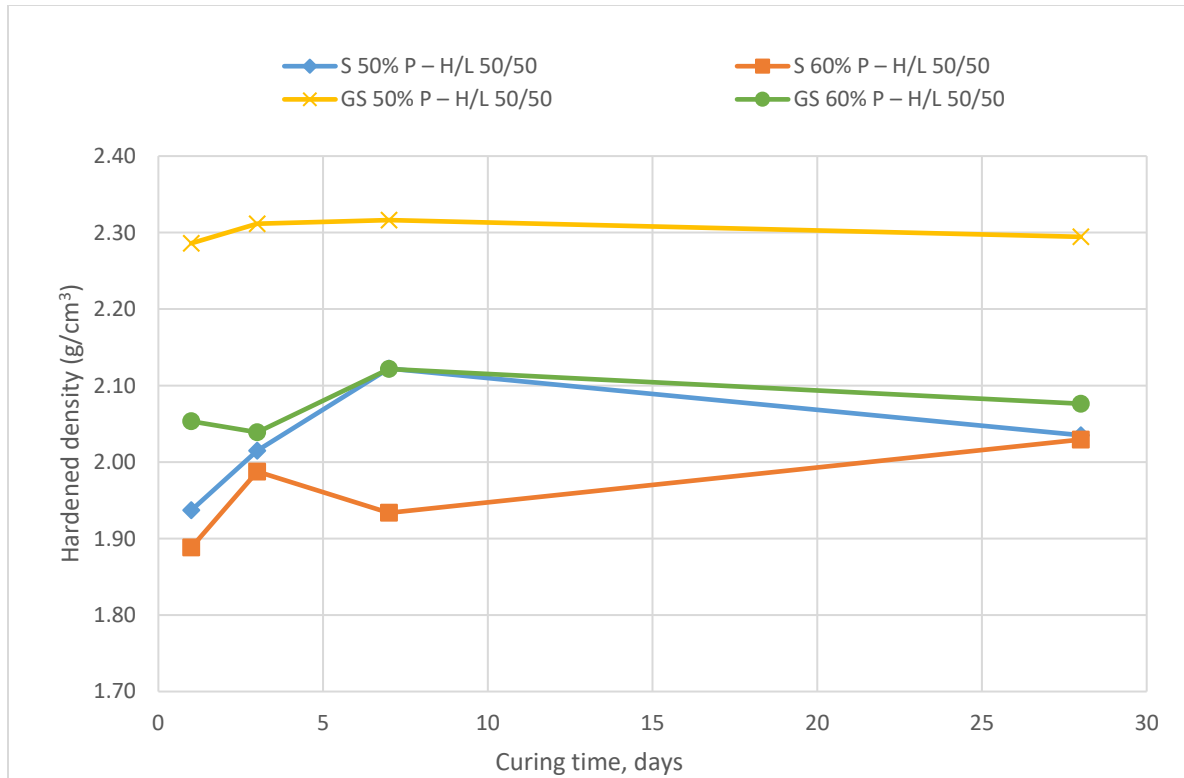


Figure 4-38: Hardened density vs curing time of various MPB samples with different granular materials and plastic content, when 30% of fine sand is replaced by larger size of sand and gravel.

From Figure 4-38, the density of GS samples was slightly higher than that of MPB containing only fine grain aggregates. With the presence of fine and larger grain particles, the small grains will occupy the void left by the large grains during the compaction with the applied force allowing to get close to the denser configuration. Thus, the presence of these larger granular materials in a given specimen leads to higher packing density (Kou et al. 2009; Hannawi et al. 2010; Uysal et al. 2012). The same mechanism is responsible for the reduction of the porosity and pores interconnectivity, which subsequently lead to the higher strength values (compressive and splitting tensile) for the GS samples when compared to the samples prepared using only fine sand (Figures 4-39 and 4-40) (Kou et al. 2009; Hannawi et al. 2010; Uysal et al. 2012). Since the granular material is one of the major contributors in strength properties of given concrete/mortar, the improvement of the GS mortar strength has come from the reinforcement from granular material skeleton. Further studies will be needed in the future to gain deeper insight into the impact of replacing fine sand with larger granular material.

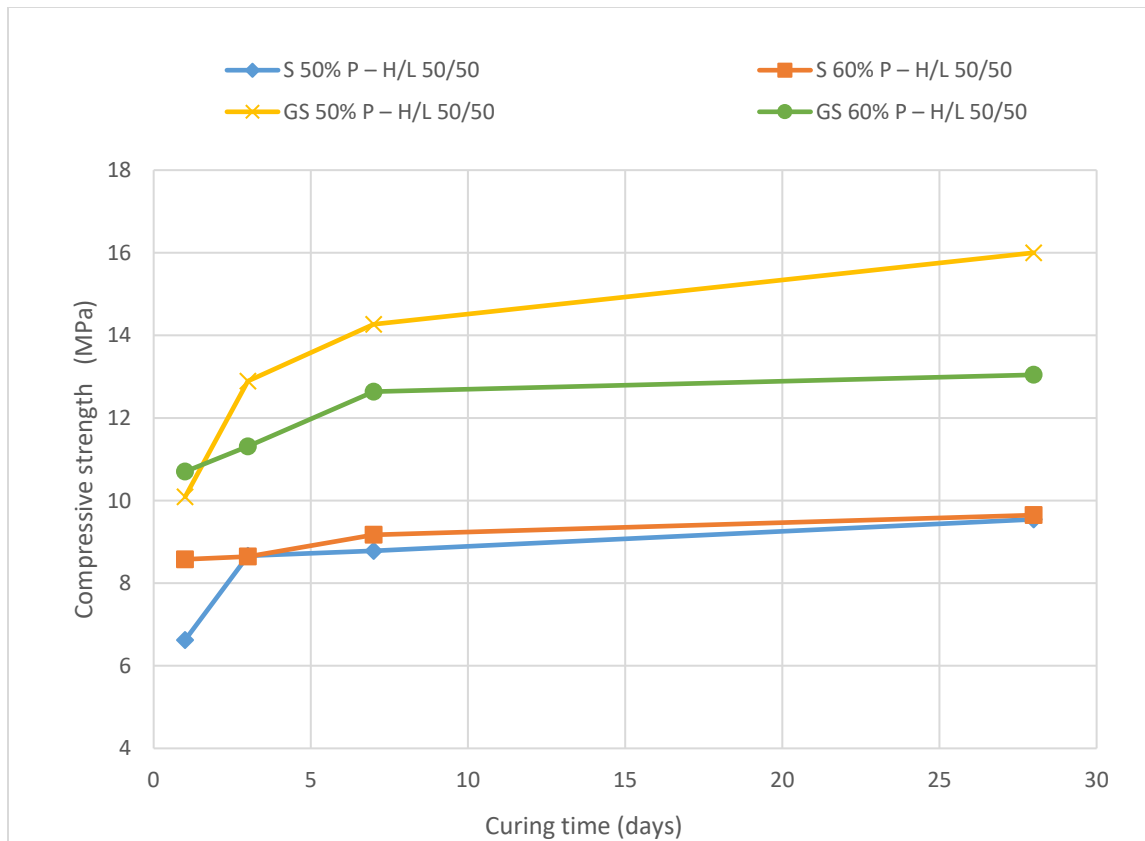


Figure 4-39: Compressive strength vs curing time of various MPB samples with different granular materials and plastic content, when 30% of fine sand is replaced by larger size sand and gravel.

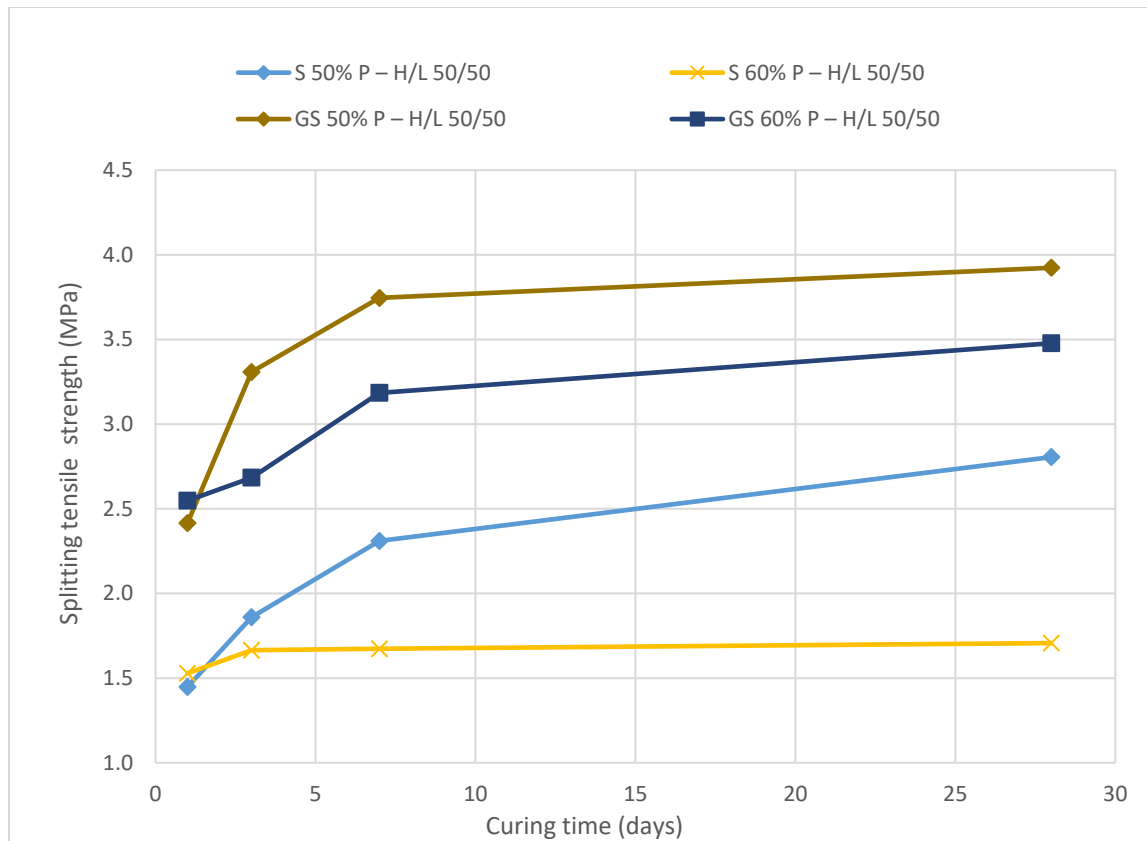


Figure 4-40: Splitting tensile strength vs curing time of various MPB samples with different granular materials and plastic content, when 30% of fine sand is replaced by larger size sand and gravel.

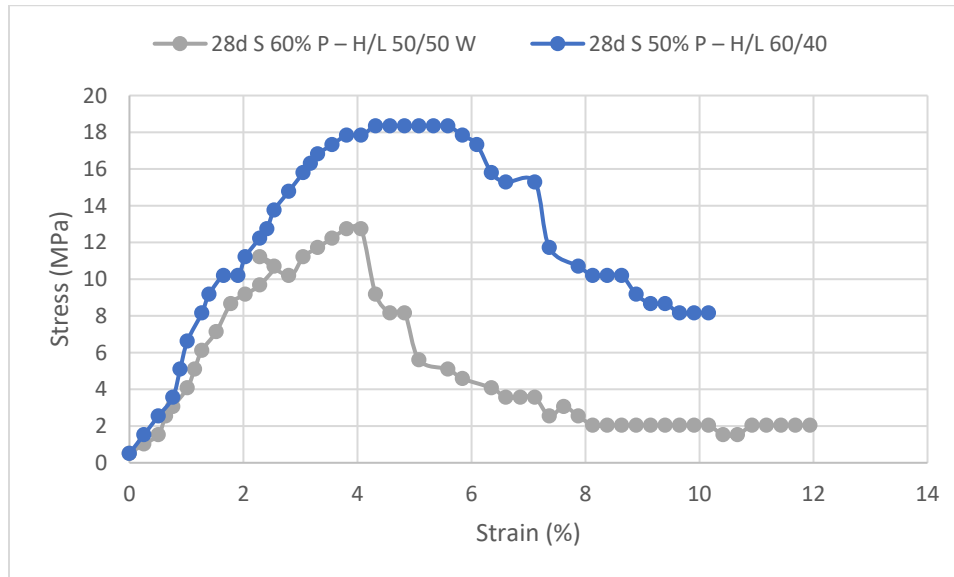
4.3.3.3 Effect of curing regime on the stress-strain behaviour of the MPB

Figure 4-41 (a and b) presents the compressive and splitting tensile stress-strain behaviour of various MPB samples at different curing ages under different conditions.

The stress-strain response is a good indicator of the degradation behaviour for a given material. In the case of this study, the main focus is to understand the impact of curing conditions on the compressive and splitting tensile stress-strain response of MPB. In general, the stress-strain behaviours in both tension and compression are qualitatively similar to the ones observed for construction material with plastic waste aggregate (Jansen et al. 2001; Hannawi et al. 2010; Alqahtani et al. 2017).

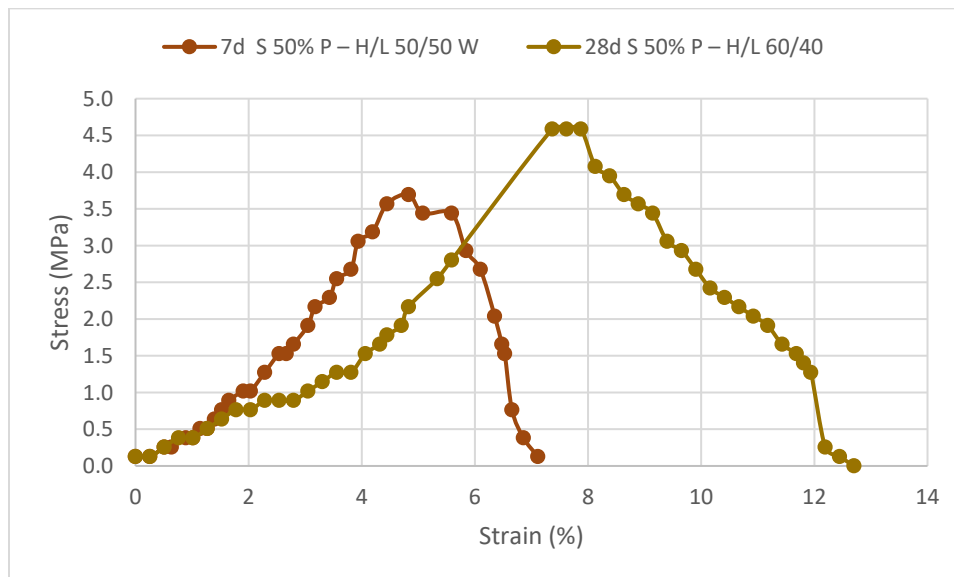
By analyzing these graphs, it can be observed that the strain corresponding to the peak stress was found to be higher for samples cured at ambient temperature than the strain recorded for the MPB samples subjected to the thermal shock. However, the opposite was observed for tensile strength (i.e., higher peak strain was obtained for thermal shocked MPB sample rather than the samples cured at ambient temperature). Nevertheless, independent of the curing conditions, all the MPB

specimens undergo plastic deformation before reaching the peak value. The samples supported loads after peak stress with sequential deformation for a large range of strain. Thus, the curing conditions influenced the peak stress of the MPB samples but the ductile behaviour of the MPB products was similar for both curing regimes.



* The letters S at the beginning of the sample names refer to MPB with only fine sand smaller than 2 mm in their composition

(a) Compressive stress-strain behaviour of MPBs



* The letters S at the beginning of the sample names refer to MPB with only fine sand smaller than 2 mm in their composition

(b) Splitting tensile stress-strain behaviour of MPBs

Figure 4-41: (a) Compressive and (b) Splitting tensile stress-strain behaviour of MPB samples cured under different regimes for various ages.

4.3.4 Summary and conclusions

In this paper, experimental program has been conducted to study the effect of curing conditions and fineness of granular materials on the physical, mechanical and deformations behaviours of MPB samples containing different melted plastic contents as the only binder with various H/L ratios. The results led to the following conclusions:

- Curing conditions was found to have no significant impact on the hardened density of MPB. In general, the average density for MPB samples was close to 2 g/cm^3 , considered by RILEM classification as the lightweight construction material
- Adding 30% of granular materials (sand and gravel), with grain-size in the range of 2 to 4.75 mm, slightly increases the hardened density as well as the compressive strength and the splitting tensile strength of the MPB.
- The thermal shock with its induced heat transfer in the MPB samples (at temperature higher than 100°C) when placed in water tank (at 26 to 30°C) will create a temperature difference of more than 70°C , impacting the internal pores structure and the ITZ within the MPB sample body. Thus, contributing to decrease its compressive and splitting tensile strengths when compared to the samples cured at ambient temperature under laboratory-controlled conditions
- Linear relationship between splitting tensile and compressive strengths has been derived from experimental data, which allows to estimate either parameter if the other is known
- The immersion absorption result for MPB samples was in line with the strength results. The absorption values are higher for MPB that was subjected to thermal shock, confirming its higher porosity, pores interconnectivity and subsequently lower strength of these samples when compared to the specimen cured at ambient temperature in controlled laboratory conditions.
- Independent to the curing conditions, the absorption of MPB was found to be lower than the ones obtained for the conventional mortar made of sand and cement
- Independent of the curing conditions, MPB samples showed plastic deformation behaviour with interesting capacity of supporting loads for a longer period of time after the failure without showing brittle failure with full disintegration as observed for conventional cement-based mortar

The findings from this study are encouraging and offers basis for further research on the properties of MPB for extending its applications in the construction field. This work reinforces our pursuit to valorize plastic wastes in the construction sector by using it as a binder to develop new type of building materials, which are cost effective and contribute towards saving the environment from solid wastes related problems.

4.3.5 References

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4.4 Summary and conclusions

In this study, experimental tests were conducted to determine the optimal plastic contents that can provide the best strength to the MPB.

Samples with different mix formulations were subject to various mechanical and physical tests, such as compressive and splitting tensile tests and density determination, respectively, which allowed to gain a good understanding of the variation of the mechanical and physical properties with the time for various mix compositions. Moreover, absorption (capillary and immersion) tests were performed on MPB samples to assess their fluid transportability, which is can give critical information about the durability of the proposed new construction material. The obtained results were also supported by microstructural analyses (SEM and MIP) as well as the thermal analysis (TG/DTG).

Additional experiments on the new MPB poured in cylindrical molds with variation of granular materials characteristics and others subjected to two curing conditions (air dried and thermal shock in water) allowed to deepen the knowledge on the impact granular material size and curing conditions on the material performance.

Based on the aforementioned results from previous sections, the following conclusions were drawn for MPB and a number of appropriate recommendations provided for future applications

- Several hours after casting the MPB sample, the MPB sample has not reached its final shape and solidification occurs which affects its compressive strength.
- During the initial stage of curing, the ITZ between the plastic paste and the sand particles has some weak points. With time, these weak points strengthen and become stronger during solidification and increase the compactness of the MPB with an increase in the elasticity of the material. Therefore, a high elastic modulus and better adhesion in the MPB will lead to an improvement in its strength with time.
- For the compressive strength tests, the highest values are obtained for samples with plastic contents of 50% and 60% and an H/L ratio of 50/50. Regardless of the curing time of the MPB, the compressive strength is increased for a plastic content between 45% and 50% before showing a slower increase for a plastic content between 50% and 60%. The strength decreases afterwards for a plastic content in the range of 60% to 65%. When changing the H/L, the best result in terms of the compressive strength is obtained with 50% plastic and H/L of 60/40 and 60% plastic and H/L of 40/60.
- In the splitting tensile tests, the plastic contents of the 50%P - H/L 60/40 and 60%P - H/L 40/60 samples show the highest splitting tensile strengths.
- Independent to the curing conditions of MPB samples with the optimum plastic content, linear relationship between the tensile strength (F_t) and the compressive strength (F_c) has been derived from experimental data, which allows to determine either parameter if the other is known.

- The MPB reaches around 60 to 80% of its final strength after just one day of curing, much higher than the conventional mortar which typically reaches less than 40% of its ultimate strength in one day. The splitting tensile strength appears to be very sensitive to cracking, which is linked to the porosity of MPB.
- The EM is more ductile with a higher degree of plasticity than the conventional mortar with Portland cement. Even after failure at the peak strength, the MPB is able to sustain further straining before complete disintegration.
- Failure cones, longitudinal cracking and localized disintegration are the common failure modes of the MPB samples.
- The initial and secondary sorptivities, and total water absorption by immersion and capillarity are found to be lower for the MPB samples at any given time in comparison with the conventional mortar.
- The decomposition temperature at 90% of mass loss for different MPB samples is found to be between 450°C and 475°C, which is higher than the 90% decomposition temperature of pure plastics. That means that there is an improvement in the thermal stability of plastic due to melting and/or interaction with inorganic materials.
- Curing conditions was found to not have significant impact on the hardened density of MPB. In general, the average density for MPB samples was close to 2 g/cm³, considered by RILEM classification as the lightweight construction material
- Adding 30% of coarser granular materials (sand and gravel), with grain-size in the range of 2 to 4.75 mm, slightly increases the hardened density as well as the compressive strength and the splitting tensile strength of the MPB.
- The thermal shock, heat transfer and physico-chemical transformations in the MPB samples when placed in water tank was found to decrease its compressive and splitting tensile strengths when compared to the samples cured at ambient temperature under laboratory-controlled conditions
- The immersion absorption result for MPB samples was in line with the strength results, with lower absorption corresponding to the samples with less porosity stand better strength result when compared with the other samples
- Independent of the curing conditions, MPB samples showed plastic deformation behaviour with interesting capacity of supporting loads for a longer period of time after the failure without showing brittle failure with full disintegration as observed for commercial cement-based pavers

This MPB material has good potential for use as a construction material to recycle plastic waste and reduce the impact of plastic on the environment.

Chapter 5. A building material (PlasticWasteCrete) with melted plastic waste as the only binding phase: Development and engineering properties

5.1 Introduction

This chapter presents the experimental program conducted to develop the proposed new building material called PlasticWasteCrete (PWC) as well as to study its performance properties. The obtained experimental results are presented in two research papers (technical papers III and IV). In the first part, the engineering properties of the proposed new material will be studied and discussed. In the second part, the impacts of physical factors and curing conditions on the performance properties of the PWC will be presented and discussed.

5.2 Technical Paper 3: Engineering properties of a building material with melted plastic waste as the only binder

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Abstract

In this paper, the use of plastic wastes as the only binding material to develop a cemented construction material, PlasticWasteCrete (PWC), was investigated. Two types of plastic waste (high density polyethylene (HDPE), low density polyethylene (LDPE)) are blended (HDPE/ LDPE blend ratio: 50/50) and then melted at a temperature of 250°C to develop the binding phase of the PWC. Subsequently, the melted plastic is mixed with mineral aggregates (sand, gravel) in two plastic contents (50% and 60%) to prepare the PWC samples. Then, the compressive and split tensile strength, stress–strain behavior, microstructure, density and water absorption ability of the PWC samples cured at different times (1, 3, 7, 28 days) are evaluated. The results of this study show the feasibility of using melted plastics as the only binder to develop a building material. From the mercury intrusion porosimetry (MIP) test and Imagej analysis, the PWC with 50% plastic content (PWC50) was found to have more voids and coarser pore structure than that with 60% plastic content (PWC60). These MIP results were also confirmed by the larger capillary pores and higher rate of absorption for PWC50 when compared to PWC60. These results were found to be in line with the strength tests for which the PWC60 with less porosity has higher strength in compression and tension than PWC50. Regardless of age and plastic waste content, the compressive strength of PWC was found to be higher than 10 MPa, which somehow exhibit interesting mechanical strength behaviour with ductile deformation and interesting post peak strength capable of supporting loads after failure. The density was found to decrease with the increase of plastic content, and the average density was close to 2 g/cm³, considered as lightweight material. The findings of this study are encouraging and place this PWC as a promising candidate for producing construction materials while diminishing the amount of plastic waste to be managed and the associated environmental issues as well as contributing to generate additional revenues.

Keyword: Plastic Waste; Concrete; Recycling; Building material; Sustainability; Cement

5.2.1 Introduction

Every second about 190 m³ of concrete is cast in the world, which translates to 6 billion m³ per year. This makes concrete one of the most widely used manufactured material, especially in the sector of construction and infrastructure maintenance (Conso 2019). Concrete offers great advantages, such as low manufacturing cost, wide availability and versatility, but also has negative impacts on the environment and puts a lot of pressure on natural resources. Every year, 8 to 12 billion tons of natural resources are used as raw materials in the construction sector (Tosun and Sahin 2019), and cement production contributes to approximately 7% of all global carbon dioxide emissions (Alqahtani et al. 2017).

In the recent decades, environment protection has been gaining key attention, with authorities and decision makers supporting alternatives and/or initiatives towards creating eco-friendly materials across the world in order to address the overexploitation of natural resources, water scarcity in some regions of the world, reduce CO₂ emissions and minimize the global carbon footprint. Thus, the construction market is embracing initiatives that aim to develop eco-friendlier materials as alternative for conventional Portland cement-based concrete.

Recycling is one of the most important actions available to reduce the aforementioned environmental concerns and represents one of the most dynamic areas to reduce disposed wastes quantity and their corresponding gas emissions. Thus, many initiatives have been developed to recycle postconsumer products, such as plastic wastes, into different construction materials.

The use of plastics with their versatile properties and low cost is growing steadily and plastics can be found everywhere in today's life style. After their lifetime, these plastics will often end up in landfill or oceans, contributing to the pollution of water and the land with huge impacts on environment (Jambeck et al. 2015; Gu and Ozbakkaloglu, 2016). The total amount of plastic produced in 2015 was estimated to be 322 million tonnes (PlasticsEurope 2016, Alqathtani et al., 2017), and 2.2 billion tonnes of Municipal Solid Waste (MSW) are forecasted by 2025 (Hoornweg and Bhada-Tata 2012). In 2018, 29.1 million tonnes of post-consumer plastic waste were collected in EU, 24.9% of which ended up in landfill (PlasticsEurope 2019 and 2020). Only 50% of the plastic wastes are recycled in countries with the highest recycling rate, while 90% of these plastic wastes end up in landfills in most of the developing countries with high plastic waste generation (Gourmelon 2015). About 8.8% of plastic wastes were recycled in USA in 2012 and 29.7% in Europe in 2014 (EPA 2014; PlasticsEurope 2016). From the facts mentioned above, it is clear that effort still needs to be put in plastics recycling sectors, particularly alternative ways need to be found to recycle plastic wastes into construction materials.

Many researchers have attempted to study the possibility of incorporating plastic wastes in concrete (e.g., Choi et al. 2005; Ismail and Al-Hashmi 2008; Hannawi et al. 2010; Saikia and de Brito 2014; Alqathtani et al. 2017). A number of studies have used plastics as replacement/substitute of natural aggregates (sand and/or gravel) and others as additives in concrete materials. For example, Choi et al. (2005) studied the air content and splitting tensile strength of concrete that contains the polyethylene terephthalate (PET) as partial replacement of fine aggregate. With four different w/c ratios and three sand replacement percentages, they observed a decrease of air content and splitting tensile strength of concrete with PET plastic by reference to the conventional concrete with same w/c ratio. For the same w/c ratio, the air content in concrete with PET plastic decreased with an increase of PET plastics, while the splitting tensile strength increased with the reduction in w/c ratio for a given particular PET aggregate content. Hannawi et al (2010) reported that the fresh and dry densities of mortars decrease with the increase of PET and polycarbonate (PC) plastic aggregates content. The dry density was 2173 kg/m³, 1755 kg/m³ and 1643 kg/m³ for mixes that contain 0% of plastic aggregates, 50% of PET and 50% of PC plastic wastes, respectively. This translates to up to 19% and 24% decrease by reference to the density of normal mortar with 0% of replacement. Ismail and Al-Hashmi (2008) reported that the fresh density of concrete with 10%, 15%, and 20% of plastic aggregates as a replacement of fine

aggregates decreased by 5%, 7%, and 8.7%, respectively, below the reference concrete without any replacement. Saikia and de Brito (2014) observed a reduction of the density and elastic modulus of concrete that incorporates three differently shaped PET waste aggregates compared to the concrete containing natural aggregate. The authors found the trend of density reduction of concrete with pellet plastic aggregates to be the lowest followed by the ones made using fine fraction of flaky plastic aggregates, and the highest density values were recorded for concrete made using coarse fraction of flaky plastic aggregates.

Bayasi and Zeng (1993) reported that 12.7 mm long polypropylene fibers improved the compressive strength of concrete when used at volume proportion of less than 0.5% without adverse effects on the workability. However, many other authors observed in general, a reduction in the compressive strength of concrete due to the incorporation of plastic aggregates. Batayneh et al. (2007) reported that replacement by 20% shows a sharp reduction of compressive strength up to 72% of the original strength and for 5% replacement, the compressive strength drops by 23%. Similar behaviour, but of lesser magnitude, was observed in both the splitting and flexural strengths of the tested samples. Ismail and Al-Hashmi (2008) concluded that the compressive strength of concrete prepared by replacing 10%, 15% and 20% of fine natural aggregate with PET aggregate are lower than the compressive strength of concrete that has only natural aggregate, but higher than the minimum compressive strength required for structural concrete. Kou et al. (2009) observed the reduction in 28-day compressive strength of the lightweight concrete mixes prepared by replacing 5%, 15%, 30% and 45% of natural fine aggregate with PVC granules to be respectively 9.1%, 18.6%, 21.8% and 47.3% with respect to the control mix. Al-Manaseer and Dalal (1997) concluded that the splitting tensile strength decreased with the increase in plastic aggregates percentage, it decreased by 17% for concrete with 10% of plastic aggregates. For a given plastic aggregate content, the splitting tensile strength was found to decrease when w/c ratio was increased and the splitting failure of concrete samples having plastic aggregates was more ductile with the increase of plastic aggregates. Thus, the concrete with plastic aggregates did not exhibit the typical brittle failure observed for the conventional concrete with natural aggregates. Alqahtani et al. (2014) and Alqahtani et al. (2017) observed the 28-day compressive strength variations between 14 to 18 MPa while the fresh density and slump ranging from 1827 to 2055 kg/m³ and 40 to 220 mm, respectively, for concrete samples with various types of plastic and fillers prepared using compression moulding press.

Furthermore, durability characteristics or parameters, such as water absorption, permeability and permeable voids, were studied for concrete that incorporates plastic (waste) aggregates. Albano et al. (2009) reported higher water absorption for concrete with PET aggregates than the concrete made using only natural aggregates. The water absorption was found to increase when the PET aggregate proportion and/or size increase in the concrete. From a study by Bayasi and Zeng (1993) on the effect of recycled plastic aggregate on the permeability of composite concrete, a significant increase of the permeability of concrete with an inconsistent effect on the volume fraction of permeable voids for 19-mm polypropylene fibers was observed. Fibers with length of 12.7-mm somewhat increased the permeability of the concrete.

As highlighted above, several relevant studies have been performed on concrete materials that contain plastic wastes and valuable results were obtained. However, in all of the aforementioned studies, plastic waste was used as aggregates to partially replace natural aggregates or as additives in the concrete material. None of them, to date, has examined the use of melted plastic wastes as the only binder to develop concrete-like material. This technology and research gap is addressed in this study.

In consideration of the aforementioned facts, a research program has been performed to evaluate the possibility of developing a cemented construction material with plastic wastes as the only binding material (this material is called PlasticWasteCrete, PWC). The objectives of this paper are to present and discuss the results of the experimental investigations of key engineering properties of the PWC. The engineering properties investigated include mechanical (compressive and split tensile strength, deformation behavior), microstructural and physical (density, water absorption) properties.

5.2.2 Experimental Program

5.2.2.1 *Materials used*

5.2.2.1.1 *Sand and gravel aggregates*

Natural sand and gravel from Niger River in Mali were sampled for the purpose of this experiment (Figure 5.1). Sieve analysis following ASTM C136 / C136M procedures was performed on these materials and the particle size distributions are presented in Figure 5.2.

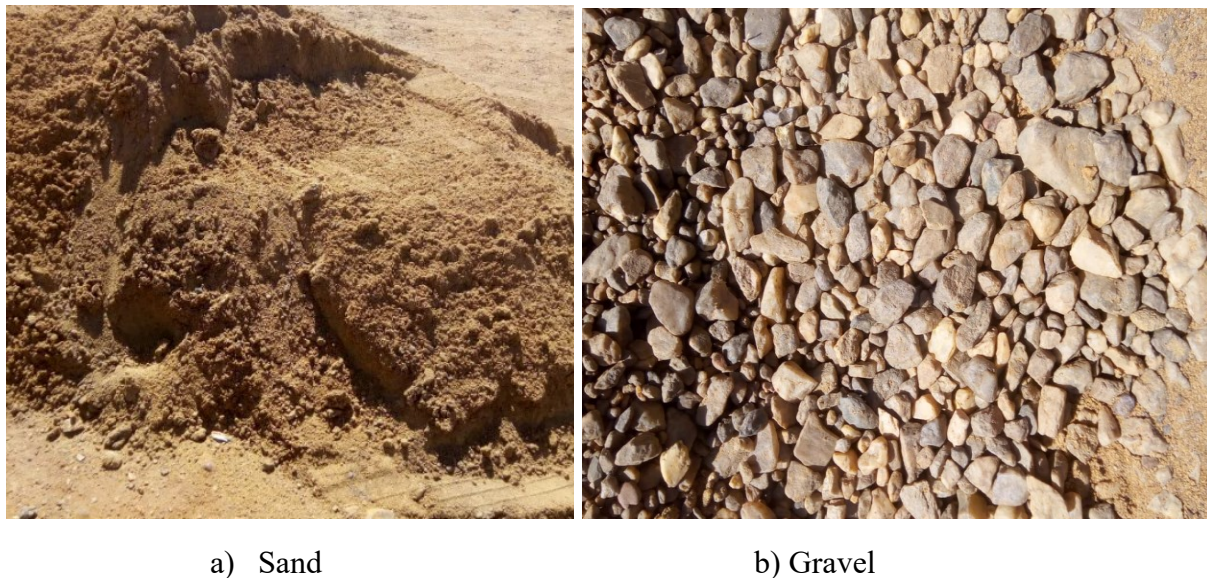


Figure 5-1: Granular materials (sand and gravel) from Niger River (Banks of Kalaban - Coro in Bamako, Mali) used in this study.

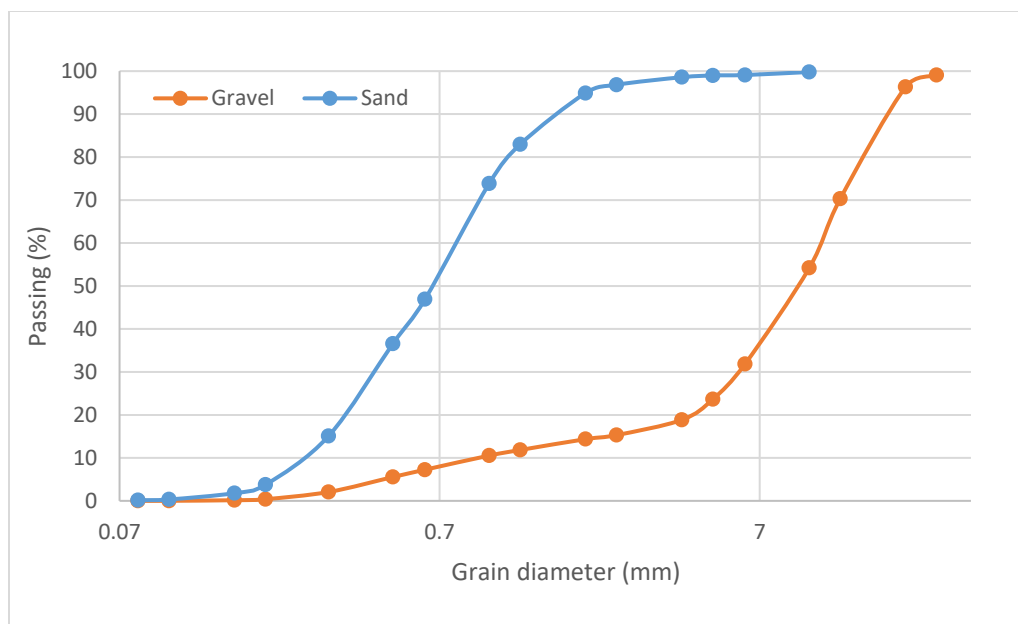


Figure 5-2: Particle size distribution of sand and gravel materials used in this study.

5.2.2.1.2 Plastic materials

Two main types of plastic wastes (High-density polyethylene, HDPE, and Low-density polyethylene, LDPE), collected at waste transit deposit in Medina-Coura (Bamako), were used in the preparation of the PWC. LDPE and HDPE are the main polyethylene compounds in plastic bags as well as bottles, tubes, garbage bags, plastic wraps, milk and juice pouches. Before starting the experiment, the plastic wastes were washed to remove impurities; air-dried and then cut in small pieces (Figure 5.3).

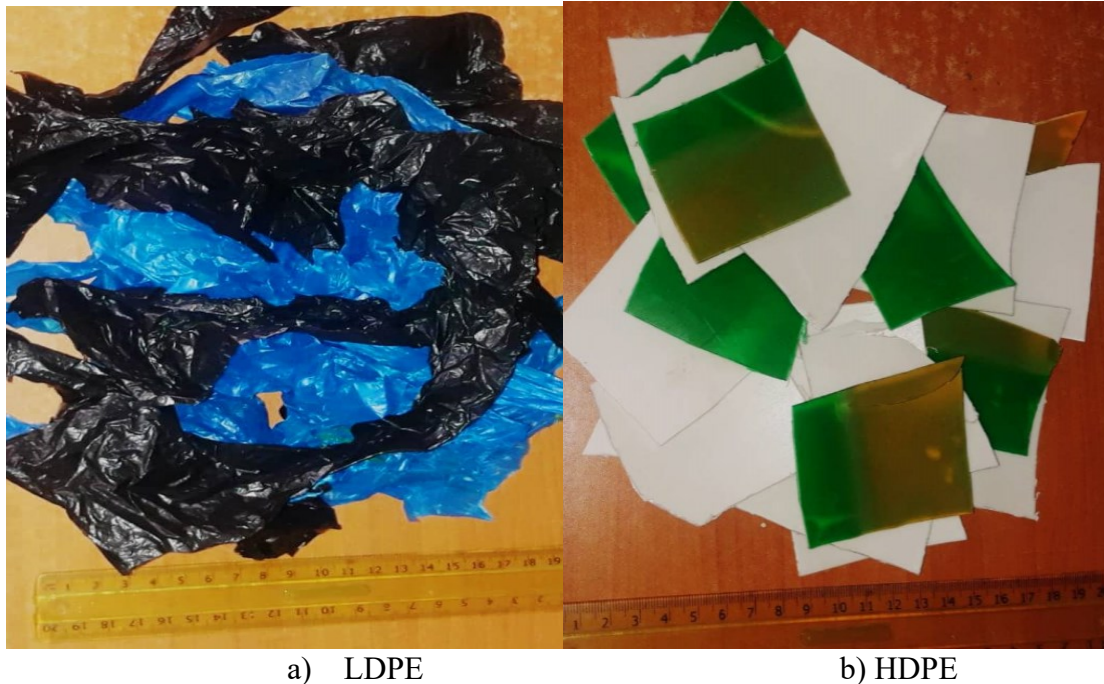


Figure 5-3: Illustrations of a) LDPE and b) HDPE plastic wastes used in the preparation of ecological concrete.

5.2.2.1.3 *Portland cement and water*

Ordinary Portland cement and tap water were used to prepare conventional concrete samples, which served as control specimens in this study.

5.2.2.2 *Sample preparation and curing*

5.2.2.2.1 *Conventional concrete*

A number of conventional concrete specimens (water-to-cement ratio, w/c , of 0.5 and granular material (gravel + sand) to cement ratio, $G+S / C$, of 3) were prepared. Tap water and Portland cement type I were used for preparing these samples. The ingredients were mixed in a concrete mixer for about 7 minutes, and then poured in cylinders, 5 cm in diameter and 10 cm in height. The cylinders were then sealed (to avoid evaporation) and cured at room temperature under laboratory-controlled conditions. Moreover, cement paste (CP) samples for microstructural analysis were also prepared by following the same procedure with constant w/c ratio of 0.5 for all samples. Selected specimens were dried in the oven at 45°C over a period of four days until a constant mass was attained for various experiments.

The results of various tests on the conventional concrete, one of the most popular construction material, were used as reference for gaining better understanding and more insight into the properties of the proposed new PWC samples. It should be underlined that the goal of this exercise is not to compare the performance of these materials, but rather to gain a better understanding of the properties or behavior of the PWC.

5.2.2.2.2 PWC with melted plastic wastes

Experiments on PWC materials have been performed using two plastic contents (50% and 60%) with different ratios of HDPE and LDPE (Table 5.1). Optimized parameters obtained from exploration phase of ecological mortar manufacturing procedures (Thiam and Fall, 2020), namely the timing to introduce the different types of plastics and sand materials, the melting and casting temperature (250°C) for an ambient temperature ranging from 24 to 30°C, were adopted for the preparation of PWC.

Sampled gravel and sand were oven dried at 105°C and passed through the corresponding sieves in order to achieve in the total mass of aggregates: 50% of sand (size smaller than 2 mm), 30% of sand and gravel (2 mm to 4.75 mm) and 20% of gravel (4.75 mm to 10 mm). For each mixture, the required amount of plastic wastes in small pieces (less than 6 cm) was placed in an oven at 250°C for 20 to 45 minutes depending on the formulation to produce a plastic paste used as binding material for PWC with regular recording of the temperature. Next, the appropriate quantity of granular materials (sand and gravel) were added and well mixed at high temperature (above 100°C) for about 15 min to obtain a homogeneous mixture. Then, the inner surface of metallic cylindrical molds (10 cm in diameter and 20 cm in height, or 5 cm in diameter and 10 cm in height) were coated with lubricant to facilitate demolding. The hot liquid of fresh PWC was poured into the molds, compacted using a manual hand press and kept under pressure to limit sagging of the final product. Half an hour after, the PWC samples were demolded. Figure 4 shows some steps of the preparation. After demolding, the samples were cured at room temperature for periods of 1, 3, 7, and 28 days.

Table 5-1: Mix composition of the PWC with melted HDPE and LDPE plastic wastes as binder

PWC sample	Plastic binder type	Plastic binder content (%)	HDPE / LDPE	Granular materials	Curing time (days)
50% P – H/L 50/50	HDPE - LDPE	50	50/50	Sand and Gravel	1, 3, 7, 28
60% P – H/L 50/50	HDPE - LDPE	60	50/50	Sand and Gravel	1, 3, 7, 28

P: plastic content in (wt%) by reference to the dry mass of granular materials (sand and gravel), H/L ratio of HDPE to LDPE.



a) 5 cm in diameter and 10 cm in height b) 10 cm in diameter and 20 cm in height
Figure 5-4: Samples of PWC with melted plastic wastes before (right) and after (left) demolding.

5.2.2.3 *Mechanical tests*

Mechanical properties, such as strength and stress-strain behavior, are very important for concrete or cemented materials with regard to its capacity to withstand load and cracking potential when forces are applied to reduce the concrete sample sizes. Thus, these properties establish the service life that can be expected for a given material and can allow to have better understanding about its strain at failure, which is indicative of its tolerance of high strain before failure. Hence, mechanical tests were conducted to determine the strength and deformation behavior of the PWC.

The mechanical tests include uniaxial compression strength (COMPRESSIVE STRENGTH) and split tensile tests. Each test was repeated three times to ensure the repeatability of the results. Computer-controlled mechanical press was used to determine the uniaxial compressive strength of cylindrical specimens of the PWC according to ASTM C39 / C39M – 18 procedures. Moreover, the axial deformation was recorded to determine the deformation behaviour. The splitting tensile strength was determined in accordance with ASTM C496 / C496M - 17 procedures. Also, known as Brazilian test, this test was conducted on various samples to understand the tensile properties of the PWC.

5.2.2.4 *Hardened density test*

Hardened density of the construction material is closely linked to its mechanical properties as well as its porosity and durability. Hardened density is indicative if the material is lightweight and may provide more information for transport cost. Denser construction material corresponds generally to a material with fewer voids and higher strength, thus less permeable to aggressive solutions,

which can affect the durability of the material. Thus, following the ASTM C 138 / C138M – 17a procedures, the densities of cylindrical samples of PWC and conventional concrete samples were determined based on their mass (M) weighted. Each measurement was repeated at least three times for each formulation to confirm the repeatability of the results.

5.2.2.5 *Microstructural analyses*

Microstructural analyses or tests were conducted on samples with different compositions to understand how the mechanical properties of the PWC can be affected by its microstructure. For that purpose, a number of microstructural analyses or tests, namely mercury intrusion porosimeter (MIP) tests, scanning electron microscope (SEM) observations and thermogravimetric (TGA/DTG) analysis were performed on various samples of conventional concrete and PWC. Samples for microstructural analyses were first oven dried at 45°C until achieving a constant mass.

The MIP was used to evaluate the pore size distribution in the PWC by injecting mercury under high pressure with gradual increase rate in the pore system of dried samples. The tests were performed on various specimens of conventional concrete and PWC by using a Micromeritics Auto Pore III 9420 mercury porosimeter in accordance with ASTM D4404-10 specifications.

Various SEM images with different magnifications were obtained from the use of Joel JSM-6610LV device on different square carbon coated samples of PWC and conventional concrete. By switching between various modes of the SEM imaging, the topography and the compositions of various specimens from different formulations were observed and images are used to analyze the morphology, texture and adhesion of the samples constitutive elements. The images were further analyzed using Imagej software, in order to obtain more details concerning the pore structures and cohesion between different elements present in the PWC and conventional cemented materials.

Thermal analysis (thermogravimetric (TGA) and derivative (DTG)) were performed on various samples of the PWC with TGA Q5000 V3.15 Build 263 apparatus to evaluate their thermal degradation and compare them with the pure plastic wastes and conventional concrete. Less than 40 mg of samples were placed on alumina pan and heated under nitrogen atmosphere from 10 to 1000 °C, the heating rate was set at 10°C / min with the flow rate of 10 mL/min, and the weight variation was recorded as function of the temperature for various samples.

5.2.2.6 *Absorption tests*

Water absorption is used to understand the porosity and pore structure of the PWC. The porosity and pores structure will provide more details about the quality and behaviour of given material in weathering or its capacity to limit the amount of water that may cause failure when exposed to aggressive agents (salt attack) or freeze thaw cycle, which are directly linked to the material durability during its service life (Marzouk et al. 2007).

Thus, different samples of PWC and conventional concrete were subjected to capillary and immersion absorption tests. The specimen (5 cm in diameter and 10 cm in height) were oven dried

at 60°C until achieving a constant mass. An hour later from removing them from the oven, the specimens were weighted to obtain the initial mass before starting the experiments. Following the procedures of ASTM C97/C97M – 18 standard, a number of PWC and conventional concrete specimens were immersed in distilled water tank for 7 days to determine their immersion absorption.

Another set of samples comprising PWC and conventional concrete samples were tested according to the ASTM C1585 – 13 standard to understand their behavior when subjected to capillary absorption. The absorption is determined as function of the density of water and the variation of mass in the sample body (Hall 1989). Care was taken to fully cover the samples with plastic and only expose a 3 mm portion at the bottom, allowing to control the flow direction of water and have appropriate understanding of the material porosity. This sheds light on how interconnected are the pores in these materials. The rate of capillary absorption (initial and secondary) are the slopes of the graph of capillary absorption vs the square root of time up to 7 days. Based on the ASTM C1585 – 13 procedures, the slope change between initial and secondary sorptivities was expected at 6 hours, which was not the case for PWC, for which the slope change was observed at 10 hours, thus the details in this paper will consider that aspect.

5.2.3 Results and discussions

5.2.3.1 *Microstructural properties of the PWC*

5.2.3.1.1 *Thermogravimetric Analysis*

Figure 5.5 presents typical TG/DTG results of pure plastic wastes (HDPE and LDPE) used to prepare the PWC. From zero to 300°C there is no variation in mass for both HDPE and LDPE materials, indicating the absence of water in the specimen. Then, major peak of 0.163% per °C was observed between 340°C and 445 °C for HDPE, 0.215% per °C for LDPE between 400°C and 550°C. A 50% mass reduction was observed at 410°C and 470°C for HDPE and LDPE, respectively. These two plastic types are polymer dependent plastics, which were mixed and melted to obtain plastic paste binder to form the PWC.

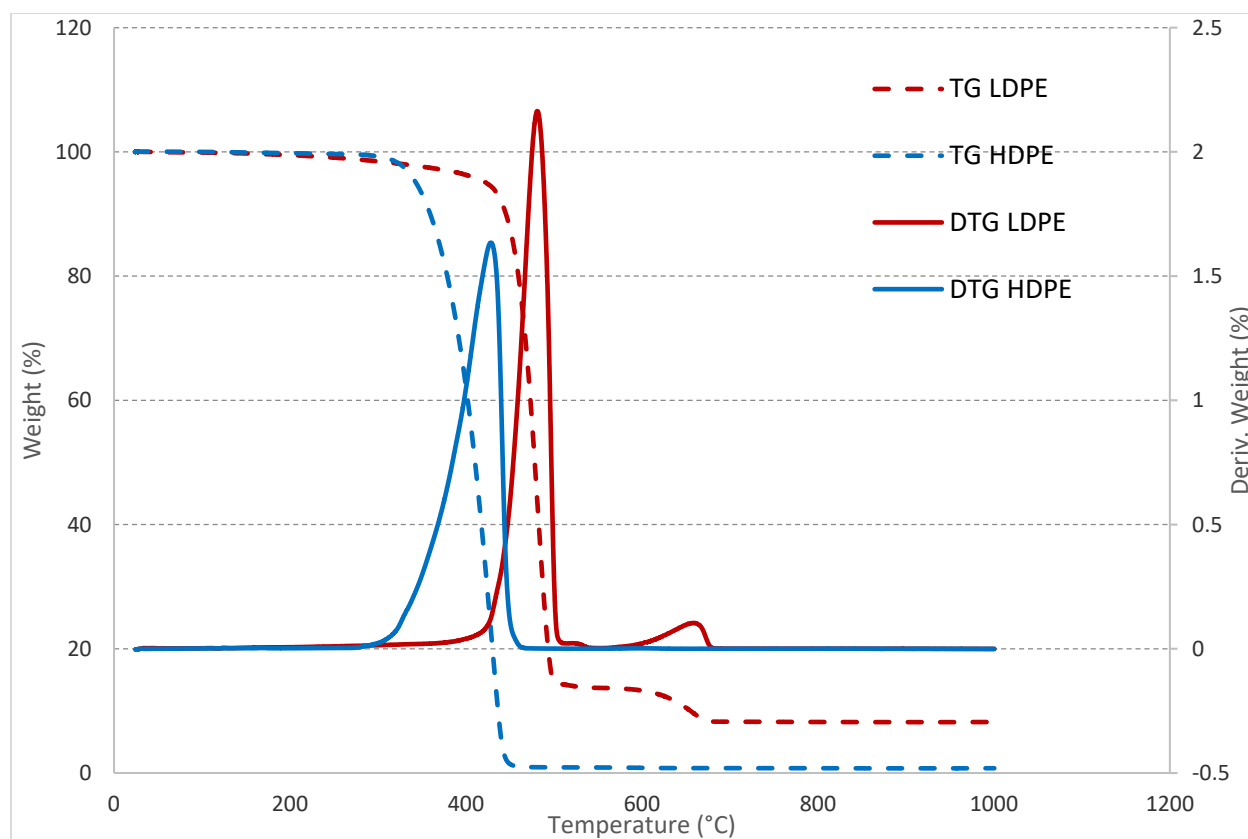


Figure 5-5: TG and DTG curves for virgin (or pure) HDPE and LDPE plastic wastes

Figure 5.6 shows the TG/DTG results for PWC with 50% (PWC50) and 60% (PWC60) of plastics (HDPE and LDPE) at equal proportion. From zero to 360°C, no mass change was observed for all the PWC samples. Starting from that point, PWC60 shows a large mass variation within the temperature of 360°C to 470°C with a peak value of 0.422% per °C between 470°C to 600°C, while the peak of 0.618% per °C was observed for PWC50 between 360°C and 480°C. After 480°C, the TG graph for both PWC50 and PWC60 tends to become stable with the constant mass higher than 50%, representing the inert materials (gravel and sand) in the PWC. However, small peaks of 0.101% per °C at 637°C and 0.238% per °C at 667°C were observed for PWC60 and PWC50, respectively. However, after the melting of plastic wastes (HDPE and LDPE), there was a lag with delay in thermal degradation of PWC by comparison to the pure plastics, indicating that the TG/DTG results for PWC is not cumulative of the individual polymer degradation (Murty et al. 1996; Rajasekaran and Maji 2018, Tondl et al. 2018, Thiam and Fall 2020). According to these results, the mixing process and heat transfer during the melting phase of plastic wastes have influenced in some ways the thermal behaviour of the new material from the constituents binding elements. To attain 80% of mass loss, the PWC needs more heat (465°C) than the pure plastic wastes (HDPE and LDPE) which only required between 360°C and 460°C. Thus, it appears that the inorganic material (sand and gravel aggregates) and melting process enhance the thermal stability of the PWC material (Barbara et al. 2014). After the entire structural breakdown, there is almost no solid residue (less than 5%) for the pure plastic wastes (LDPE and HDPE) (Figure 5.5), while more than 65% of solid residue was left for the PWC (Figure 5.6).

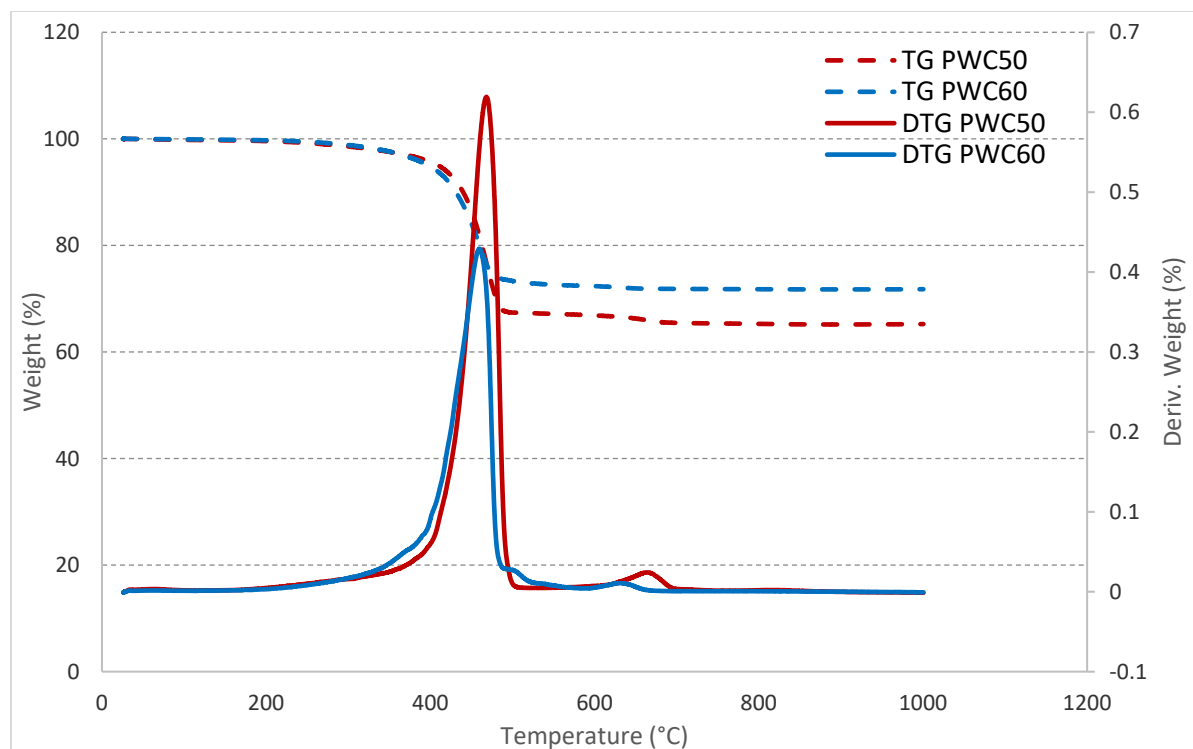


Figure 5-6: TGA and DTG curves for PWC containing 60%P - H/L 50/50 and 50%P - H/L 50/50 of plastic contents

Comparing the thermal behaviour (DT/DTG) of the proposed PWC with the well-known thermal behaviour of the conventional concrete will help to gain a deeper insight into the PWC thermal properties. Figure 5.7 presents the results of TG/DTG analyses on the conventional concrete described previously. It can be observed from the graph that between 0 and 200°C, the mass drop with the peak of 0.019% per °C at 54°C, which can be related to the loss of hygroscopic water, the destruction of C-S-H gel and the decomposition of ettringite and gypsum (Fall et al. 2010; Torres et al. 2013). In the interval of 400°C to 600°C, the dehydroxylation of calcium hydroxide CH resulting in multiple peaks, with the highest of 0.09 % per °C at 466°C (Fall et al. 2010; Torres et al. 2013). Between 600°C and 815°C, the larger peak of 0.208 % per °C was observed at 733°C, which is the consequence of the decomposition of the calcite and the hydrated aluminate phases (Fall et al. 2010; Torres et al. 2013). From 815°C, the mass variation became constant at 74%, thus the remaining component are gravel and sand which need higher temperature to decompose.

The results of TG/DTG analyses on PWC and conventional concrete samples presented above indicate that, after the complete breakdown, the mass of inert components left was 74% for the conventional concrete, which was found to be between 65 to 71% for the PWC. On the other hand, the peak decomposition temperature for convention concrete (733°C) was found to be higher than what was obtained for PWC samples (432 °C and 482 °C). This can be associated to the behaviour of the PWC plastic component when exposed to high temperatures.

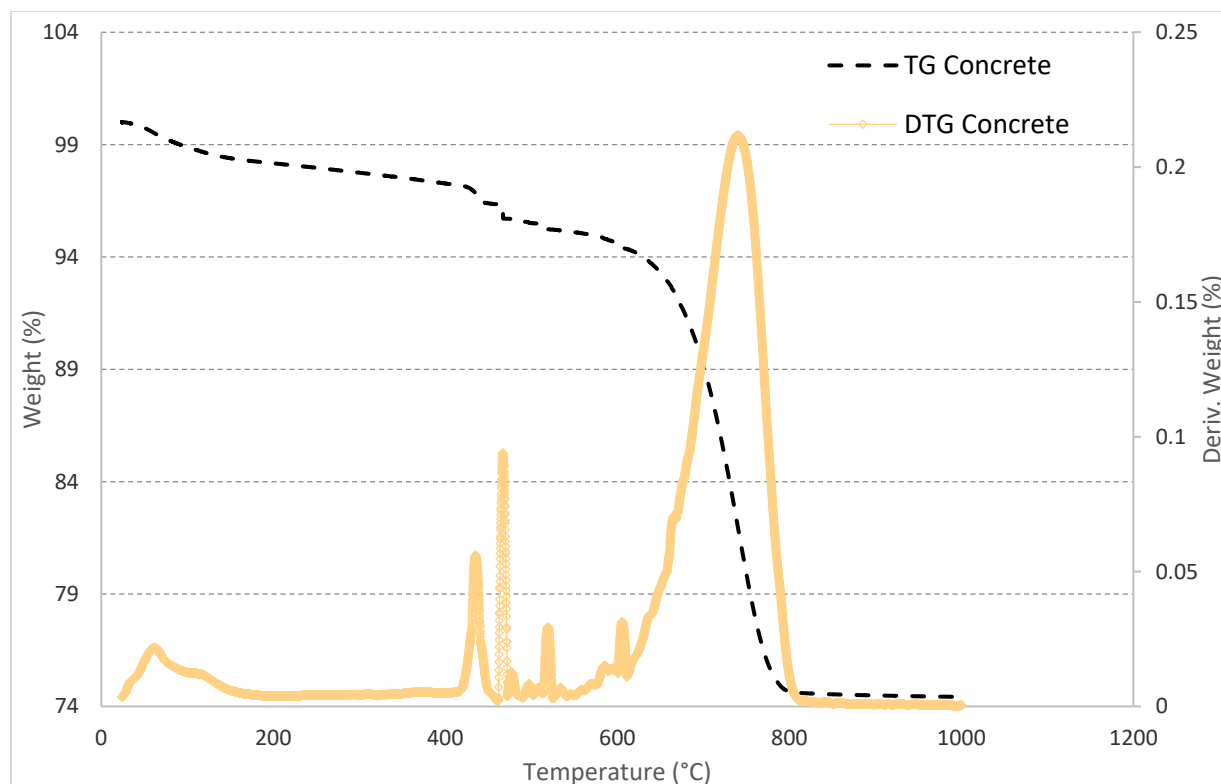


Figure 5-7: TGA and DTG curves for conventional concrete

5.2.3.1.2 Mercury Intrusion porosimetry results

Figure 5.8 (a and b) presents the variations in cumulative pore volumes and the incremental porosity with respect to the pore sizes for the PWC and conventional concrete samples (PWC50 and PWC60). For the purpose of MIP results analysis, different divisions of pore size distribution were proposed (Ramachandran and Beaudoin 2000; Zeng et al. 2012, Choi et al. 2017; Ouellet et al. 2018). Ouellet et al. (2018) divided into two portions ($<0.3\mu\text{m}$) and ($\geq 0.3\mu\text{m}$ corresponding to capillary pores), while Choi et al. (2017) used three ranges: mesopores (6-10 nm, 10-25nm, 25-50 nm), middle capillary pores (50-100 nm) and larger capillary pores (>100 nm). In the present study, for better characterization of the obtained MIP results, the pore size distribution is divided in three categories: small pores ($0.003 - 0.03 \mu\text{m}$), middle capillary pores ($0.03 - 0.3 \mu\text{m}$) and larger capillary pores ($>0.3 \mu\text{m}$). The pores with diameter higher than $0.3 \mu\text{m}$ correspond to the main interconnected ones (Powers 1958).

There is clear difference between the cumulative pore volume of PWC50 and PWC60 (Figure 5.8a). Similar trends were observed for both graphs; however, the cumulative porosity was higher for PWC50 than PWC60 before the pore diameter of 57 microns and from that point, they became almost the same. This difference in cumulative pore volume and porosity between the PWC50 and PWC60 is related to the difference in plastic content. The cumulative pore volume of PWCs (PWC50 and PWC60) was found to be higher than that of the conventional concrete. Summary of analysis of various MIP graphs from Figure 5.8 is presented in Table 5.2 with different parameters,

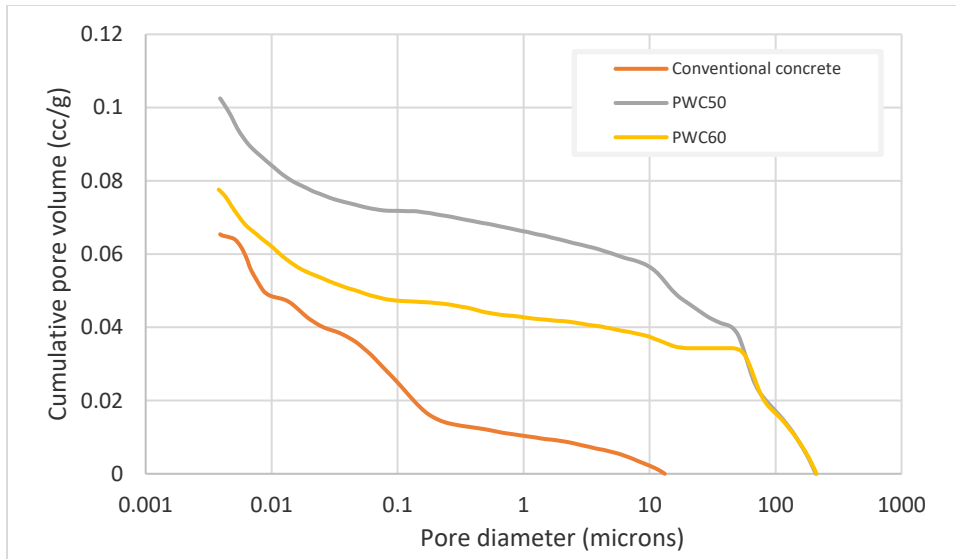
such as the threshold diameter, d_t , corresponding to the pore size under which mercury intrusion percolation occurs, an important parameter, which plays essential role when looking into the connectivity of the pore structure.

From the Table 5.2, it can be clearly seen that the total porosity values for PWC50 and PWC60 (0.1025 cc/g and 0.0776 cc/g, respectively) are higher than that of the conventional concrete (0.0654 cc/g). The total volume of pores (small and medium capillary) increases with the plastic content of PWC, thus PWC50 has higher number of larger capillary pores than PWC60. This will have an impact on the permeability behaviour and other engineering properties of the PWC such as compressive strength and absorption. On the other hand, the amount of larger capillary pores for conventional concrete (20.3% of the total porosity) is low compared to the ones obtained for PWC (67.9% and 59.2%). In other words, the conventional concrete has finer pore structure. However, all the categories of pore diameters are well represented in conventional concrete pores distribution, which can play an important role in terms of pores interconnectivity and affect the materials mechanical and permeability properties. The threshold diameter was found to be at 50.8 μm , 57.9 μm , and 0.2 μm , respectively, for PWC50, PWC60, and conventional concrete.

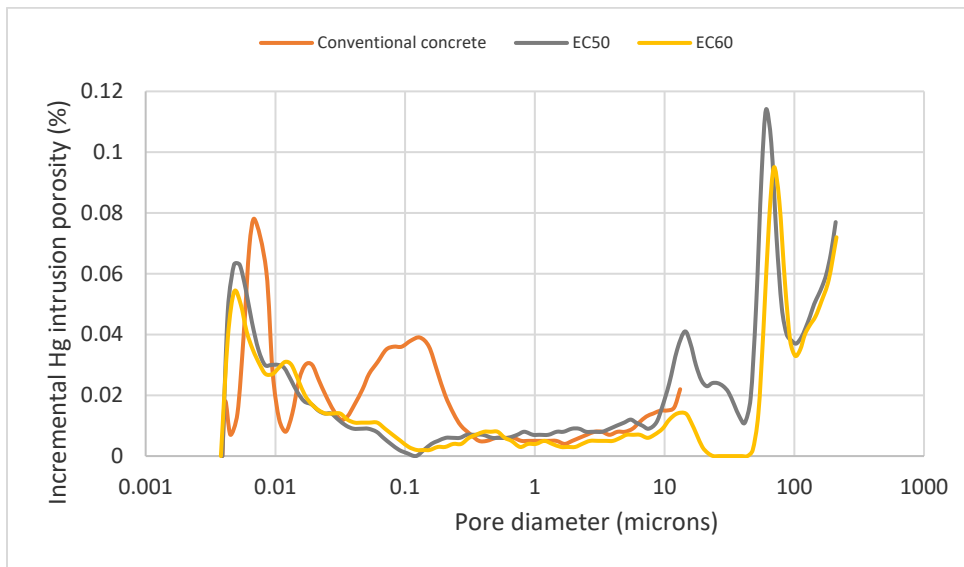
Table 5-2: Results of the MIP analysis and determination of the characteristic parameters of pore structure for various formulations of PWC and conventional concrete

Samples	PWC50	PWC60	Concrete
Porosity (0.003 – 0.03 μm) cc/g	0.027	0.026	0.026
% Porosity (0.003 – 0.03 μm)	26.7	33.0	40.1
Porosity (0.03 – 0.3 μm) cc/g	0.006	0.006	0.026
% Porosity (0.03 – 0.3 μm)	5.4	7.9	39.6
Porosity (> 0.3 μm) cc/g	0.069	0.046	0.013
% Porosity (> 0.3 μm)	67.9	59.2	20.3
Total pore volume, V_t cc/g	0.103	0.078	0.065
TD or d_t , microns	50.8	57.9	0.2

PWC50: PWC with 50% plastic content; PWC60: PWC with 60% plastic content; TD (d_t): threshold diameter



a- MIP Cumulative pore volume for PWC and conventional concrete



b- MIP pore size distribution for PWC and conventional concrete

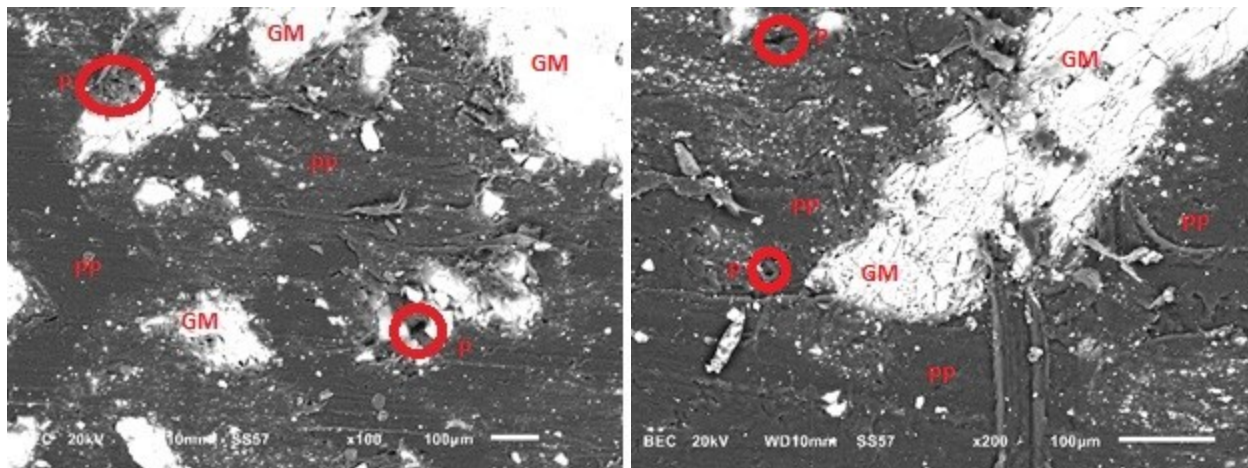
Figure 5-8: MIP results for various formulations of the PWC and conventional concrete (PWC50: PWC with 50% plastic content; PWC60: PWC with 60% plastic content)

Moreover, the PWC samples (PWC50, PWC60) show similar differential porosity with apparition of one small peak before the diameter of 10 microns. Beyond this peak, a clear difference was observed with higher values for PWC50. Both PWC samples showed a small peak followed by the larger between 10 and 100 microns, the higher differential porosity peaks were 0.114% and 0.095% for PWC50 and PWC60 corresponding to the cumulative porosity of 0.1003 cm³/g and 0.0776 cm³/g, respectively. The major peaks in term of differential porosity for PWC was observed after 10 microns corresponding to the larger capillary pores (Choi et al. 2017), which was not the case for conventional concrete that showed three peaks before 1 micron with the major peak of

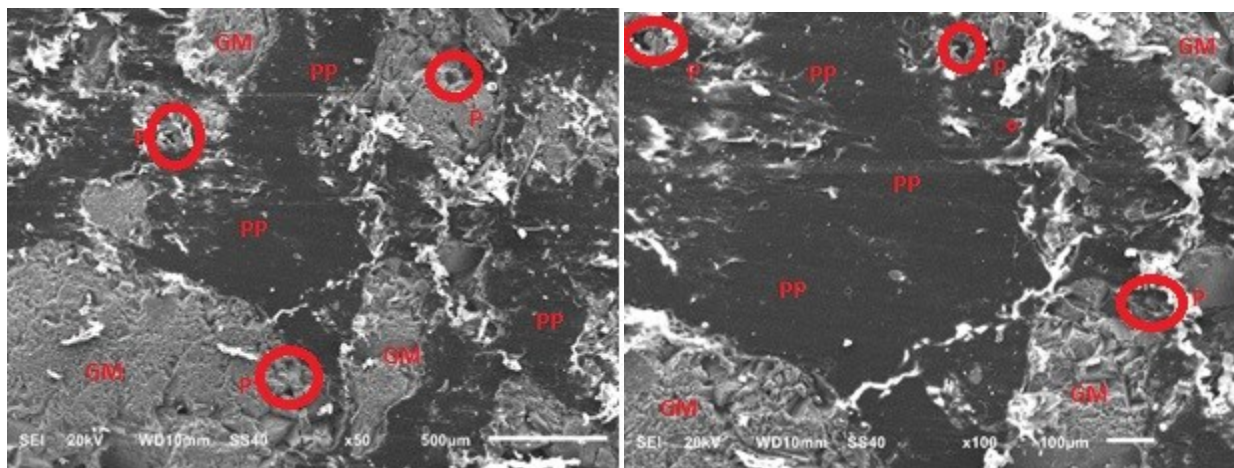
0.078% at 0.0069 micron. Most of the variations in differential porosity were observed in small pores dimension for the conventional concrete, while the PWC showed its variations for larger capillary pores dimension.

5.2.3.1.3 Scanning Electron Microscope observations

Figures 5.9-5.11 present SEM images for various samples of PWC and conventional concrete, with BEC (Backscattered electron composition image) showing the composition of the samples and SEI (Secondary Electron Images) giving a clear view on their topography. From these figures, both PWC and conventional concrete seem to be porous construction materials with voids/pores in the samples bodies.

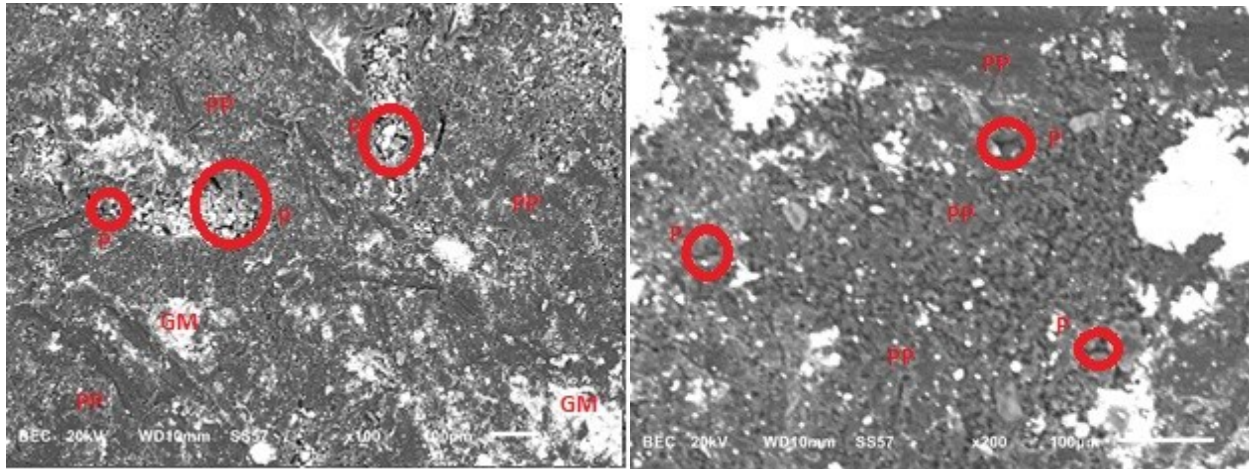


a) SEM images (magnified x100 (left) and x200 (right)) showing the composition (BEC) of the PWC, PWC50, containing 50%P – H/L 50/50 of plastic contents

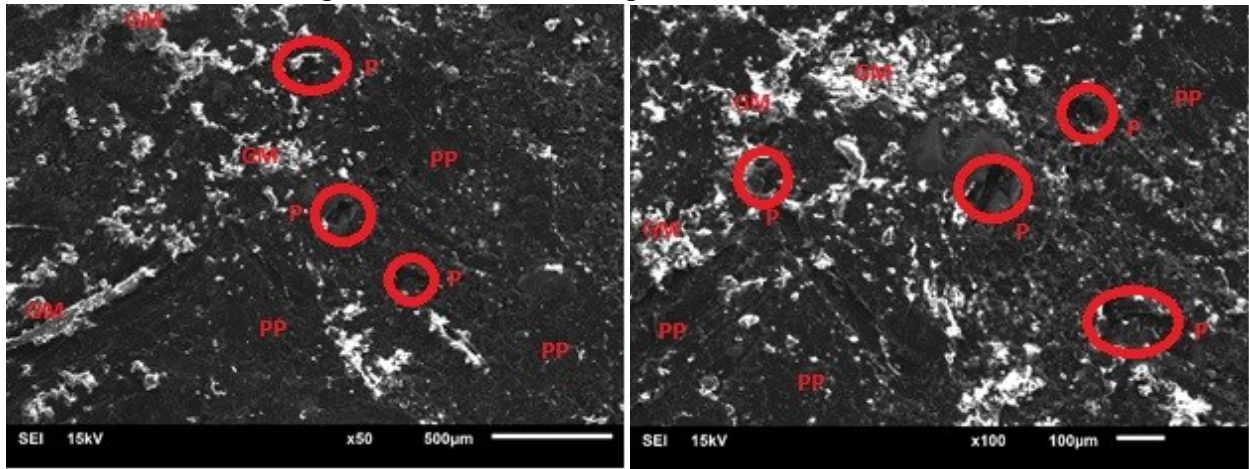


b) SEM images (magnified x50 (left) and x100 (right)) showing the topography of the PWC, PWC50, with 50%P – H/L 50/50 of plastic contents

Figure 5-9: SEM topography (SEI) and composition (BEC) images of the PWC, PWC50 (GM: granular material, sand/gravel; PP: plastic paste; P: pore; SEI: Secondary Electron Images; BEC: Backscattered electron composition image)



a) SEM images (magnified x100 (left) and x200 (right)) showing the composition (BEC) of the PWC, PWC60 containing 60%P – H/L 50/50 of plastic contents



b) SEM images (magnified x50 (left) and x100 (right)) showing the topography of the PWC, PWC60 with 60%P – H/L 50/50 of plastic contents

Figure 5-10: SEM topography (SEI) and composition (BEC) images of PWC, PWC60 (GM: granular material, sand/gravel; PP: plastic paste; P: pore; SEI: Secondary Electron Images; BEC: Backscattered electron composition image)

From the topography (SEI) (Figure 5.9 b and figure 5.10 b), more pores/voids can be observed in PWC50 than PWC60, and the size of pores in PWC50 seems to be higher than that in the PWC60, confirming the obtained results from MIP analysis of the PWC. On the BEC images (Figure 5.9 a and figure 5.10 a), the dark color represents the plastic paste which is the light component of the PWC and the white color corresponds to the granular material which is the heavy constituents of the PWC. In general, the plastic paste was found to bind granular materials with the presence of voids/pores, especially at the interfacial transition zone between melted plastic waste used as binder and the granular materials (sand and gravel). These voids/pores, which are weak points are found to be more present in the PWC50 than the PWC60, resulting in higher porosity for PWC50 in comparison to PWC60. The pores in PWC50 have higher tendency of being interconnected,

because the adhesion between different elements seems to be in good configuration for PWC60 than PWC50. These observations are in line with the obtained porosity results from MIP analysis.

From Figure 5.11, it is clear that the pores size for conventional concrete seems to be smaller than the ones obtained for PWC, confirming the larger amount of small and middle capillary pores or finer pore structure for conventional concrete from MIP analysis.

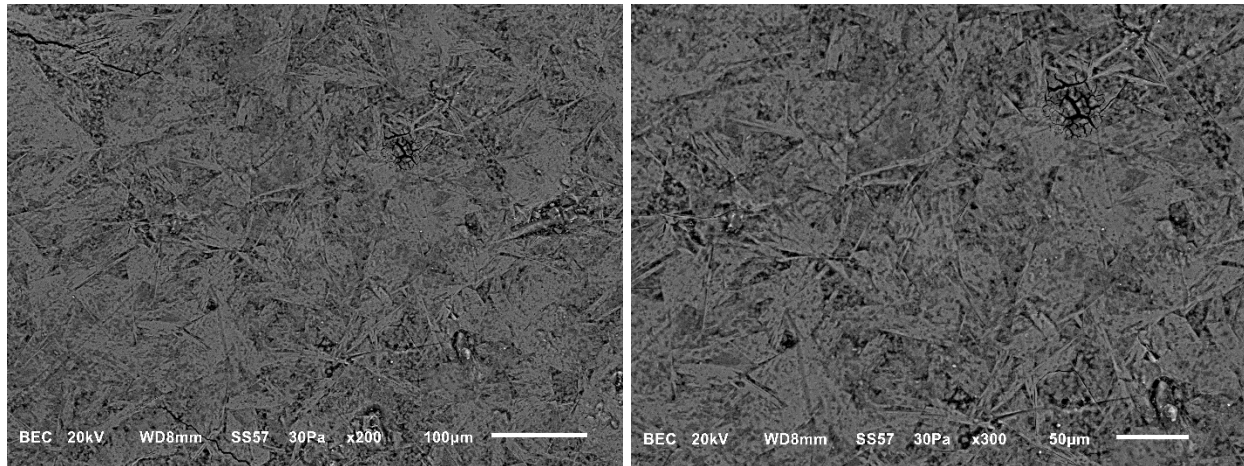


Figure 5-11: SEM images (magnified x200 and x300) showing the composition (BEC) of the conventional concrete

To gain a deeper insight into the porosity and pore structure of given construction materials, several studies (Rasband 1997; Grove and Jerram 2011; Berrezueta et al. 2019) used different image analysis techniques and/software. Thus, to support the understanding of PWC samples porosity, Imagej software is used in this study to analyse a number of SEM images for PWC and conventional concretes. Analysis with Imagej, a public domain Java image processing program, allows to determine the area occupied by the pores as well as the average pore diameter for various samples. Figures 5.12 and 5.13 present the results for various samples and Table 5.3 provides obtained results for pores area and Feret's diameter of different specimen.

From these results, the percentage pores area of PWC60 was found to be lower than that of PWC50 and the amount of pores for conventional concrete was higher than the ones for PWC, which can be associated to the effect of water in Portland cement based concrete. Nevertheless, the average feret diameter was small for conventional concrete when compared to PWC, and subsequently the conventional concrete pores appear to be smaller and less interconnected than the ones of PWC, confirming the results from SEM and MIP analysis.

Table 5-3: % pores area and Feret's diameter of of PWC (PWC50, PWC60) and conventional concrete from imagej porosity analysis

Specimen	% Pores area	Feret's diameter (microns)
PWC50	25.79	6.41
PWC60	11.99	6.45
Conventional concrete	85.04	6.06

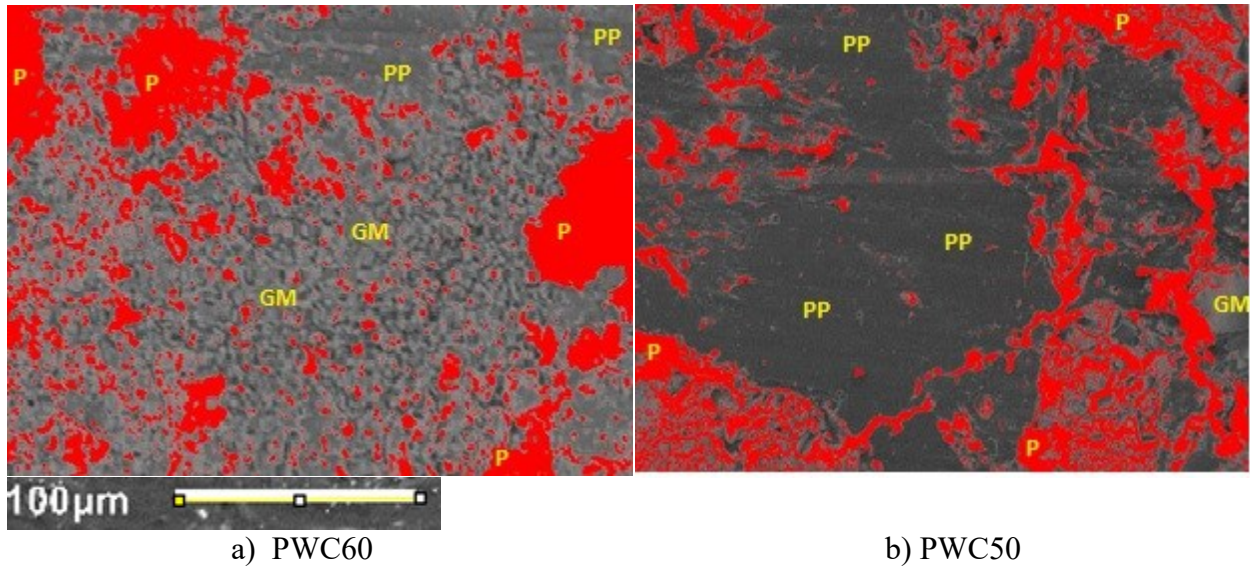


Figure 5-12: SEM images showing the PWC after ImageJ porosity analysis (GM: granular material, sand/gravel; PP: plastic paste; P: pore)

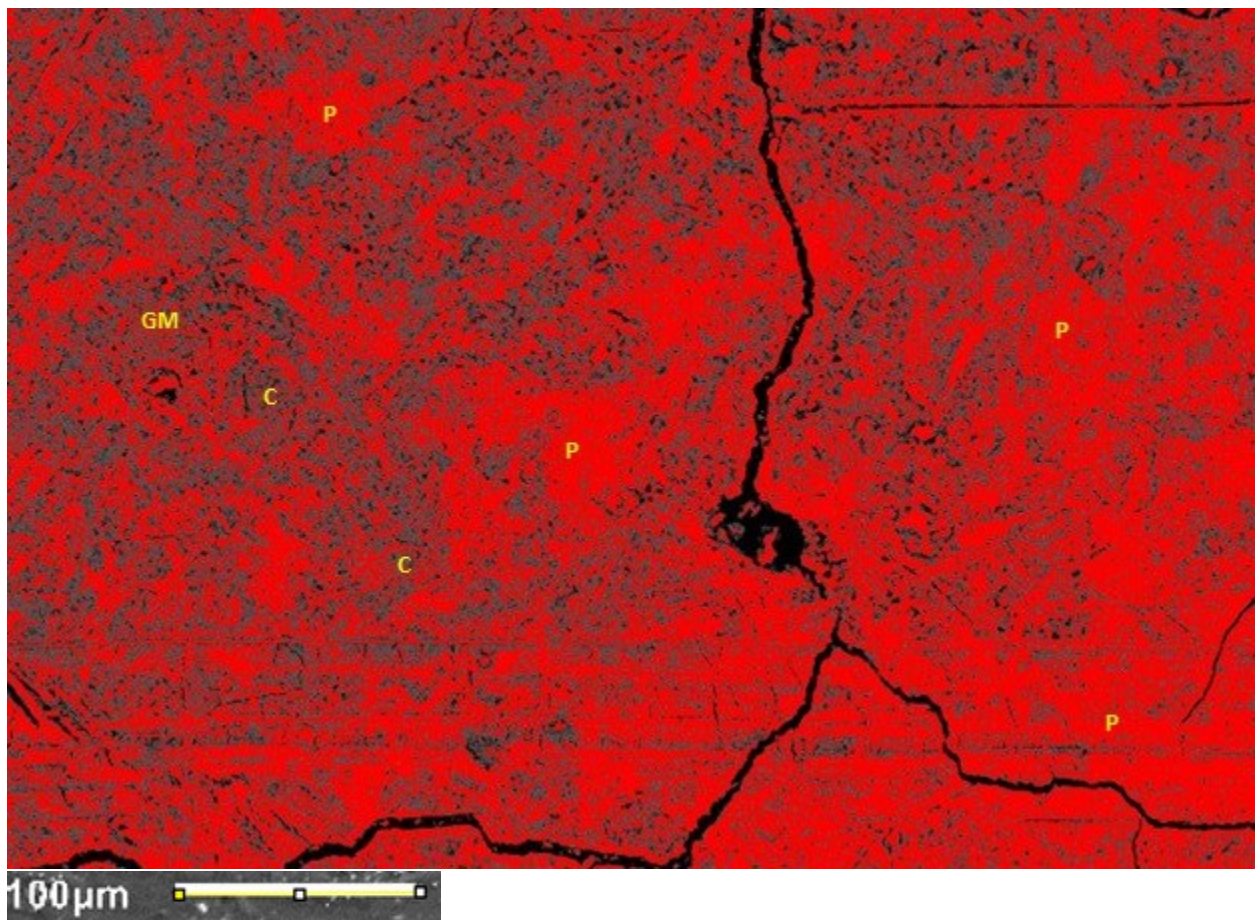


Figure 5-13: SEM images showing the conventional concrete after ImageJ porosity analysis (GM: granular material, sand/gravel; C: cement; P: pore)

5.2.3.2 Compressive strength development of the PWC

Figure 5.14 shows the development of the compressive strength of the PWC (PWC50 and PWC60) with time. The strength increases with time regardless of the plastic waste content. The plastic paste used as the binder for PWC is polymer dependent (Braun 2002; Thiam and Fall 2020), thus the increase in strength with time can be related to the polymer type and crystallinity (da Silva and Wiebeck 2017) as well as the solidification of plastic paste when exposed to ambient temperature (Ragaert et al. 2017; Sun et al. 2018).

The strength values of PWC60 are observed to be higher than the ones of PWC50. The reasons for that difference can be deduced from the MIP and SEM results. The PWC60 has less porosity than PWC50 and the configuration of its interfacial transition zone looks more compacted (stronger) with less voids than PWC50. That influences the strength vary inversely, proportional with the porosity as supported by previous works on various construction materials (Lui 1997; Poon et al. 2004; Cheng et al. 2008; Chen et al. 2013).

Moreover, the compressive strength of all PWC samples, regardless of age and plastic content, were found to be higher than 10 MPa, which somehow exhibit interesting mechanical strength behaviour compared to the cementitious composite concrete when the sand volume is completely substituted by PET aggregates (Marzouk et al. 2007).

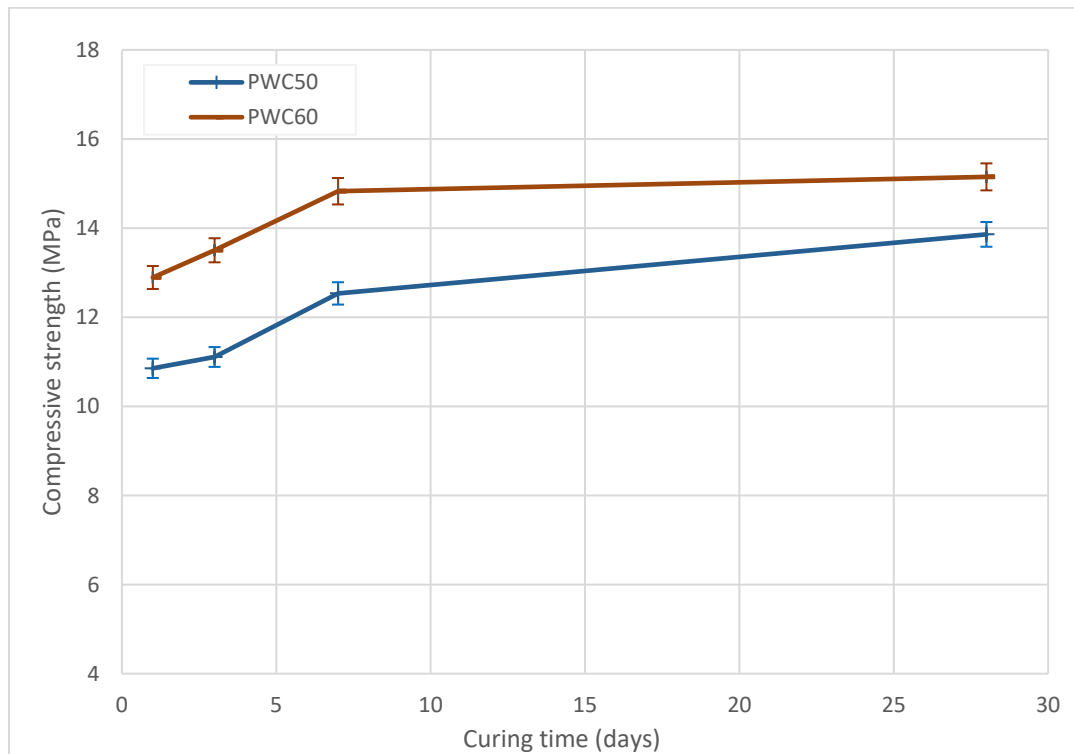


Figure 5-14 : Compressive strength development vs time of the PWC with 50%(PWC50) and 60% (PWC60) of melted plastic wastes (HDPE/LDPE ratio of 50/50).

5.2.3.3 Split tensile strength development of the PWC

Figure 5.15 presents the splitting tensile strength vs time of the PWC. The splitting tensile strength changes with time and plastic content, similarly to what was observed for the compressive strength in the previous section. The mechanisms responsible for these changes in splitting tensile strength are the same explained above on compressive strength. The higher splitting tensile strength for PWC60 than PWC50 can also be linked to the lower porosity and good bonding properties at ITZ for PWC60 by comparison to PWC50 as discussed above in MIP and SEM results sections.

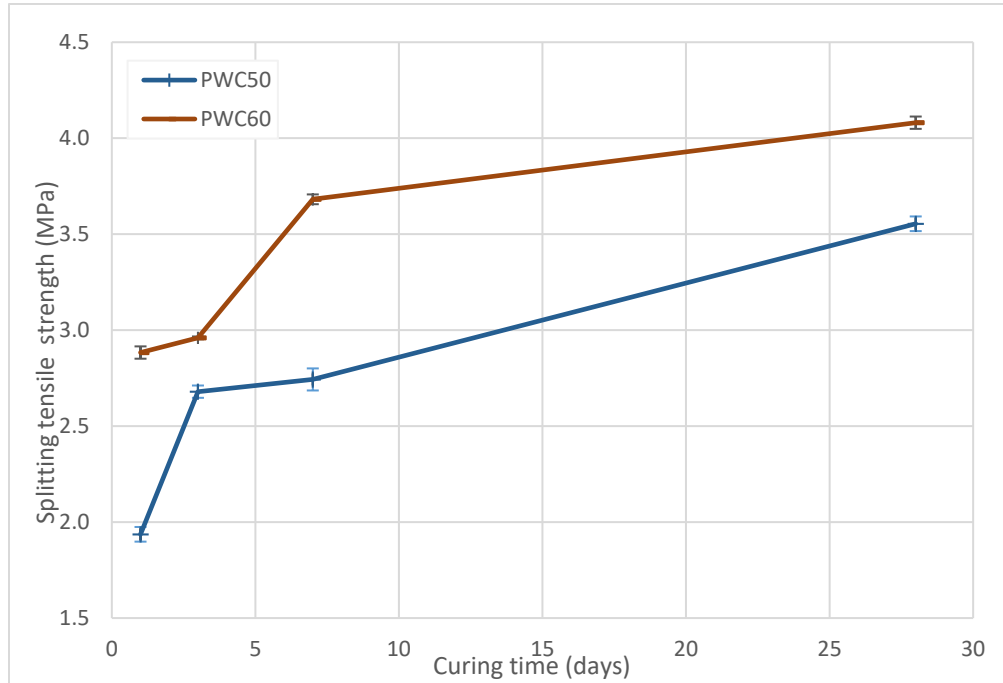


Figure 5-15: Splitting tensile strength development of the the PWC cemented with 50% (PWC50) and 60% (PWC60) of melted plastic wastes (HDPE/LDPE ratio of 50/50)

5.2.3.4 Split tensile strength vs compressive strength of the PWC

Figure 5.16 shows the variations of splitting tensile strength as function of compressive strength were drawn for PWC50 and PWC60 (Figure 5.16). From this figure, it can be seen that the split tensile strength increases with an increase of compressive strength for both formulations of the PWC at different ages. The ratio between the splitting tensile strength and uniaxial compressive strength is generally in the range of 0.20 to 0.25.

Commonly, only the compressive strength of the cemented construction materials is experimentally determined for the objective of quality control. The splitting tensile strength is frequently estimated from the uniaxial compressive strength by adopting empirical correlation equations. Thus, using the experimental data from tests performed during this study, it is found that the splitting tensile strength of the PWC can be predicted using the following prediction equation (equation 5.1). This equation was obtained by fitting linear regression lines through each set of data on the splitting tensile (f_t) vs. uniaxial compressive strength (f_c) data, as illustrated in Figure 5.17.

$$f_t = a * f_c - b$$

Equation 5-1

Where $a = 0.3856$; $b = -1.9832$ in this study.

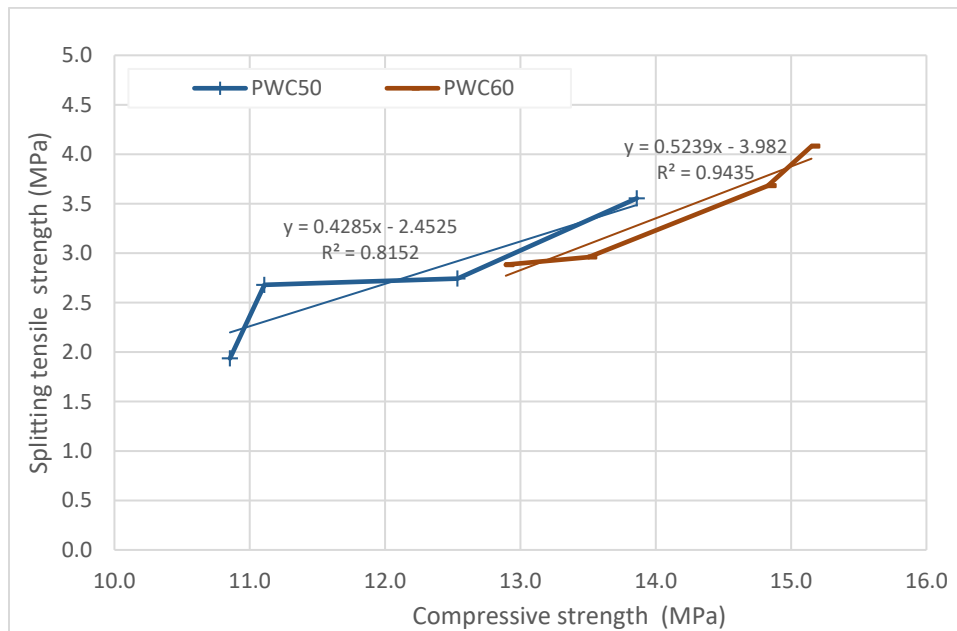


Figure 5-16: Splitting tensile strength vs compressive strength (COMPRESSIVE STRENGTH) of PWC cemented with 50% (PWC50) and 60% (PWC60) of melted plastic wastes (HDPE/LDPE ratio of 50/50)

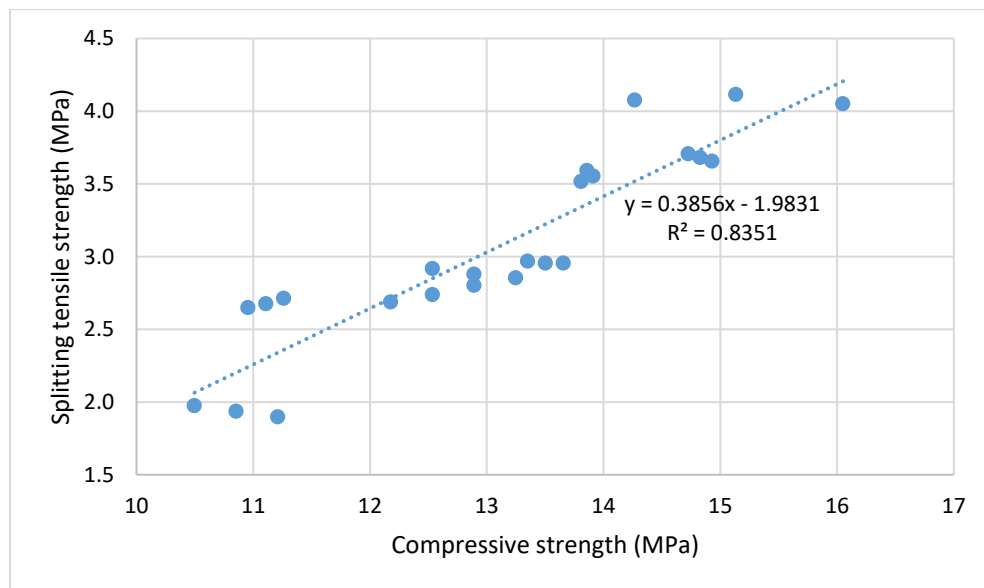
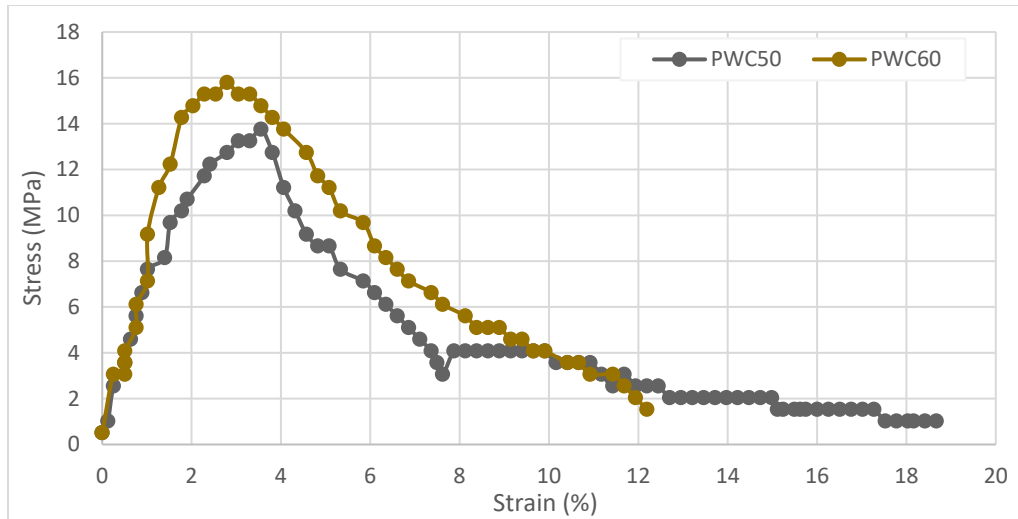


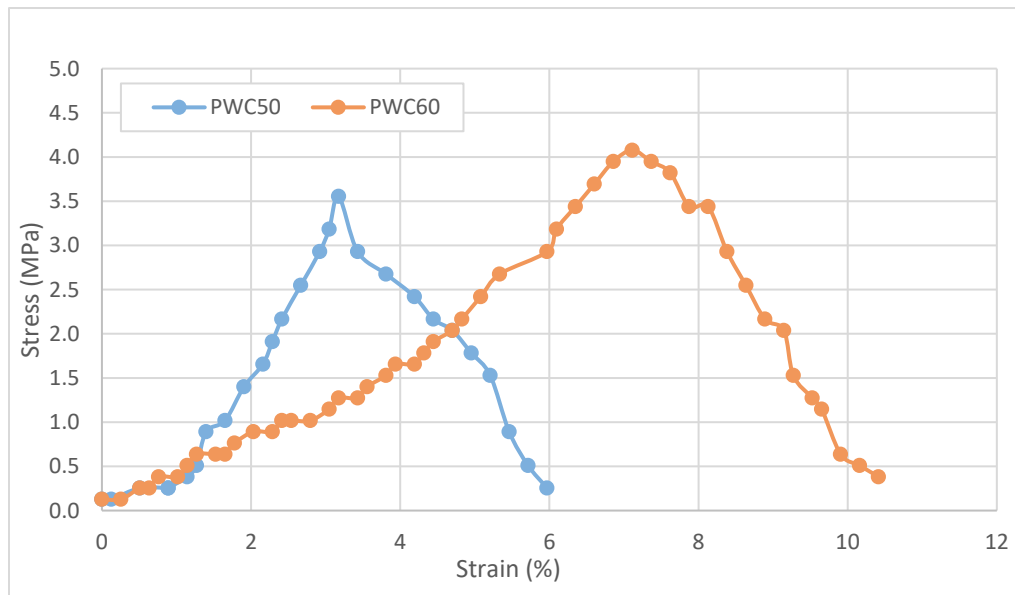
Figure 5-17: Linear correlation between splitting tensile and compressive strengths of the PWC cemented with 50% and 60% of melted plastic wastes (HDPE/LDPE ratio of 50/50)

5.2.3.5 *Stress-strain behaviour and failure mode of the PWC*

Figure 5.18 (a and b) presents typical stress-strain behavior of the PWC when subjected to compression and splitting tensile strength tests. The graphs consist of two parts separated by the peak value of the stress (strength). In other words, the stress-strain behavior of the PWC is represented by an ascending (including a pre-peak region and a peak-region) and a descending branch, as also observed in the stress-strain behavior of conventional concrete (Figure 5.19). Figure 5.19 illustrates the compressive stress-strain behavior of the 28-day old conventional Portland cement based concrete. From Figure 5.18, it can be also observed that before the peak stress, i.e. in the ascending branch, an increase in tensile/compressive stress leads to the increase of PWC deformation (strain). The strain at the peak stress is not constant, but it is a function of the plastic content. For example, the value of the strain at the peak compressive stress is 2.8% for the PWC60, while it is equal to 3.6% for the PWC50. The PWC samples show failures at lower compressive stresses, but at much higher strain (2.8%-3.8%; Figure 5.18) than conventional concretes (~0.1-0.2%). In the descending branch of the stress-strain curves of the PWC, i.e. after the peak stress level is reached, the stress level decreases slowly causing an increase in strain (Figure 5.18). In other words, the slope of the descending part of the stress-strain curve is low. In contrast, after the compressive failure of the conventional concrete, the stress decreases rapidly (Figure 5.19), which results from the well-known quasi-brittle behavior of conventional concrete materials. The slope of the descending part of the stress-strain curve of the conventional concrete is steep (Figure 5.19). The failure of the conventional concrete sample occurred with brittle/sudden deformation. Figure 5.20 shows images of typical deformations observed after failure for conventional concrete. This much slower decrease of the stress-strain curve of a PWC can be attributed to the fact that, due to its lower strength, the PWC specimen accumulates only a low amount of energy up to the peak stress. This results in a slow propagation of cracks in the failure zone and, accordingly, the stress decreases slowly (Fall et al. 2007). In other words, after the failure, PWC samples can resist to the stress for some period of time. Consequently, before full disintegration, the failed PWC can support loads and the deformation is more ductile than that of conventional concretes. Longitudinal splitting and diagonal shear failures were randomly observed on PWC samples after failure (Figure 5.21), which seems to be relatively similar to the findings from the work done by other studies on concrete containing fibers or plastic (Hannawi et al. 2010; Jiang et al. 2017).



a) Compressive stress-strain deformation curves of PWCs for various contents of plastic wastes (28 days and HDPE/LDPE = 50/50)



b) Splitting tensile stress-strain deformation curves of PWCs for various contents of plastic wastes (28 days and HDPE/LDPE = 50/50)

Figure 5-18: Stress strain behaviour of various PWC samples under the effect of the constraints or loads.

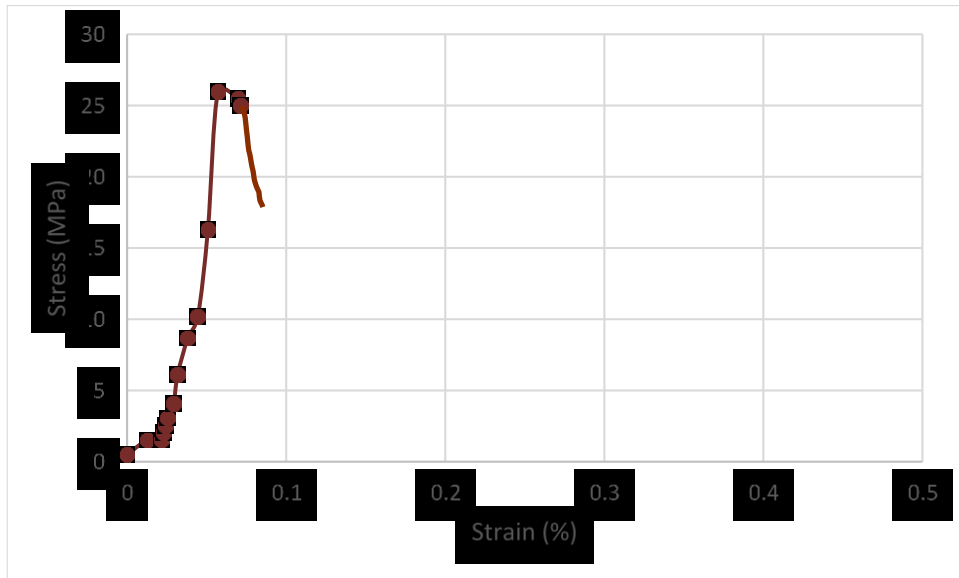
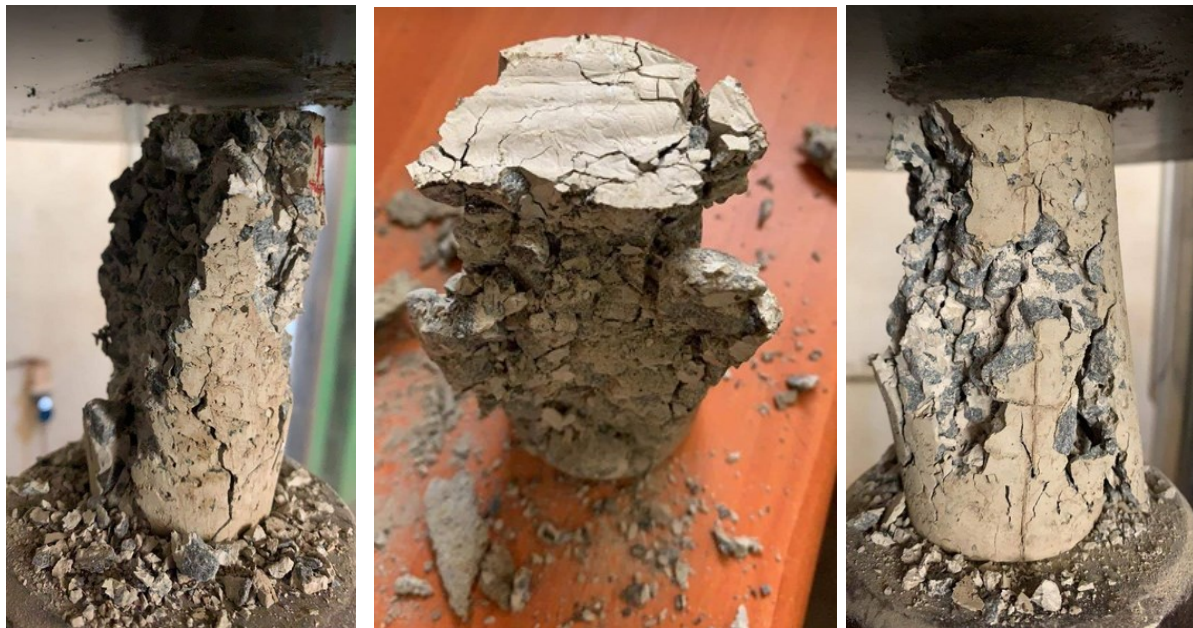


Figure 5-19: Compressive stress-strain deformation curves of 28 days old conventional concrete.



a) Longitudinal failure b) Failure with cone formation c) side fracture

Figure 5-20: Images of typical deformations observed after failure for conventional concrete.



a) Longitudinal failure b) Failure with cone formation c) side fracture

Figure 5-21: Images of typical deformations observed after failure for various PWC formulations samples under the effect of the constraints or loads.

5.2.3.6 *Density of the PWC*

Figure 5.22 presents the evolution of the PWC density vs time for different plastic contents and Figure 5.23 shows the variation of PWC density as function of plastic content for different curing ages. In general, the density of PWC was found to decrease with the increase in plastic content as observed for other construction materials containing plastic waste aggregates (Marzouk et al 2007; Bărbuță and Toma 2015; Alqahtani et al. 2017; Belmokaddem et al. 2020). The average densities between 1 and 28 days were 2.26 g/cm^3 for PWC50 with less than 1.34% variation and 2.14 g/cm^3 for PWC60 with less than 3.35 % variation. The density reduction is related to the lower density of plastic materials ($0.915\text{-}0.940 \text{ g cm}^{-3}$ for LDPE and $0.940\text{-}0.965 \text{ g cm}^{-3}$ for HDPE; Hannawi et al. 2010; HDPE 2018; LDPE 2018) by comparison to natural aggregates ($\sim 2.7 \text{ g cm}^{-3}$).

Nevertheless, the average density at different ages of the PWC was found to be between 2.09 g/cm^3 and 2.27 g/cm^3 , which is acceptable by Rilem classification as lightweight concrete (RILEM 1978; Saikia et De Brito 2012). These values were higher than the values obtained for concrete containing conventional lightweight aggregate ($1.79 - 2.03 \text{ g/cm}^3$) (Alqahtani et al. 2017) and less than the density of conventional cement (2.8 g/cm^3) used to prepare the paste for conventional concrete. This lightening property of PWC can be of great relevance in saving energy in the field of construction and reduce the size of various elements in the building. It can also contribute to reduce transport cost and minimize the risk related to excessive weight when failure occurs.

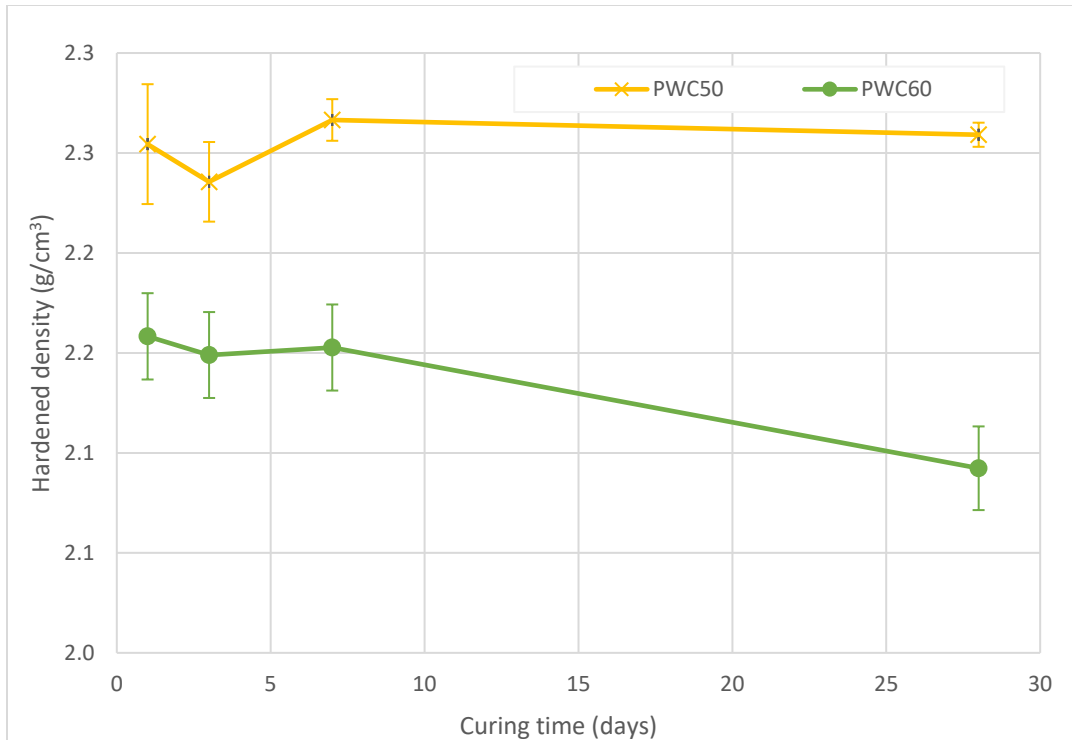


Figure 5-22: Hardened density of PWC for various plastic content values

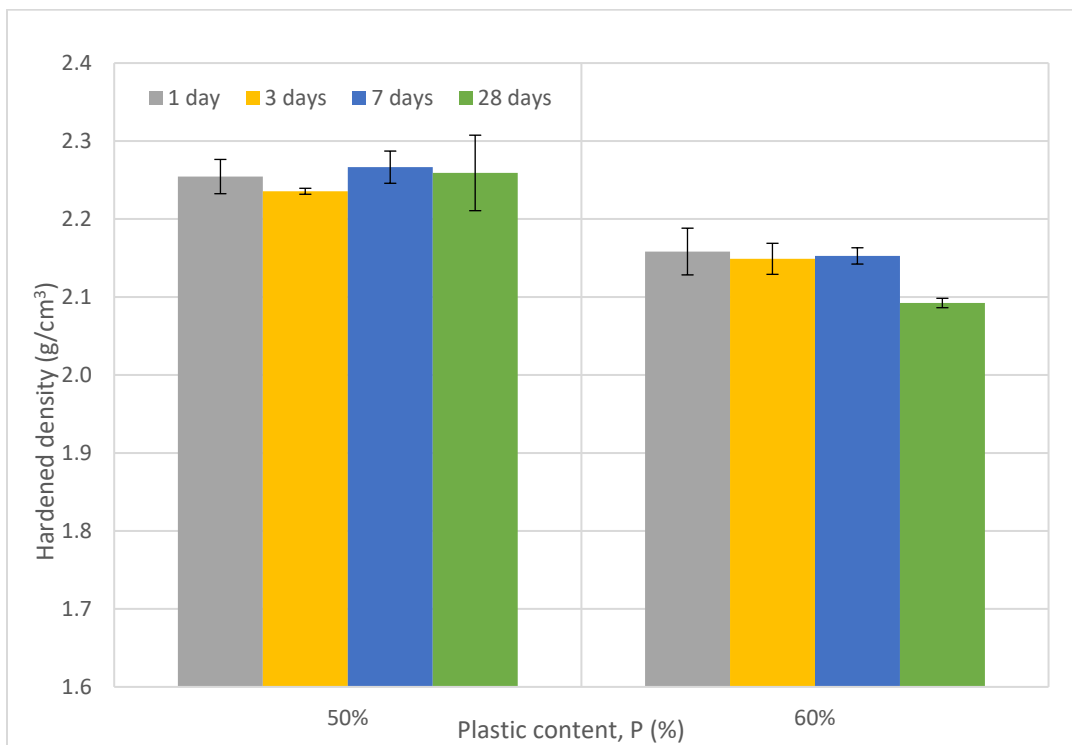


Figure 5-23: Density of PWC vs percentage of plastic content with the ratio HDPE / LDPE of 50% -50% for different curing times.

5.2.3.7 Absorption properties of the PWC

Figure 5.24 presents the immersion absorption of the PWC and conventional concrete. The 48-hour immersion absorption values are 0.37% and 0.35% for PWC50 and PWC60, respectively, which are very small compared to the obtained value of conventional cement-based concrete (4.52%). To enhance the understanding of the absorption properties of these materials, experiment was conducted up to seven days (Figure 5.25). Again, the absorption of conventional concrete is higher than that of the PWC. This fact can be related to the hydrophobic behavior of plastic used as binder for PWC. Moreover, the initial water content of the Portland cement based-concrete has contributed to create a larger amount of voids or higher percentage of pores areas in the conventional concrete than in the PWC, thus leading to higher absorption of water, as evidenced by the results of analysis with Imagej discussed previously. Moreover, the immersion absorption of PWC50 was found to be higher than that of the PWC60, confirming that the pores are more interconnected in PWC50 than PWC60 (Alderete et al. 2017).

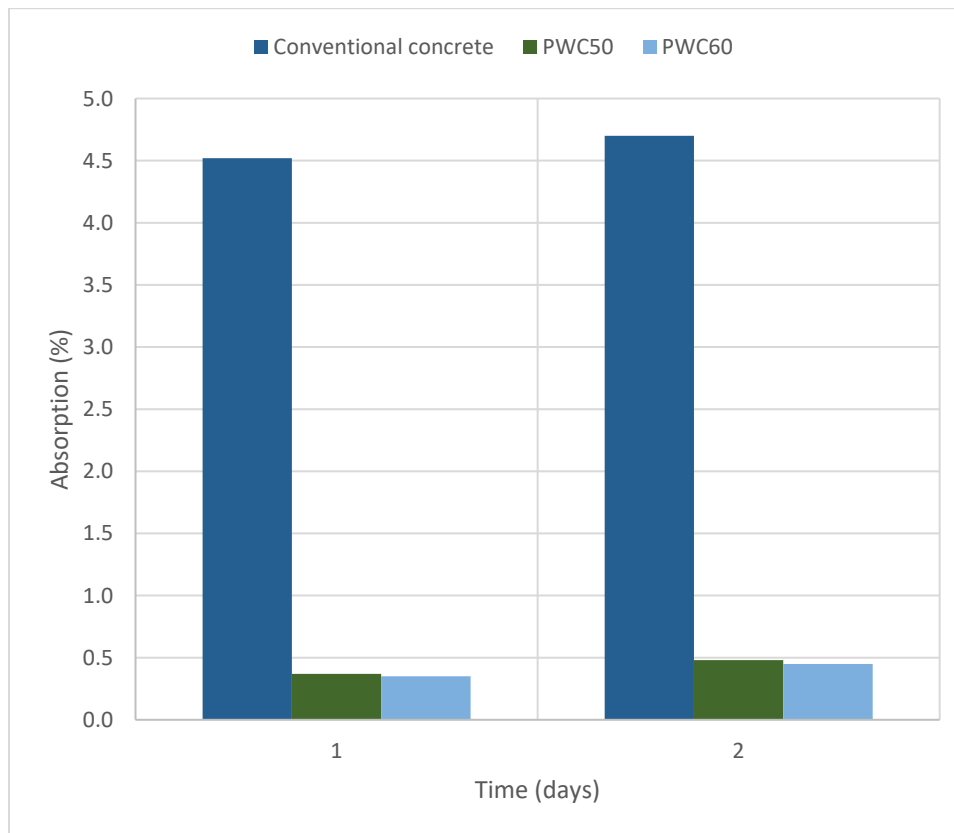
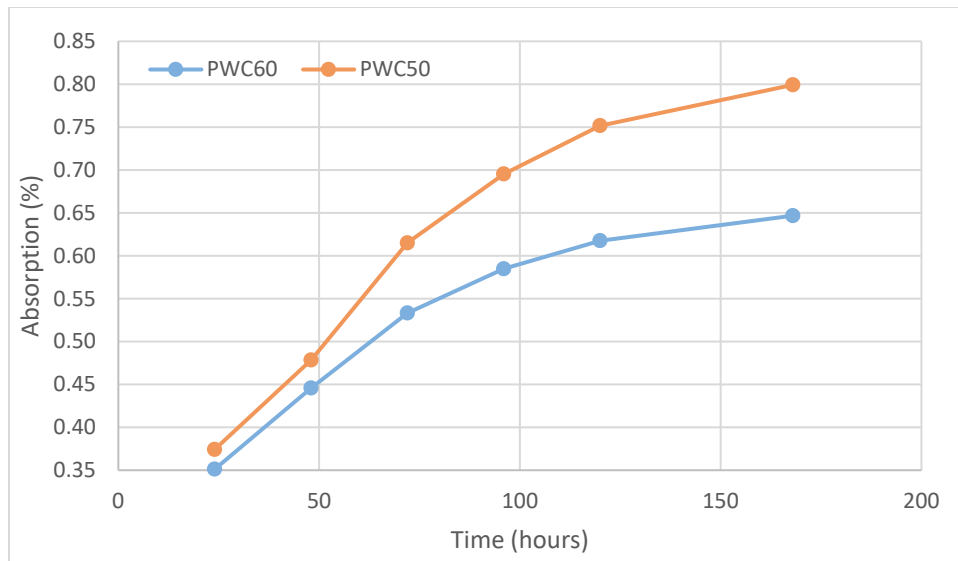
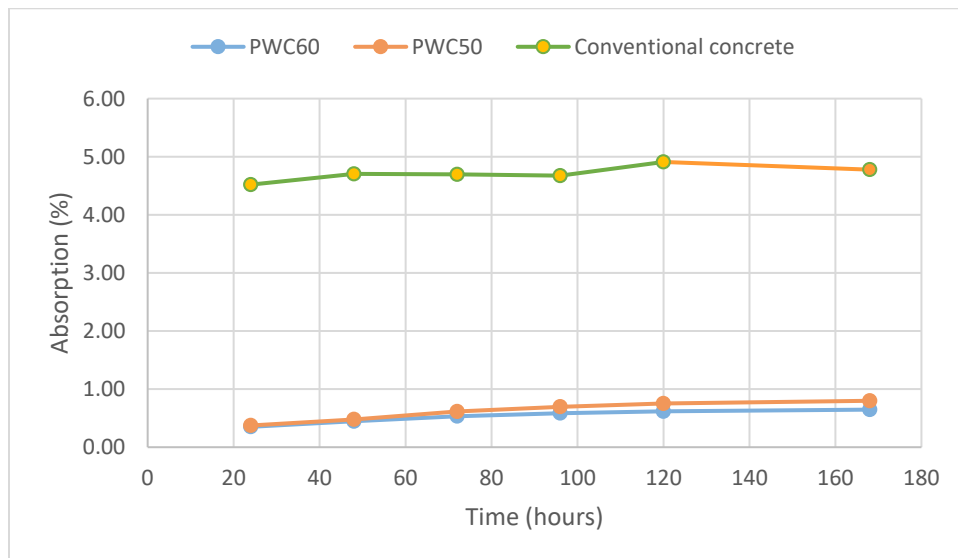


Figure 5-24: Water absorption by immersion vs time for PWC and conventional cemented concrete



a) Water absorption by immersion vs time for various formulations of PWC



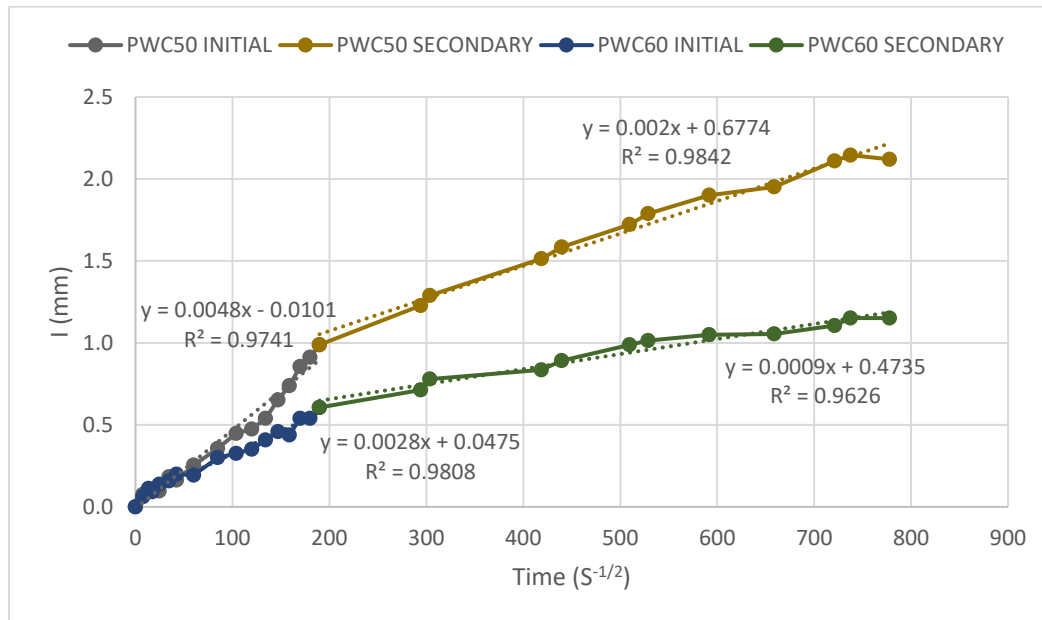
b) Water absorption by immersion vs time for PWC and conventional concrete

Figure 5-25: comparative figures showing water absorption by immersion vs time for PWC and conventional concrete

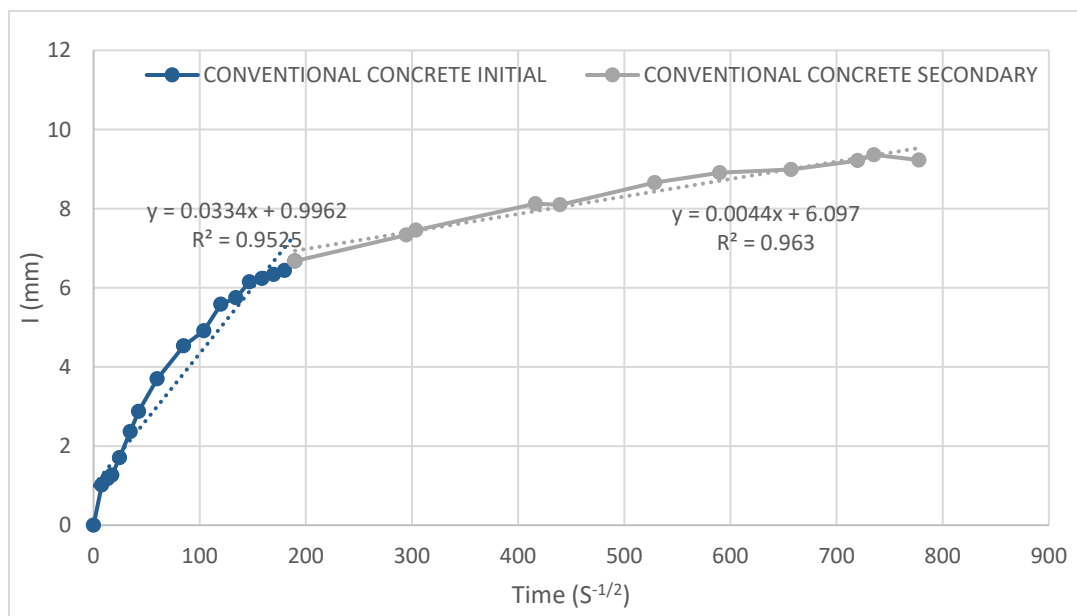
Figures 5.26 a and b present the obtained results of capillary absorption vs. the square root of time for PWC and conventional concrete. The graphs have two parts with different slope called sorptivity, a parameter that expresses the ease/facility of water penetration into given construction material (Marzouk et al. 2007). The results of initial and secondary sorptivity for PWC and conventional concrete are summarized in the Table 5.4. The sorptivity of PWC was found to vary between $0.0009 \text{ cm}^3/\text{cm}^2 \text{ S}^{1/2}$ and $0.0048 \text{ cm}^3/\text{cm}^2 \text{ S}^{1/2}$, which are smaller than the values obtained for conventional concrete ($0.0044 \text{ cm}^3/\text{cm}^2 \text{ S}^{1/2}$ to $0.0334 \text{ cm}^3/\text{cm}^2 \text{ S}^{1/2}$). In addition, PWC sorptivities were smaller than the ones obtained for similar composite material containing plastic

as aggregates replacement by volume of 50% ($0.00136 \text{ cm}^3/\text{cm}^2 \text{ S}^{1/2}$ to $0.0014 \text{ cm}^3/\text{cm}^2 \text{ S}^{1/2}$) (Marzouk et al. 2005; Marzouk et al. 2007).

Up to 3 days, PWC50 and PWC60 seem to have similar capillary absorption values. Beyond 3 days, there is apparition of net difference with high value for PWC50 than PWC60. All the values for PWC were lower than that of the conventional concrete. The reasons of the differential capillary absorption behaviour for PWC50, PWC60 and conventional concrete are the same as cited for immersion absorption.



a) Initial and secondary rate of absorption determination for the PWCs, PWC50 and PWC60



b) Initial and secondary rate of absorption determination for conventional concrete using cement as binder

Figure 5-26: Capillary absorption vs square root of time for PWC and conventional concrete.

Table 5-4: results of initial and secondary sorptivity for PWC and conventional concrete from capillary absorption analysis

Specimen	Initial sorptivity ($\text{cm}^3/\text{cm}^2 \text{ S}^{1/2}$)	Secondary sorptivity ($\text{cm}^3/\text{cm}^2 \text{ S}^{1/2}$)
PWC50	0.0048	0.002
PWC60	0.0028	0.0009
Conventional concrete	0.0334	0.0044

An attempt was made to predict the variation of capillary absorption as function of immersion absorption at specific time for given PWC. Both PWC50 and PWC60 show great linear relations with high determination factors as observed on Figure 5.27. Thus, for the two optimal plastic contents used, the below general linear equations with a determination factor of 0.98 has been deducted for future practical uses.

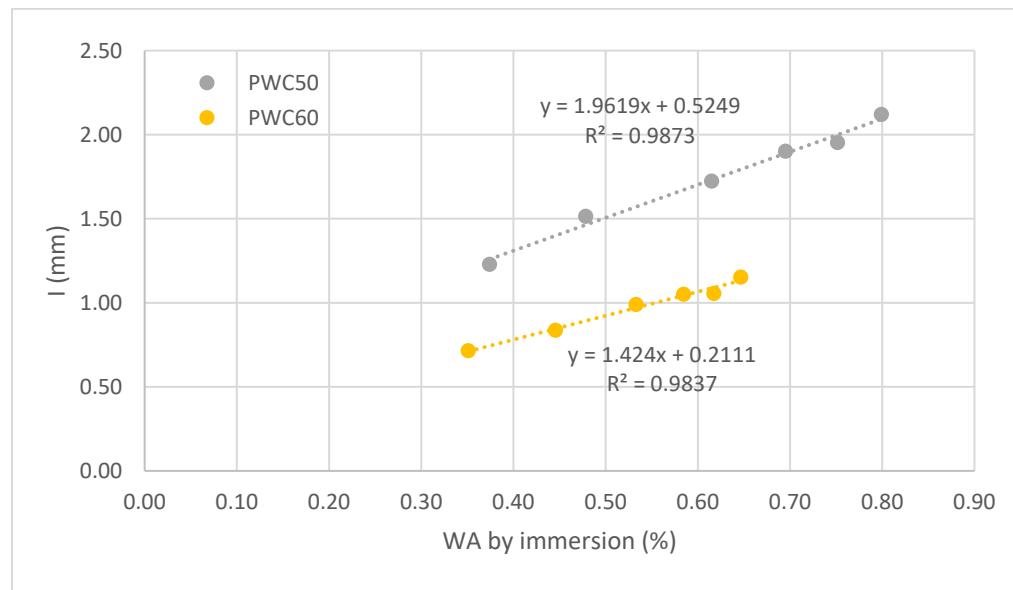


Figure 5-27: Water absorption by capillarity vs water absorption by immersion for various formulations of the PWC.

5.2.4 Summary and conclusions

This present study aims to identify alternative ways of recycling plastic wastes and reduce the pressure on the environment by exploring the use of molten HDPE and LDPE as the only binder in developing new types of cemented construction material (PlasticWasteCrete). Two plastic contents (50% and 60% with equal ratio of HDPE and LDPE) were used as binder and the microstructural, mechanical and physical properties of the proposed construction material were investigated. Based on the obtained results, the following conclusions are drawn from the experimental work:

- The TGA/DTG results show that there is a delay in the thermal degradation of the PWC in comparison to the pure plastic wastes, which indicates that the thermal degradation or behaviour of PWC is not cumulative of the individual polymer degradation. The PWC mixing, the inorganic materials (sand, gravel) and heat transfer during the melting phase of the plastic wastes influence the thermal behaviour of the PWC. To achieve 80% of mass loss, the PWC needs more heat than the pure plastic wastes (HDPE and LDPE), indicating that the sand and gravel as well as the melting process contribute to the reinforcement of the thermal stability of the PWC.
- The MIP results indicate that the PWC with 60% plastic waste content (PWC60) has finer pore structure and smaller porosity than that with 50% plastic content (PWC50). This difference in pore structure and porosity between the PWC50 and PWC60 is due to the difference in plastic content. The total volume of pores (small and medium capillary) increases with the plastic content of PWC, thus PWC50 has higher number of larger capillary pores than PWC60. It is also found that the conventional concrete has finer pore structure, but a higher percentage of pores areas than the PWC.
- The SEM analyses indicate that the melted plastic paste binds granular materials (sand, gravel) with the presence of voids/pores, especially at the interfacial transition zone between melted plastic waste and the granular materials. These voids/pores, which are weak points, are more present in the PWC50 than the PWC60. From the results of the image analyses, it is observed that the amount of pores for conventional concrete was higher than the ones for PWC, which can be associated to the effect of water in Portland cement based concrete.
- The compressive strength of the proposed new material is found to be between 10 and 15 MPa, regardless of age and plastic content, while its splitting tensile strength varies between 2 and 4 MPa. The tensile strength of PWC is approximately 20% to 25% of the compressive strength. The strengths depend on the plastic waste content and curing time. The strength of the young PWC increases with time due the solidification of plastic paste when exposed to ambient temperature. The PWC60 has higher compressive and splitting tensile strengths than that the PWC50. This is because the PWC60 has finer pore structure and better bonding properties at its interfacial transition zone. An empirical relationship has been proposed to provide a simple means to estimate the splitting tensile strength of

the PWC from its uniaxial compressive strength. This relationship may allow a simple, but consistent use in practical applications.

- The stress-strain behavior of the PWC is characterized by an ascending and a descending branch, as in conventional concrete. However, the strain corresponding to the peak compressive stress is much higher in the PWC (2.8%-3.6%) than in the conventional concrete (0.1-0.2%). The PWC shows interesting post peak strength capable of supporting loads and the deformation is more ductile than that of conventional concretes. Longitudinal splitting and diagonal shear failures were randomly identified on PWC samples after failure. This ductile behavior can be very advantageous for the PWC when subjected to deformation and could minimize cracks formation during its lifespan.
- In general, the density of PWC was found to decrease with the increase in plastic waste. The average density at different ages of the PWC was found to be between 2.09 g/cm^3 and 2.27 g/cm^3 , which is acceptable by Rilem classification as lightweight concrete. These values are smaller than the density of conventional cement (2.8 g/cm^3) used to prepare the paste for conventional concretes.
- The sorptivity of PWC was found to vary between $0.0009 \text{ cm}^3/\text{cm}^2 \text{ S}^{1/2}$ and $0.0048 \text{ cm}^3/\text{cm}^2 \text{ S}^{1/2}$, which are smaller than the values obtained for conventional concrete ($0.0044 \text{ cm}^3/\text{cm}^2 \text{ S}^{1/2}$ to $0.0334 \text{ cm}^3/\text{cm}^2 \text{ S}^{1/2}$). The 48-hour immersion absorptions were 0.37% and 0.35% for PWC50 and PWC60, which were very small compared to the obtained value of conventional cement-based concrete (4.52%). A prediction equation has been proposed to predict the variation of capillary absorption as function of immersion absorption at specific time for given PWC.

The results obtained show the potential of using molten HDPE and LDPE plastic wastes as the only binder without any use of water to develop a new cemented material for construction. From the promising results obtained, it can be concluded that the findings of this study would be of great benefit in the field of recycling plastic wastes, by setting some basis for future explorations of the development of construction material with appropriate reinforced engineering proprieties for various applications in civil engineering.

5.2.5 References

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- ASTM C138/C138M - 17a Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete
- ASTM C496/C496M - 17 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens
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5.3 Technical paper 4: Properties of a building material with melted plastic waste as the only binder: Impact of granular material size and curing conditions

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Abstract

In recent years, environmental protection has drawn considerable attention across the world and new initiatives are being adopted to develop eco-friendly or cementless concrete or building material as an alternative to Portland cement based concrete or construction materials. Among these works, there are the use of plastic wastes as a binder or substitute/replacement for granular materials in the concrete. This paper aims to investigate the effect of curing conditions and granular material size on the physical and mechanical properties of a cemented construction material, PlasticWasteCrete (PWC), using melted plastic wastes (HDPE and LDPE) as the only binder. Two curing conditions, namely, air dry at ambient temperature and thermal shock in water were used for this research. Moreover, the size of the granular materials (sand and gravel) was varied in order to test its impact on the physical and mechanical properties of the corresponding PWC sample formulations with given plastic content and HDPE/LDPE (H/L) ratio. Independent of the plastic content and H/L ratio, the reinforcement of granular material skeleton by adding coarser grains was found to increase both uniaxial compressive strength and splitting tensile strengths of the corresponding PWC samples. However, subjecting the hot PWC to thermal shock in water shortly after casting was found to decrease its strengths (compressive strength and tensile) in comparison to the PWC samples cured at ambient temperature. These changes in the material strength, which are linked to the porosity and pores interconnectivity of the tested samples, are in good correlation with the permeability/absorption results. The samples with lower strength were observed to have higher rate of absorption. Linear relationship with high correlation coefficient was established between the COMPRESSIVE STRENGTH and splitting tensile strength of the PWC subjected to thermal shock in water.

5.3.1 Introduction

Concrete with its durability and ability to take different forms is one of the most widely used materials in the modern societies (Shi et al. 2012). From its invention to date, several improvements have been made to enhance the properties of this ubiquitous product used in various sectors of the construction industry. The conventional concrete comprises of water, sand, gravel, cement and additives depending on the final use of the product. The cement paste is an essential component in the concrete, which binds other constituent elements together in order to meet the final requirements for which the concrete is designed.

The concrete industry is known to have an enormous environmental footprint because of sheer volume of raw materials needed in its production process. The production of cement alone is believed to be responsible for 7% of the global CO₂ emissions (Meyer, 2009). Also, the cost of cement in vis-a-vis other constituent elements of the concrete is considerable, and the cement production industry is one of the major contributors of greenhouse gases in the atmosphere with

impact on human and the environment (Meyer, 2009). Thus, with key attention being given to the protection of the environment, various initiatives have emerged towards developing environmentally friendly materials as an alternative to help reduce the rate of pollution and enhance diversification in the construction industry.

Several researchers have studied different parameters of concrete containing different materials as additives or binder, among which there is plastic, a product that can be found everywhere in today lifestyle from rural to urban areas around the world. With its long life and its very affordable cost, plastic is often discarded after a limited number of uses, ending up in rivers, oceans or at landfills with huge consequences (Zuberi and Ali, 2015; Boucher and Damien, 2017; Barboza et al. 2018; Schwarz et al. 2019). Numerous studies have been conducted on the engineering properties of conventional concretes, in which plastic waste was used as aggregates to partially replace natural aggregates or as additives in the concrete material (e.g., Vaverka, 1991; Reibeiz, 1996; Al-Manaseer and Dalaal 1997; Sam and Tam 2002; Kumar and Bhattacharjee, 2003; Choi et al. 2005; Ismail and Al-Hasmi 2008; Kou et al. 2009; Zhang and Li 2011; Zarnaghi et al. 2018). Tremendous progress has been made by these studies in understanding the impact of plastic waste aggregates or additives on the mechanical (e.g., strength, deformation behaviour), physical (density, sorptivity) of conventional concrete. However, none of the aforementioned studies assessed the engineering properties of concrete material made by using plastic wastes as the only binding material.

Thiam and Fall (2020) performed studies on the mechanical, physical and microscopic properties of PWC containing molten plastic wastes (HDPE and LDPE) as the only binder and cured at room temperature. They found that the compressive strength of the tested PWC material is higher than 10 MPa, regardless of age and plastic content. Furthermore, its splitting is approximately 20% to 25% of its compressive strength. They also observed that the PWC material exhibits interesting post peak strength capable of supporting loads and its deformation is more ductile than that of conventional concretes. They also concluded that the PlasticWasteCrete could meet certain construction requirements due to its lightweight and can eventually help reduce the unit weight of the structure when used in construction. However, despite the promising results obtained by Thiam and Fall (2020), the PWC samples considered in their study were only cured at ambient room temperature ($\sim 20^{\circ}\text{C}$). Moreover, the inorganic granular materials (sand, gravel) used to prepare the PWC had a fixed particle size distribution. In other words, the impact of various curing conditions and the variability of the grain size distribution of sand and gravel on key performance or engineering properties (strength, deformation behaviour, density, sorptivity) is not known. There is a need to address this knowledge gap. Indeed, curing conditions and grain size distribution of the granular materials could play an important role on strength development and durability of the proposed PWC material. Moreover, elucidating the behaviour of the PWC under different (practical) operating conditions (curing conditions, variability of the grain size of the granular materials available in a region or site) will contribute to its optimization as well as enhance its practical engineering application. The objective of the study is, therefore, to investigate the effect of curing conditions and granular material size on the physical and mechanical properties of the PWC using melted plastic wastes (HDPE and LDPE) as the only binder.

5.3.2 Experimental Program

5.3.2.1 *Materials and methods*

5.3.2.1.1 *Materials*

Plastic wastes (HDPE and LDPE) collected from Bamako's waste collection streams were washed and shredded to the corresponding sizes for the experiment purposes. Figure 5-28 shows samples of plastic used for the PWC preparation.

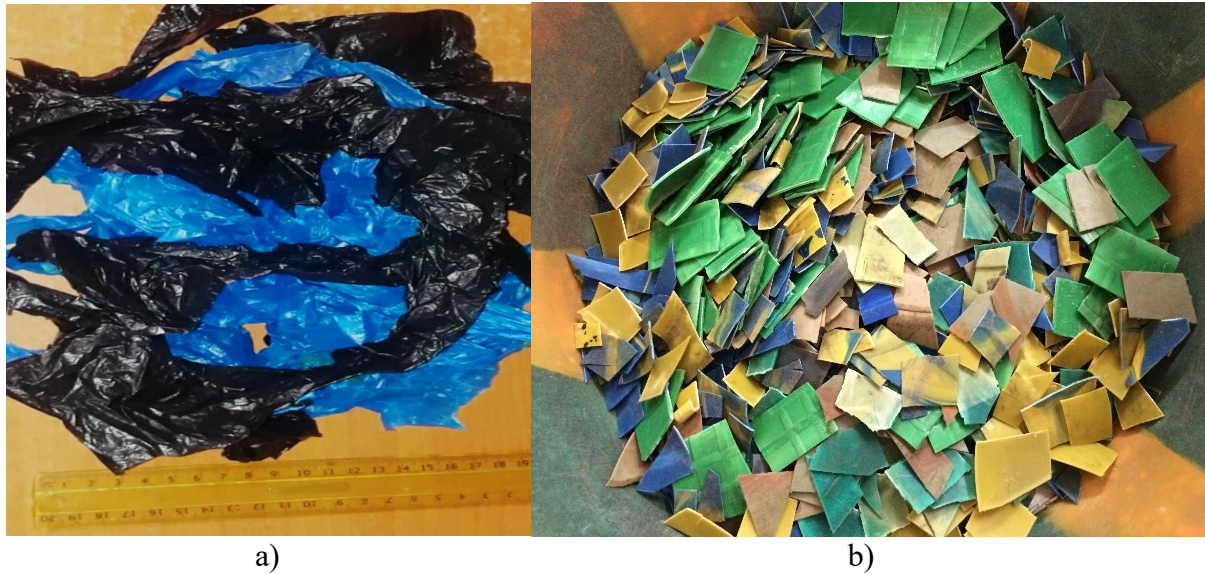


Figure 5-28: Samples of (a) LDPE and (b) HDPE plastic materials used in this study

Natural sand and gravel from Niger river in Bamako were used in this study to prepare the PWC and conventional concrete (Figure 5-29). Before their uses, sand and gravel were sampled and sieved to determine their grain size distributions according to ASTM C136 / C136M procedures. Figure 5-30 displays the obtained grain size distributions granular materials sampled and Figure 5-30 shows also the ones used for the preparation of various PWC samples.

Ordinary Portland cement type I and tap water were employed in the preparation of the conventional concrete used as a reference material in the study. It should be stressed that the purpose of preparing conventional concrete samples is not to compare the performance of the PWC and conventional concrete, but rather to acquire a better comprehension of the properties of the PWC, since conventional concrete is one of the most widely used construction material in the world.



Figure 5-29: (a) Natural gravel from Niger River in Bamako, Mali and (b) image of the sand sample used in the experiment

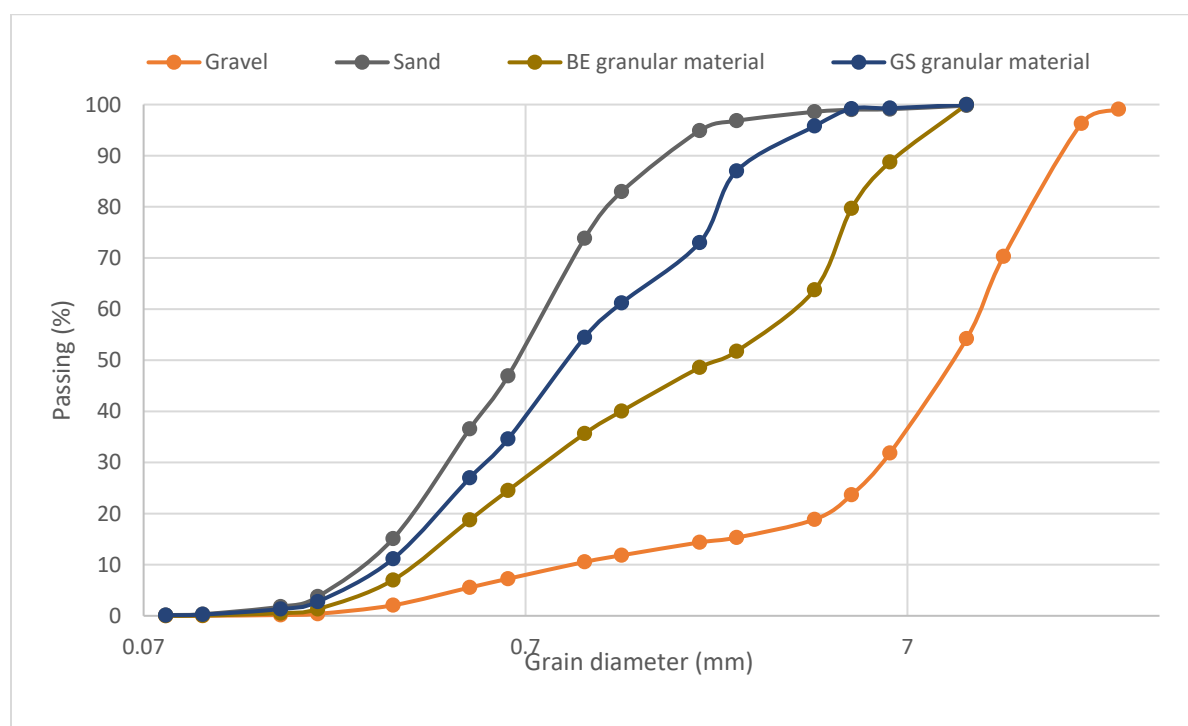


Figure 5-30: Particle size distribution of the sand and gravel materials sampled and used in this study.

5.3.2.1.2 Sample preparation and curing

Conventional concrete with water to cement ratio (W/C) of 0.5 and granular material (gravel + sand) to cement ratio, (G+S / C) of 3 were prepared and used as reference in this study. Portland

cement (type I) and tap water were used to prepare the samples. The ingredients were mixed in a concrete mixer for about 7 minutes, and then poured into metallic cylinders of 5 cm in diameter and 10 cm in height. The cylinders were then sealed (to avoid evaporation) and cured at room temperature for 1, 3, 7, and 28 days before being tested.

A preliminary explorative study was performed by Thiam and Fall (2020) to establish the optimum mix proportion conditions and melting temperature of the plastic waste for the preparation of PWC. Optimized parameters obtained from the aforementioned study were adopted for the preparation of PlasticWasteCrete samples in the present study. Accordingly, PWC samples with the composition described in Table 5-5 were prepared. The plastic contents of the PWC samples are 50% and 60% and the HDPE/LDPE (H/L) ratio is 50/50. Moreover, the melting and casting temperature of the plastic waste is about 250°C. To assess the effect of the grain size distribution or coarseness of the granular material (sand + gravel) on the properties of PWC, two mixes of granular materials (sand, gravel) were used to prepare the PWC samples. The coarser granular material, called BE, contains 50% of finer sand (< 2 mm), 30% of sand and gravel (2 mm < size < 4.75 mm) and 20% of gravel (4.75 mm < size < 10 mm), whereas the finer granular material (GS) consists of 70% of finer sand (< 2 mm) and 30% of sand and gravel (2 mm < size < 4.75 mm) (Table 5-5, Figure 5-30). Sampled gravel and sand were first oven dried at 105°C and passed through the corresponding sieves in order to achieve in the total mass of aggregates.

For each mixture, the required amount of granular materials was added to the melted plastic waste, and then well mixed at a temperature of about 100°C until obtaining a homogeneous mixture. Then, the fresh PWC was poured into the molds in a molten state and compacted using a manual hand press. After cooling down, the PWC specimens were then cured under different conditions for periods of 1, 3, 7 and 28 days before testing. Two curing conditions were applied on the PWC samples: (i) at ambient temperature with free air contact and (ii) others subjected to the thermal shock in water few times (5 min) after casting them in the molds. The samples introduced in water will have the letter (w) at the end of their names (Table 5-5).

Table 5-5: Mix proportion and curing time of the PWC containing melted HDPE and LDPE plastics as the only binder

PlasticWasteCrete sample	Plastic binder type	Plastic binder content (%)	HDPE / LDPE	Granular materials	Curing time (days)
BE50% P – H/L 50/50	HDPE - LDPE	50	50/50	Gravel-Sand	1, 3, 7, 28
BE60% P – H/L 50/50	HDPE - LDPE	60	50/50	Gravel-Sand	1, 3, 7, 28
GS60% P – H/L 50/50	HDPE - LDPE	60	50/50	Gravel-Sand	1, 3, 7, 28
GS50% P – H/L 50/50	HDPE - LDPE	50	50/50	Gravel-Sand	1, 3, 7, 28

P: plastic content in in (wt %) by reference to the dry mass of sand, H/L ratio of HDPE to LDPE.

5.3.2.2 Experimental tests

5.3.2.2.1 Uniaxial compression strength and splitting tensile strength tests

Compressive and splitting tensile strengths were determined for various PWC specimens following ASTM C39 / C39M – 18 and ASTM C496 / C496M – 17 specifications, respectively. The load was applied at slow rate (1 mm/min) using a computer-controlled press and the axial deformations were recorded using the data acquisition system. Each test was repeated at least 3 times to ensure the repeatability of the results.

5.3.2.2.2 Hardened density test

The density of various PWC samples was determined using ASTM C 138 / C138M - 17a procedures. Each density value for various formulations was determined as an average of at least three measurements from different samples to ensure the repeatability of the results.

5.3.2.2.3 Absorption test

The immersion absorption test was conducted in accordance with ASTM C97 / C97M – 18. After drying the cylindrical specimens (5 cm in diameter, 10 cm in height) in a ventilated oven at 60°C for 2 days, they were placed in a temperature-controlled room ($23 \pm 2^\circ\text{C}$) for about 30 min to cool down. Later the samples were weighted and placed in distilled water at $23 \pm 2^\circ\text{C}$ for 48 hours. The surface water on the samples was removed using dry cloth before taking their weights again. The immersion water absorption is then calculated as the difference in mass before and after immersion divided by the initial mass. The average value of at least two specimens with the same plastic content and H/L ratio was taken as the absorption of each sample. The main purpose of the absorption test was to gain a deeper insight into the porosity and pore structure of the tested PWC samples. Porosity, which is also an indicative to pore volume and structure, is reflected by the amount and speed of water suction by means of capillary action (Fall and Pokharel, 2011).

5.3.3 Results and discussions

5.3.3.1 Impact of granular material size and amount on the compressive strength of PWC

The amount and size of granular materials have previously been observed to influence the mechanical strength of cementitious materials by controlling the porosity and pore structure of the materials (Fall and Samb 2008, Azhdarpour et al. 2016, Kurad et al. 2017). Figure 5-31 presents the strength development of PWC samples made with BE or GS, and cured at room temperature. This figure shows that the grain size distribution of the granular material (sand, gravel) in the PWC materials has a significant influence on its strength gain regardless of the plastic content. The strength values of the BE samples are higher than the ones obtained for GS specimens. The main reason can be related to the difference in packing density between the PWC samples made with BE and those with GS, in other words, the difference in porosity or void ratio. Lower packing density means higher porosity and volume of void spaces between the granular particles that need to be cemented with the melted plastic. Larger porosity will result in a less dense and less resistant

material (Wu and al. 2001; Marzouk and al. 2007; Abukhettala and Fall 2020; Fang and Fall 2020; Li et al. 2020).

The BE contains only 50% of finer sand, whereas the GS consists of 70% finer sands. This high proportion of finer sand is detrimental to the packing density of the PWC, i.e. it increases the overall porosity. Consequently, for a given plastic waste content, the volume of void spaces between the granular particles to be filled by the melted plastic binder is smaller in the PWC specimens made with BE (lower porosity) than those made with GS. This is supported by the experimental results of absorption testes presented in Figure 5-32. From this figure, it can be noted that independent of the curing time, the water absorption was found to be generally higher for the GS samples than for the BE specimens. The immersion absorption reflects the ease of water penetration in a given composite material (Marzouk et al. 2007). In the BE samples, the 50% of finer sand particles fill the voids left by the larger particles, which leads to higher initial packing density, i.e. lower porosity. Moreover, the force applied during compaction brings the granular particles closer resulting in a denser configuration with less porosity thereby reducing the absorption (Uysal et al. 2012). In opposite, the high amount of finer grains (70%) in the GS samples means lower packing and not all the voids between the coarser granular materials will be occupied by the fine grains. Thus, the porosity and pores interconnectivity will be higher in the GS samples, leading to higher rate of absorption and thus lower strength than the BE samples (Uysal et al. 2012).

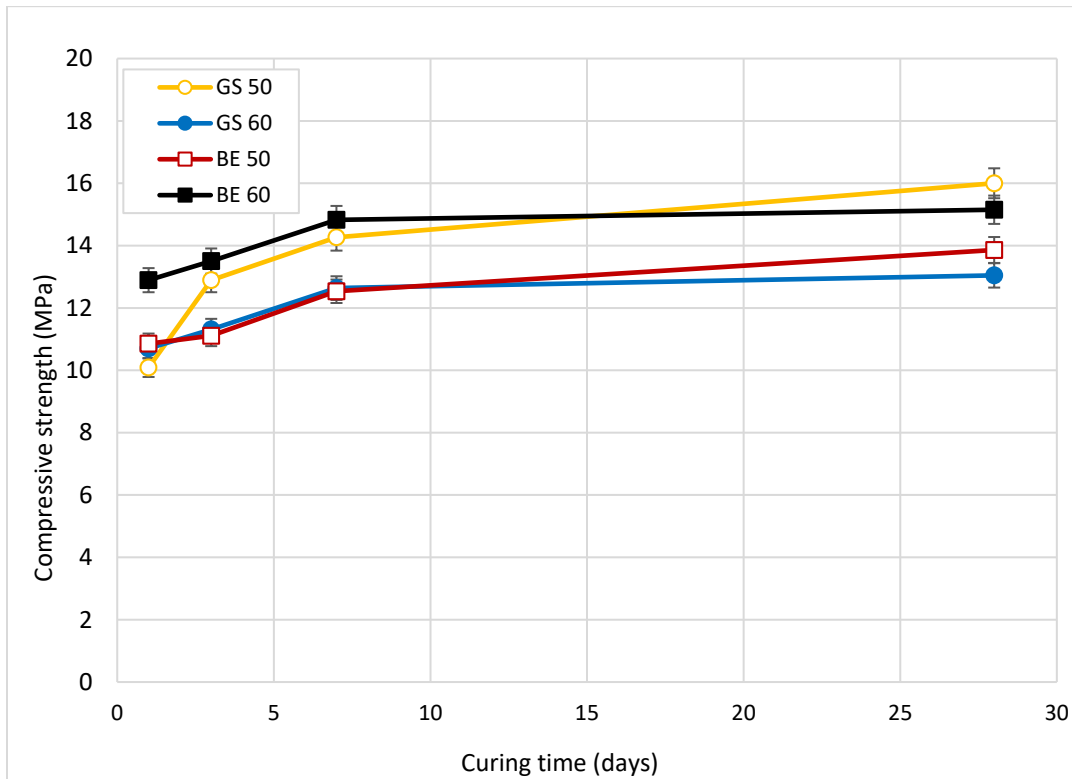


Figure 5-31: Effect of granular material size and amount on the compressive strength of PWCs for different plastic contents and constant H/L ratio of 50/50 (PWC samples cured at room temperature)

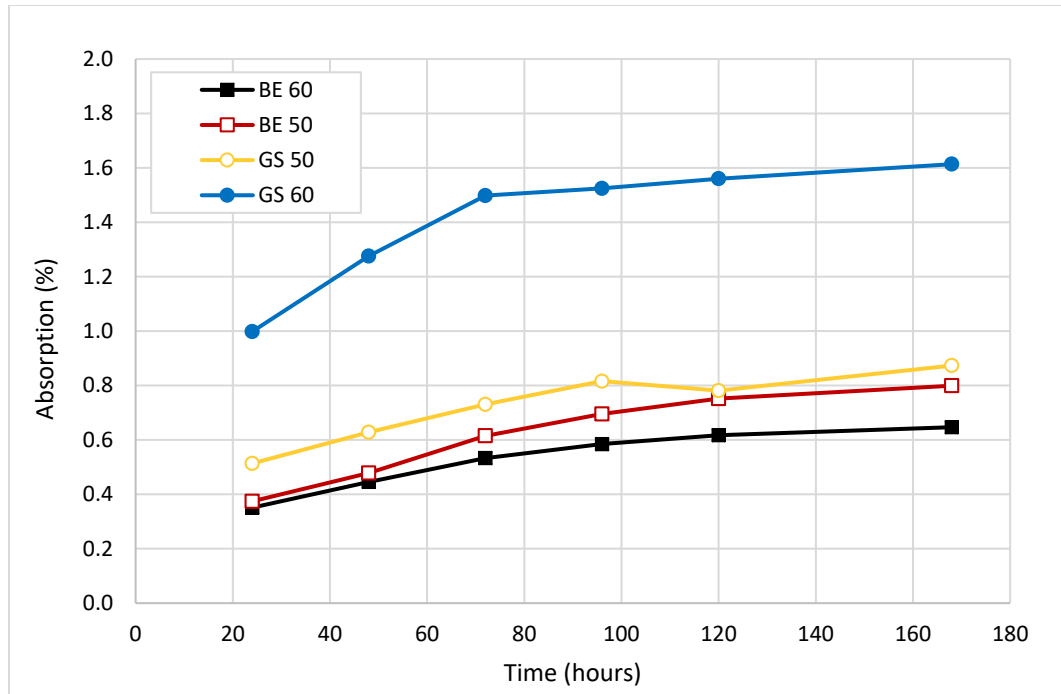


Figure 5-32: Effect of granular material size and amount on the immersion absorption of PWCs for different plastic contents and constant H/L ratio of 50/50 (PWC samples cured at room temperature for 28 days)

5.3.3.2 *Influence of curing conditions on the density and mechanical properties of ecological concrete*

Typical results of the effect the two adopted curing conditions on the density and mechanical properties of PWC are presented and discussed in this section. To recall, the applied curing conditions included: (i) curing at ambient temperature; (ii) thermal shock curing: PWC samples were submerged in water for about 5 min after being casted in the molds (samples with the letter W at the end of their name).

5.3.3.2.1 *Impact of curing regime on the density of PWC*

Figure 5-33 presents the obtained results of the density vs time for different BE samples under two different regimes. In general, no significant difference can be observed between the densities of the BE specimens cured at ambient temperature and those subjected to thermal shock in water. The average density under both curing conditions was found to be close to 2 g/cm^3 , considered by RILEM classification as lightweight construction material (RILEM, 1978). Since the density values are similar under the two curing regimes, it can be said that the sudden cooling has insignificant impact on the density of PWC containing melted HDPE and LDPE as the only binder.

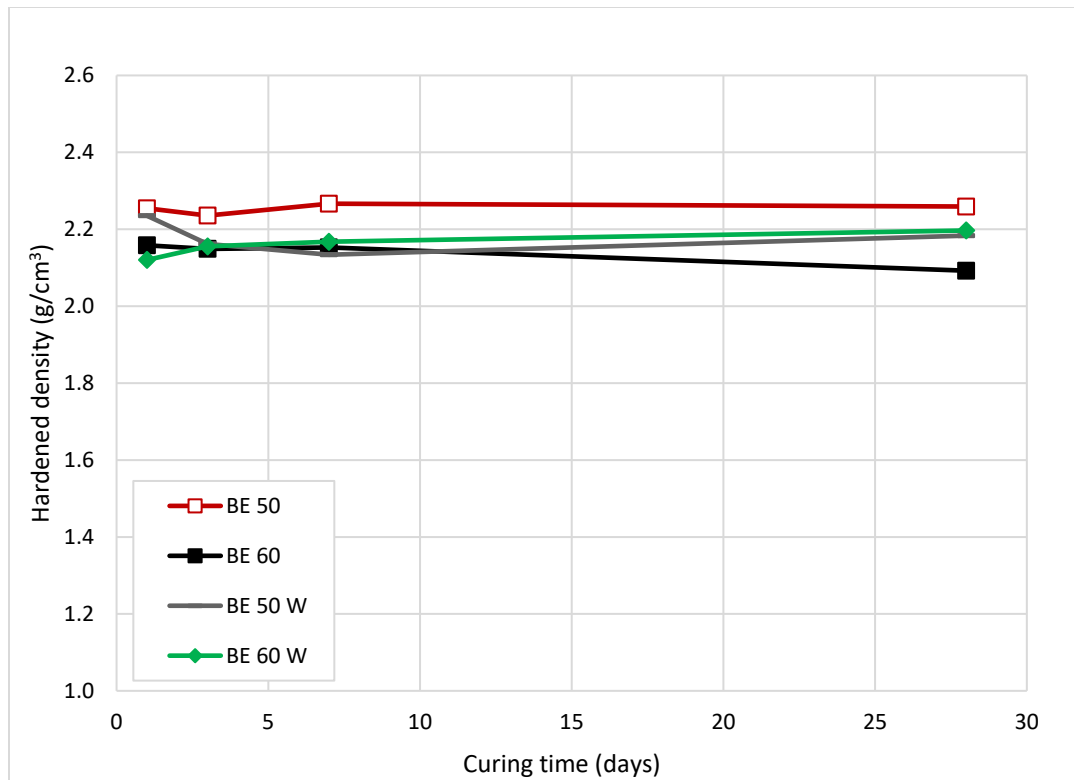


Figure 5-33: Density vs time for various BE 50 and BE 60 samples cured under two different regimes (ambient temperature and thermal shock in water (w))

5.3.3.2.2 Impact of curing conditions on the compressive strength and splitting tensile strength of the PWC

Figures 5-34 and 5-35 show the compressive and splitting tensile strengths vs time for different mixtures of PWC cured under two different regimes. A decrease of both splitting tensile and compressive strengths was observed in the BE samples subjected to the thermal shock in water. Over the whole curing period, the drop in compressive strength of BE samples subjected to thermal shock was found to be in the range of 0.46 to 3.82 MPa (corresponding to the relative values between 4.4 to 40.6%) in reference to the BE samples cured at ambient temperature. Several factors may be responsible for this drop in strengths. Since the BE is poured at hot temperature ($> 100^{\circ}\text{C}$), time is required for it to solidify and achieve strong interfacial transition zone (ITZ) between the plastic paste and the matrix, which is not observed for the case of thermal shock curing method. This could result in poor contact at the ITZ, which will affect the porosity of the corresponding samples, subsequently leading to the drop of both tensile and compressive strengths (Comby-Peyrot et al. 2006; Fall et al. 2010; Hannawi et al. 2010; Silva et al. 2013).

On the other hand, the BE sample does not take its final shape several hours after casting because the transition from liquid to solid state happens slowly. This has a strong impact on the physical and mechanical properties of the BE samples such as the strengths (Volk et al. 2015; Inai et al. 2018). Moreover, the thermal shock will also have some impacts on the physico-chemical

transmissions of the BE properties as a result of the aggressive reaction of water with the material at hot temperature. The shock will influence the solidification of the plastic paste binder with apparition of thermal induce stresses affecting the pores structures. Thus, contributing to the creation of weak points, and subsequently to the decrease of the strength. Moreover, the strength is polymer dependent, meaning that the accelerated solidification for the semi crystalline HDPE and LDPE melted paste in contact with water at lower temperature will affect the crystallization and other properties of the BE (Braun, 2002; Volk and Magniez, 2015; da Silva and Wiebeck, 2017; Ragaert and Van Geem, 2017). These thermally induced micro cracks and weak compaction points, contribute to the increase of the porosity of the materials, and cause the decrease in strength (Henkensiefken et al. 2009). Independent of the curing conditions, all the COMPRESSIVE STRENGTH values were higher than 9 MPa, which is an encouraging finding with respect to the practical application of this new construction material (Marzouk et al. 2007).

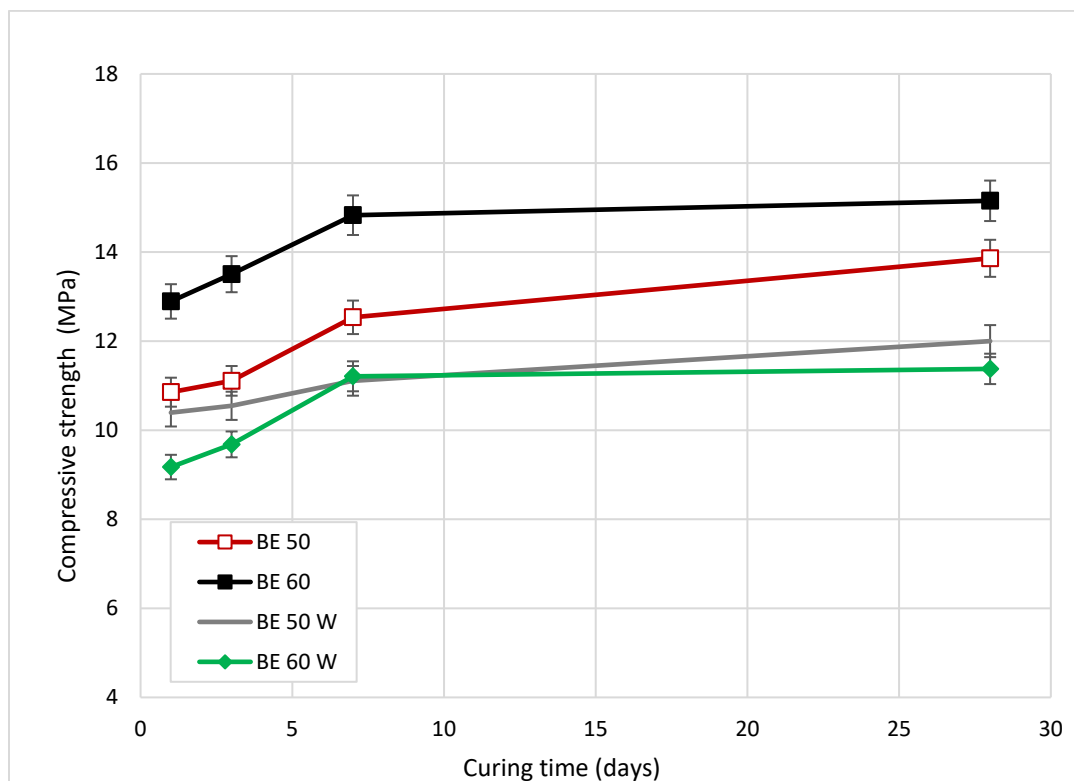


Figure 5-34: Compressive strength development vs time of the PWC with different percentages of plastic waste under two different regimes.

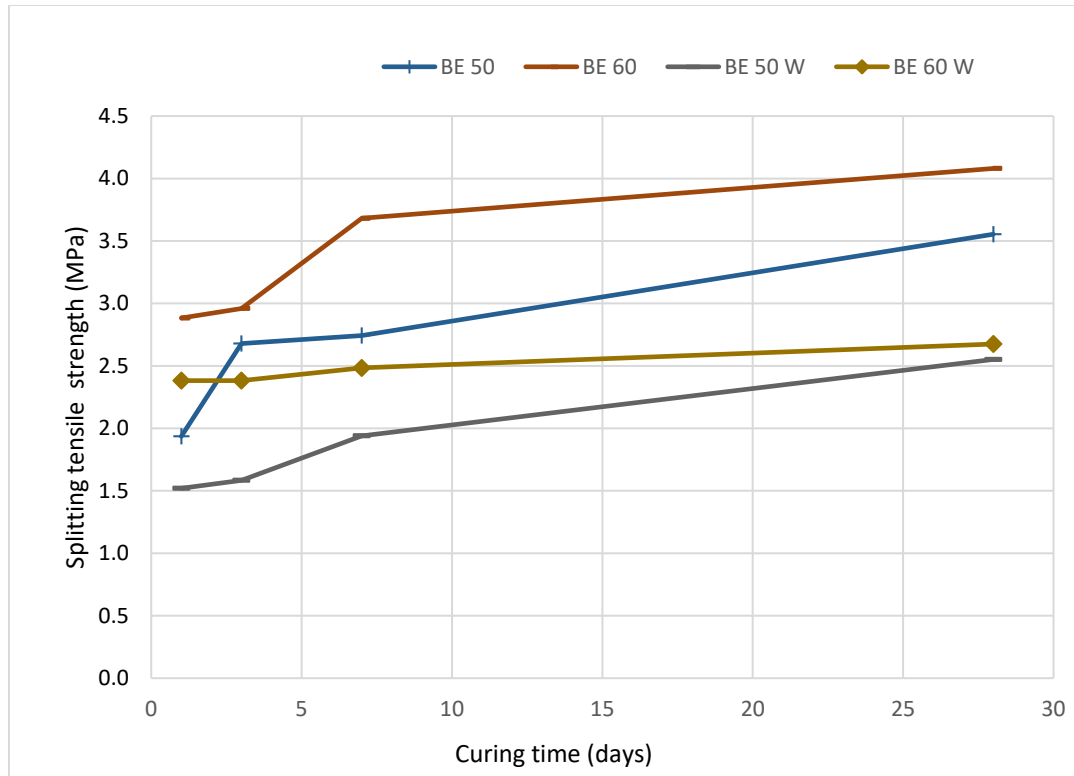


Figure 5-35: Splitting tensile strength development vs time of the PWC with different percentages of plastic waste under two different regimes.

Figure 5-36 presents the relationship between the splitting tensile strength and compressive strength for the hot BE placed in water and subjected to the thermal shock. Using the regression analysis, a linear relationship expressed below with higher determination factor was found between the splitting tensile strength (f_t) and the compressive strength (f_c). This correlation will facilitate a better understanding of the PWC behaviour under extreme external conditions in practice for regions where there is winter and summer, and strong raining seasons within the year, and also for the Sahel regions with extreme temperature difference from night to day.

$$f_t = 0.2697 * f_c + 1.3413 \quad (\text{in MPa}) \quad (\text{Equation 5-2})$$

(This equation 5.2 is only valid for compressive strength values between 5 MPa and 20 MPa)

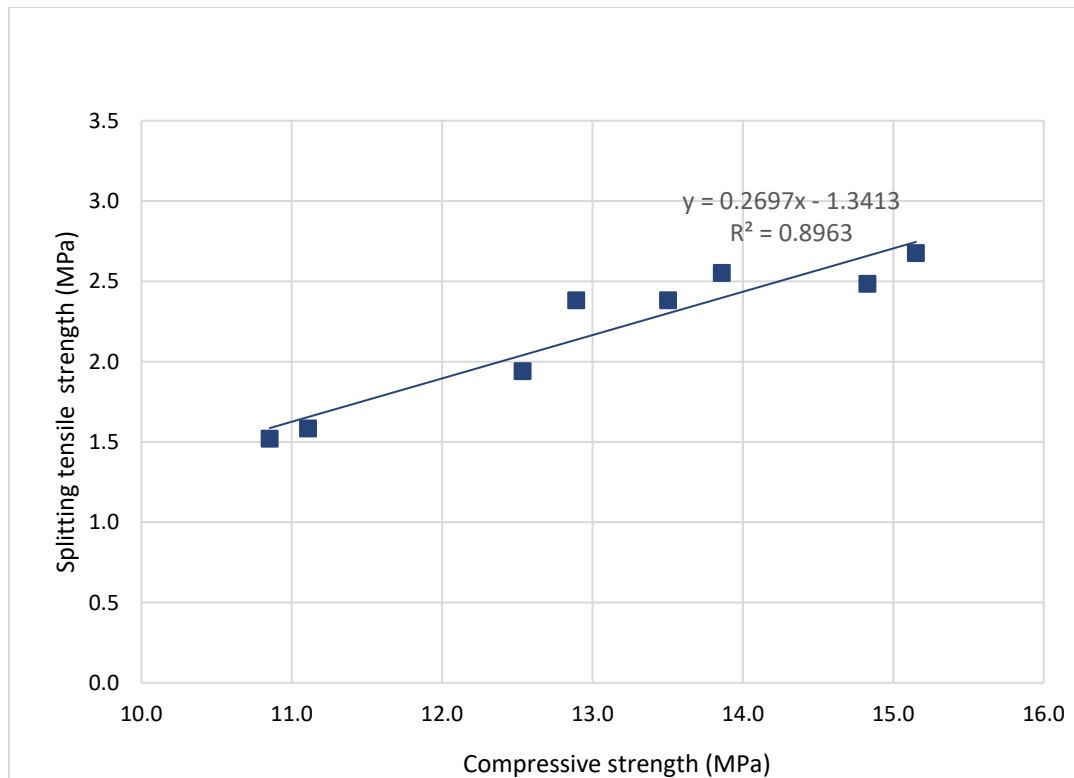
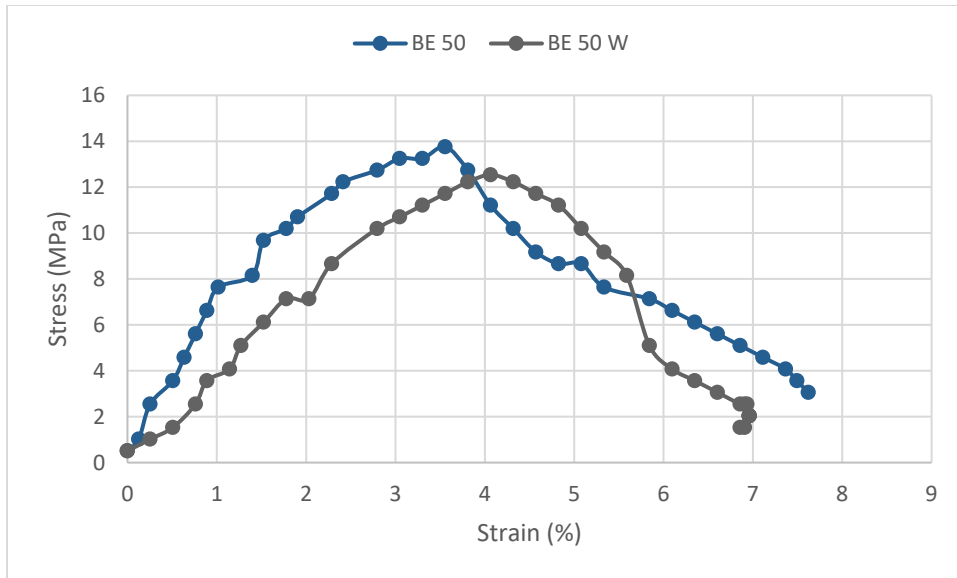


Figure 5-36: Splitting tensile strength vs COMPRESSIVE STRENGTH of the PWC with 50% and 60% of plastic content and H/L 50/50 subjected to the thermal shock in water.

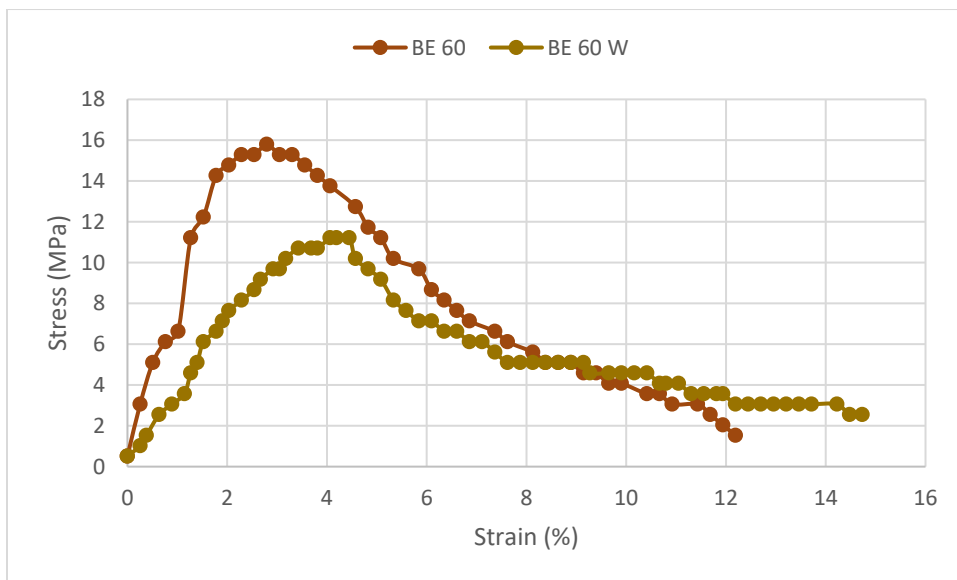
5.3.3.2.3 *Impact of curing conditions on the compressive and splitting tensile stress – strain behaviour of the PWC*

Figures 5-37 and 5-38 present the stress-strain behaviour of BE under compressive and splitting tensile forces. Independent of the curing regime, the BE samples showed relatively ductile or plastic behaviour that is similar to the concrete containing plastic wastes as aggregates or binder, due to the ability of plastic material to undergo a larger interval of cracks propagation before full disintegration (Wang and al. 2000, Song and Hwang 2004, Hannawi et al. 2010, Thiam and Fall 2020).

Similar to the samples cured at ambient temperature, after the peak stress, the PWC samples that were subjected to thermal shock undergo more plastic deformation, whereas the conventional concrete is more brittle with sudden failure (Hannawi et al. 2010; Thiam and Fall 2020). The ductile characteristic of the BE is very important for long-term fatigue behaviour of the structure using the PWC, especially when subjected to dynamic loadings.

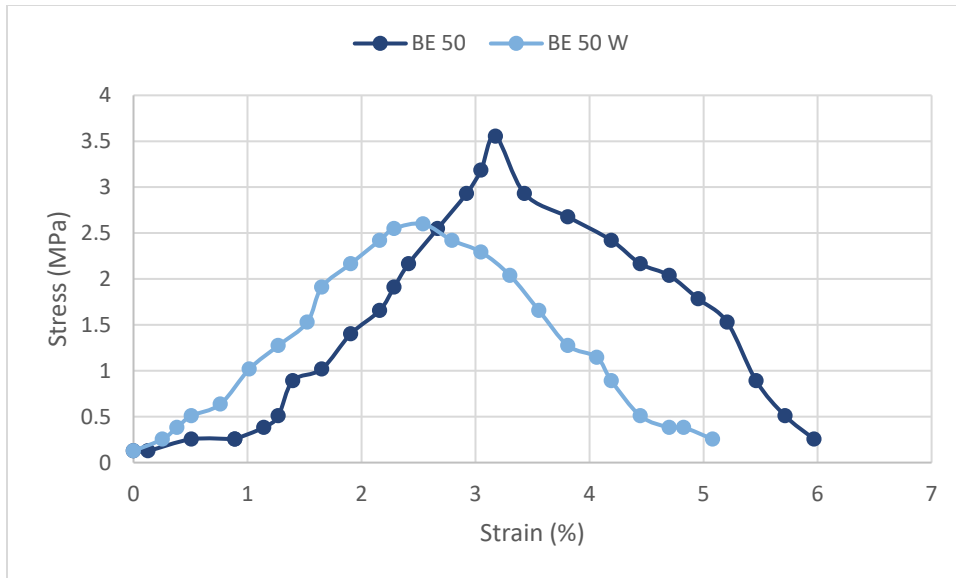


a) BE 50

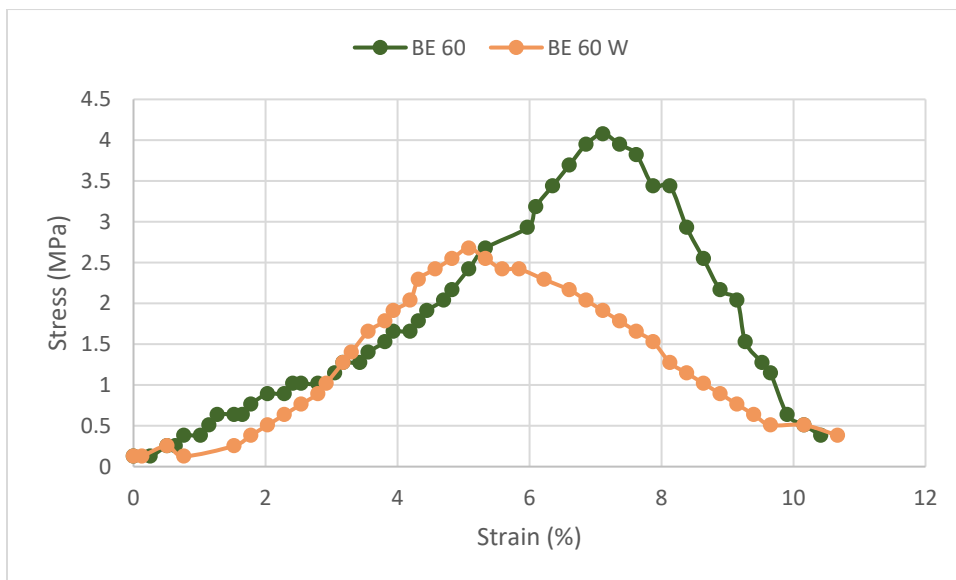


b) BE 60

Figure 5-37: Compressive stress-strain curve of the PWC under two different curing regimes after 28 days with 50% and 60% of plastic contents and H/L of 50/50



a) BE 50



b) BE 60

Figure 5-38: Splitting tensile stress-strain curve of the PWC under two different curing regimes after 28 days with 50% and 60% of plastic contents and H/L of 50/50.

5.3.4 Summary and conclusions

In this study, physical and mechanical properties of various cylindrical PWC samples were studied under two curing regimes and different sizes of granular materials (sand and gravel). The following conclusions are drawn:

- The density of the PWC is similar for both samples cured at ambient temperature and samples subjected to thermal shock. It can be said that the sudden cooling has little impact on the density of PWC made from plastic waste.
- Solidification, which allows soft materials to take shape and gain strength is accelerated when the hot PWC sample is introduced in water. However, the sudden solidification eliminates some crucial development phases, thereby impacting the strength development negatively. This is due to the development of weak points in the samples leading to an increase in the voids and weaker ITZ, which reduces the PWC ability to uniformly support load during strength test, and contribute to drop the corresponding strength values.
- When the percentage of fine sand was changed from 70% to 50%, the PWC strength under both compression and tensile forces was found to be improved.
- Independent of the curing ages, plastic content and H/L ratio, the thermal shock in water was found to decrease both compressive strength and splitting tensile strengths. However, no considerable change has been observed for density vs time graphs of the PWC between the curing regimes.
- Ductile deformations with great capacity of supporting loads after peak values was observed for PWC while brittle fractures with full disintegration was observed for commercial cement pavers from Malian Market
- Linear relation was deducted between compressive strength and splitting tensile strengths for PWC subjected to thermal shock. This allows the determination of one parameter if the other is known for future practical applications

5.3.5 References

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ASTM C97 / C97M - 18 Standard Test Methods for Absorption and Bulk Specific Gravity of Dimension Stone

ASTM C136/C136M Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates.

ASTM C138/C138M - 17a Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete

ASTM C496/C496M - 17 Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens

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5.4 Summary and conclusions

Based on the experiments conducted to study the MPB and the results obtained, changes were made in the granular materials (sand and gravel) to prepare various formulations PWC samples with the obtained optimal plastic contents of 50% and 60% with various ratios.

The samples of the PWC cured under two conditions (air dried and thermal shock in water) were subjected to various tests, such as compressive and splitting tensile strength, absorption (capillary and immersion) measurements, thermal analysis and microstructural tests (MIP, SEM, TG/DTG).

The results obtained from this study allowed to define the PWC formulation with the best strength as well as to understand the time-dependent change of the performance properties of the proposed material. The results of the microstructural and thermal analysis supported by ImageJ software analysis allowed to provide key information about the pore structure and the porosity of the PWC as well as gaining more insight on the matrix of PWC materials.

Thus, the obtained results from this chapter made it possible to better understand the performance properties of PWC and to make appropriate recommendations for future applications of this product. The following conclusions are drawn from the obtained results.

- After the melting of plastic wastes (HDPE and LDPE), there was delay in thermal degradation of PWC in comparison to the pure plastic wastes, which indicates that the

TG/DTG results for PWC is not cumulative of the individual polymer degradation. Thus, the mixing and heat transfer during the melting phase of plastic wastes influence in some ways the thermal behaviour of the new construction material, which is different from the constituents binding elements.

- To attain 80% of mass loss, the PWC need more heat (465°C) than the pure plastic wastes (HDPE and LDPE) which need between 360°C and 460°C, indicating that the inorganic material and melting process contribute to the reinforcement of its thermal stability.
- The temperature for peak decomposition of the conventional concrete (733°C) is higher than the ones obtained for PWC samples (432 °C and 482 °C). This is associated with the behaviour of the plastic component of the PWC when exposed to higher temperature.
- The total porosity is higher for PWC samples than the conventional concrete (0.2036 cc/g), and the total porosity of PWC50 (0.1025 cc/g) is higher than 0.0776 cc/g corresponding to the value obtained for PWC60. The total volume of pores (small and medium capillary) was found to increase with the plastic content of PWC, thus PWC50 has higher larger capillary pores than PWC60, impacting the permeability behaviour and other engineering properties of the PWC such as compressive strength and absorption.
- From the topography, more voids are observed in PWC50 than PWC60, and the size of voids/pores in PWC50 seems to be higher than the PWC60, confirming the obtained results from MIP analysis of the PWC.
- From Imagej analysis results of SEM images for various samples, the percentage (%) pores area of PWC60 was found to be lower than PWC50 and the amount of pores for conventional concrete was higher than the ones for PWC, which can be somehow related to the effect of water content in cement based concrete.
- The strength values of PWC60 were found to be higher than the ones of PWC50. This is because PWC60 has less pores than PWC50 and the configuration of the interfacial transition zone looks more compacted (stronger) with less voids for PWC60 than PWC50.
- The compressive strength for PWC regardless of age and plastic content is found to be higher than 9 MPa, which somehow exhibit interesting mechanical strength behaviour than the cementitious composite concrete when the sand volume is completely substituted by PET aggregates.
- The splitting tensile strength results show similar trend as the compressive strength. The higher splitting tensile strength for PWC60 than PWC50 can also be linked to the lower porosity and good bonding properties at ITZ for PWC60 in comparison to PWC50 as supported by MIP and SEM analyses.
- Right after reaching peak stress, the failure of conventional concrete occurs with a brittle/sudden deformation with clear view of incorporated aggregates. However, ductile deformations with great capacity of supporting loads after peak values was observed for PWC before full disintegration.
- Longitudinal, splitting and diagonal shear failures were randomly observed on PWC samples after failure, which is similar to the finding from previous studies.

- In general, the density of PWC was found to decrease with the increase in plastic. The density of the EC is similar for both samples cure at ambient temperature and samples subjected to thermal shock. It can be said that the sudden cooling has little impact on the density of PWC. The densities were found to be in the range accepted by Rilem classification as lightweight materials
- When the percentage of fine sand was changed from 70% to 50%, the PWC strength under both compression and tensile forces was found to be improved.
- Independent of the curing ages, plastic content and H/L ratio, the thermal shock in water was found to decrease both compressive strength and splitting tensile strengths of PWC. However, no considerable change has been observed for density vs time graphs of the PWC between the curing regimes.
- Linear relation was deducted between compressive strength and splitting tensile strengths for PWC subjected to thermal shock. This allows the determination of one parameter if the other is known for future practical applications

Chapter 6. Synthesis of the results, large-scale applications and summary

6.1 Introduction

Plastic products owing to their low cost and versatile functionalities are used in almost all sectors nowadays. However, the byproducts after the useful lifetime of plastic make-up a considerable amount of wastes with significant consequences on humans and the environment.

To contribute towards finding alternative solutions to solve plastic wastes problems, this research study explored the feasibility of using melted plastic wastes (HDPE and LDPE) as the only binder in the preparation of MPB and PWC materials.

Several parameters were studied carefully to assess the physical and mechanical properties of these new products or construction materials for future applications in the field of construction. The results obtained from this PhD research discussed in the chapters above are synthesized in this chapter.

The findings are promising and will pave the way for safe, durable, environmental friendly low-cost materials for future construction projects.

Further research will be needed to strengthen the achievements by improving the preparation conditions such as the introduction of automatic preparation system, which could improve the technical properties of these new construction materials (PWC and MPB).

6.2 Production system and formulation of MPB and PWC

A manual production system was used for the preparation of MPB and PWC. The parameters of the system under the field operating conditions in Mali were first determined before proceeding to in-depth studies of the engineering properties of the PWC and MPB . The parameters (average melting temperature of approximately 250°C, the melting time of 20 to 45 minutes depending on the type and percentage of plastics, compaction time with the press, etc.) found from the optimization of MPB formulations were kept constant throughout the experimental phase of this PhD research. Below is the image of the new product poured into a standardized mold, compacted with the manual press, and held for a certain period of time before demolding (Figure 6-1).



a) Before compaction



b) After compaction

Figure 6-1: Cementless construction materials in molds a) before and b) after compaction with the manual press.

Only sand and melted plastics waste were used in the preparation of the MPB, while gravel was added for the PWC. By changing the granular materials size and amount, certain properties of

MPB were found to be improved. The obtained parameters from the MPB preparation as well as the optimal plastic contents, which provided the best strength performance, were employed in the preparation of the PWC samples.

6.3 Tensile and compressive strengths of MPB and PWC)

The MPB and PWC samples take their final shape several hours after casting in the molds. The solidification with slow transition of the cement-less material from liquid to the solid state allows the specimens to gain mechanical strength. Regardless of the plastic content, the compressive strength was found to increase with time. The thermal and physical properties of PWC/MPB are dependent on the plastic paste.

The plastic paste used as the binder for PWC/MPB is polymer dependent (Braun 2002), thus the increase in strength with time can be related to the polymer type and crystallinity (da Silva and Wiebeck 2017). Other factors such as the solidification of plastic paste when exposed to ambient temperature that is lower than the sample temperature contribute to these changes in strength during the melting and curing process (Volk et al. 2015; Ragaert et al. 2017; Sun et al. 2018).

The PWC60 has less porosity than PW50 and the configuration of its interfacial transition zone is more compact (stronger) with less voids than PW50. This influences the strength, which varies inversely proportional with the porosity as supported by previous works on similar construction materials (Lui 1997; Poon et al. 2004; Cheng et al. 2008; Chen et al. 2013).

Moreover, at high temperature during the initial stage of cooling after casting, weak spots develop at the interfacial transition zone (ITZ) between the plastic paste and the aggregates. With time, the ITZ becomes stronger during the solidification phase, which binds the constituent elements of PWC/MPB together to act as one unit and reinforces the compactness and the elasticity of the material (Inai et al. 2018). Thus, part of the strength improvement can be linked to the high elastic modulus and better adhesion in the PWC/MPB.

These new construction materials (PWC and MPB) can reach around 60% to 80% of their final strength just after one day of curing. This increase in the early age strength for MPB is much higher than conventional mortar, which typically reaches less than 30-40% of its final strength after 1 day of curing (Yang et al. 2021).

The compressive strength of all PWC samples, regardless of age and plastic content, were found to be higher than 9 MPa, which somehow exhibit interesting mechanical strength compared to the cementitious composite concrete when the sand volume is completely substituted by PET aggregates (Marzouk et al. 2007).

The splitting tensile values are between 1.5 and 4.5 MPa. The splitting tensile strength of PWC/MPB appears to be sensitive to the presence of voids/pores in the material (Fall et al. 2010).

For future applications in real life conditions, the external temperature and weather can affect some properties of the PWC/MPB. To highlight these possible effects on the properties of PWC/MPB,

two curing conditions were used to assess the materials performance. Independent of the material type, age or plastic content, the samples cured at a controlled ambient temperature were found to have higher strengths (compressive strength and tensile) than the specimens subjected to the thermal shock in water.

This indicates that the curing conditions have an impact on the compressive strength of MPB and the reasons for this can be related to the properties of the product. At high temperature many factors such as binder type, the room temperature or heating rate may affect the strength of the corresponding construction materials (mortar, concrete, etc.) exposed to that condition (Mehta and Monteiro 2006; Krishna et al. 2019). For the MPB mortar poured in the molds at high temperature (more than 100°C), the heat transfer rate between the internal and external components at ambient temperature (26 to 30°C) will affect the thermal, physical and mechanical properties of the corresponding MPB (Türkel and Alabas, 2005; Duan et al. 2020).

Higher temperature difference between the inside and outside of the MPB leads to the development of stress within the sample body, contributing to the weakening of the ITZ between different constituents' elements of the MPB and increasing its porosity. These aspects and physico-chemical transformation in the plastic paste will have negative effect on the internal pore structure of the MPB. This will lead to internal cracks and weak ITZ within the MPB sample body, contributing to the strength reduction (Braun 2002; Mehta and Monteiro 2006; Darquennes et al. 2011; Volk et al. 2015; Ragaert et al. 2017; Krishna et al. 2019; Duan et al. 2020).

For quality control and assessment associated to the practical use of the cement-less materials, regression analysis has been employed to correlate the splitting tensile strength (f_t) and the compressive strength (f_c) for various formulations of the PWC and MPB. Figure 6-2 to 6-5 present the splitting tensile strength vs compressive strength for MPB and PWC cured under two curing conditions (ambient temperature and thermal shock in water). Independent to the material type and the curing conditions, a linear relationship with relatively high correlation factor has been found between these strengths properties.

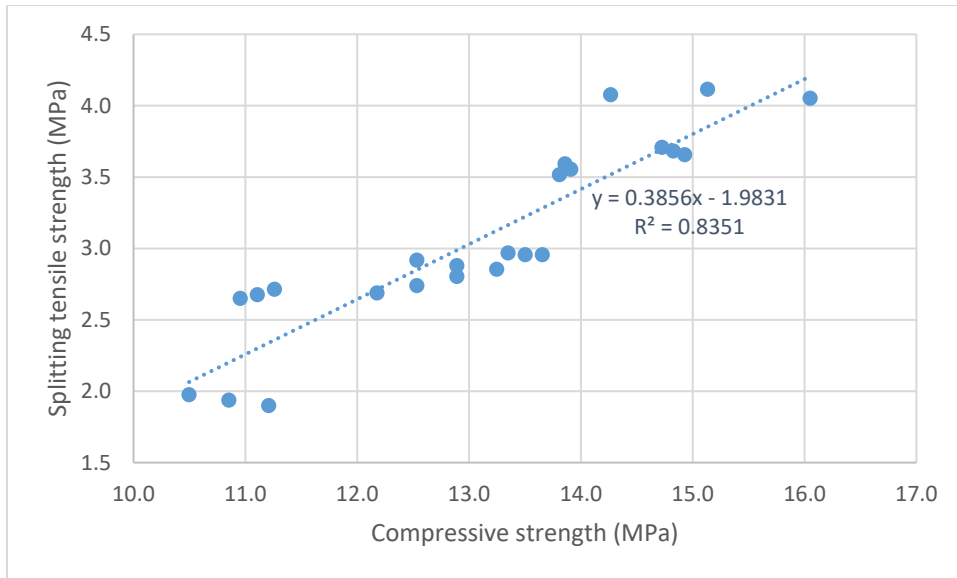


Figure 6-2: Linear correlation between splitting tensile and compressive strengths of PWC cemented with 50% and 60% of melted plastic wastes (HDPE/LDPE ratio of 50/50)

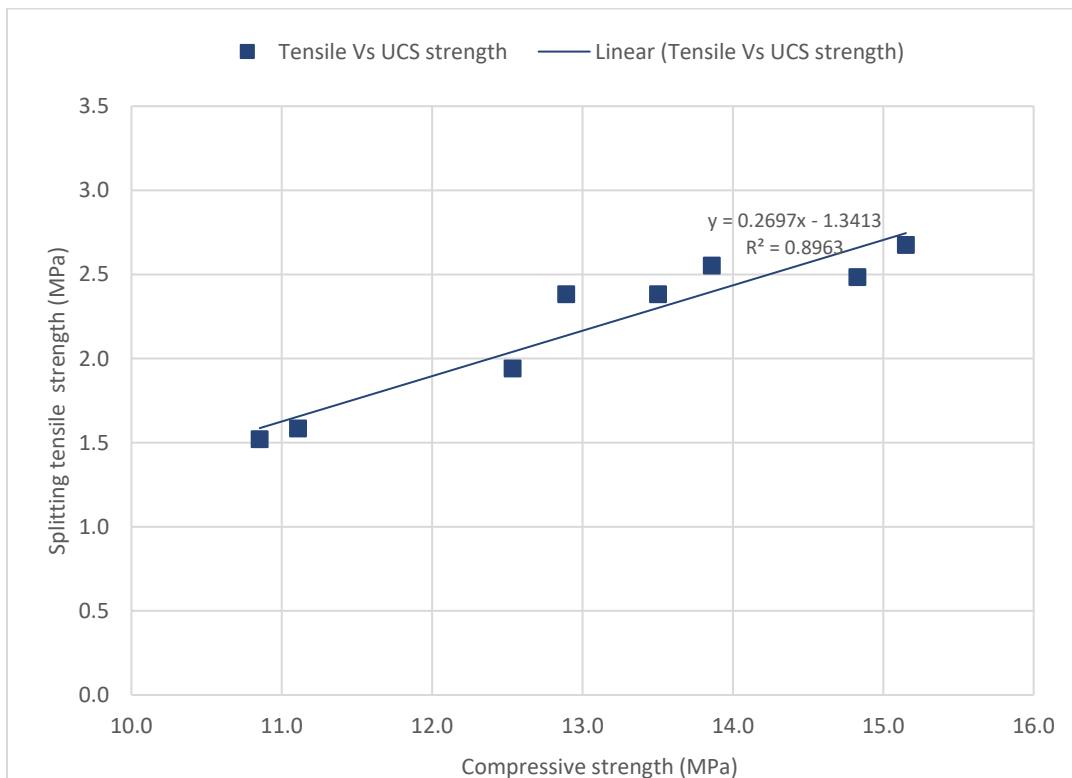


Figure 6-3: Splitting tensile strength vs compressive strength of the PWC with 50% and 60% of plastic content and H/L 50/50 subjected to the thermal shock in water.

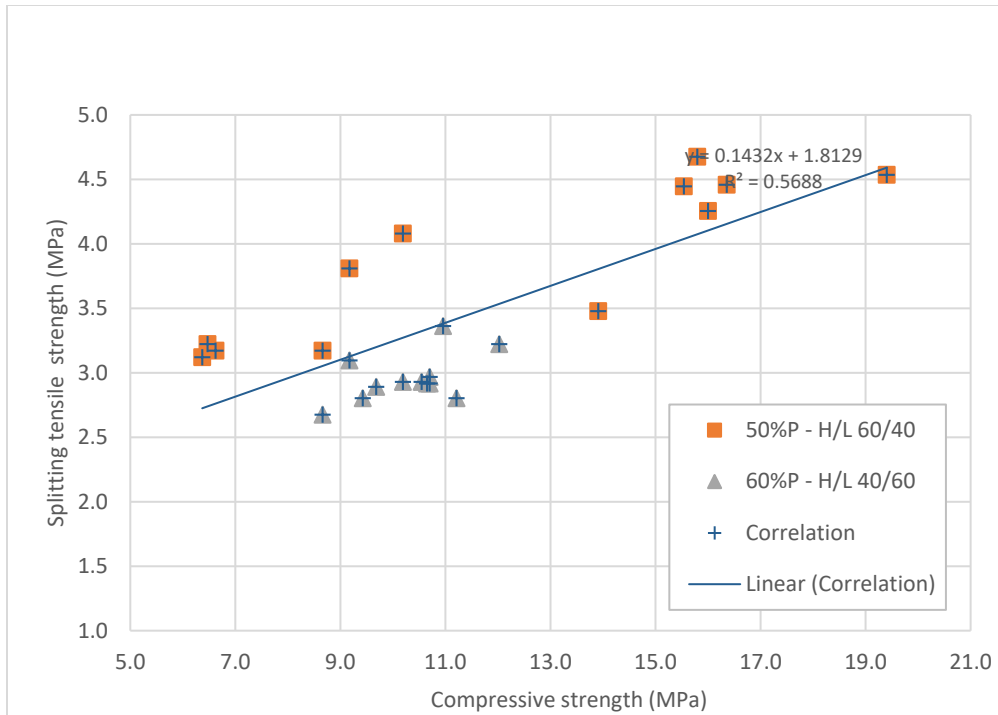


Figure 6-4: Splitting tensile strength vs compressive strength of the MPB with 50% of plastic and H/L of 60/40 and with 60% of plastic and H/L of 40/60

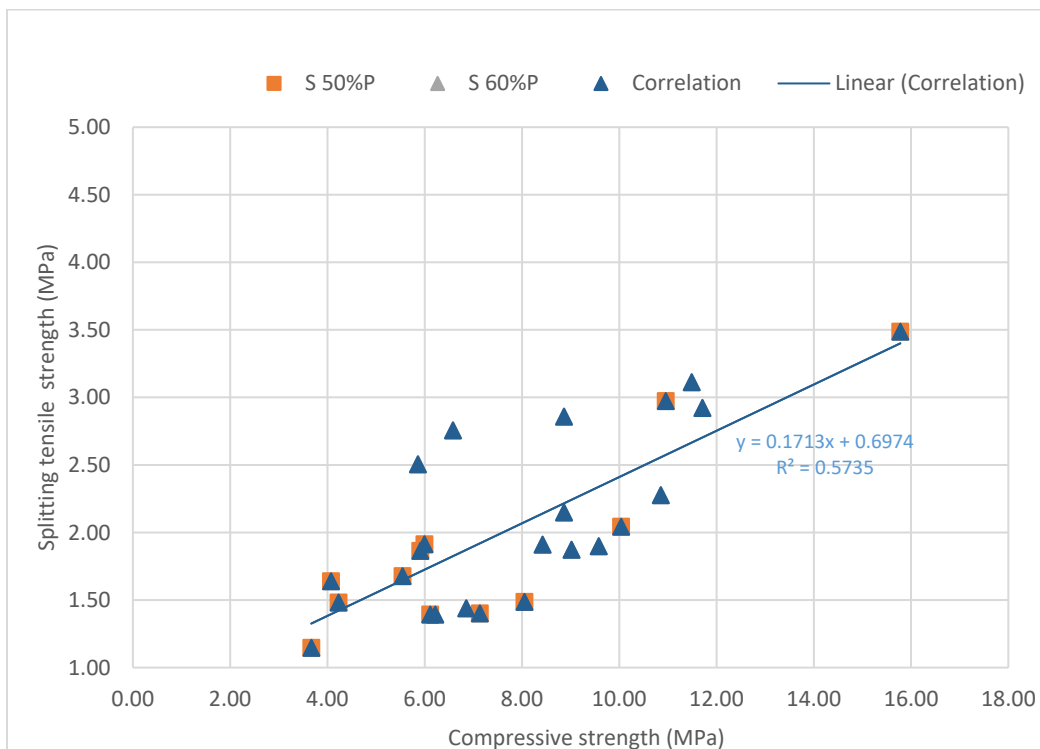


Figure 6-5: Splitting tensile strength vs compressive strength of MPB containing 50% and 60% of plastic content with various H/L ratios and subjected to thermal shock in water

6.4 Stress – strain behaviour and failure modes of MPB and PWC under different curing conditions

In general, the stress-strain behaviour in both tension and compression showed similar behaviour under each of the two curing conditions. Independent of the curing conditions, all the MPB specimens undergo plastic deformation before reaching the peak value. However, the curing condition was observed to influence the peak stress of the MPB with the samples subjected to thermal shock having lower strength than those cured at ambient temperature.

In the first part of the stress-strain curve, the increase in stress leads to an increase in strain under compressive or tensile stresses until reaching the peak value. Failure occurs at the peak stress, but the material continues to deform with a reduction in stress and continual increase in strain. This mechanism continues until full disintegration of the material. Beyond the peak stress, the PWC/MPB undergoes more plastic deformation, whereas the conventional mortar/concrete exhibits brittle deformation with sudden failure (Hannawi et al. 2010).

Longitudinal splitting localized and diagonal shear failures were randomly observed on PWC/MPB samples after failure, which seems to be similar to the findings from previous studies on concrete and mortar containing fibers or plastics aggregates (Hannawi et al. 2010; Jiang et al. 2017).

Furthermore, for future studies, different deductions in form of mathematical models can be derived from the stress - strain graphs to estimate certain parameters such as deformation and fire resistance of PWC and MPB construction materials (Krishna et al. 2019).

6.5 Density and absorption/permeability of PWC and MPB

The density of both PWC and MPB was found to decrease with the increase in plastic content as observed for other construction materials containing plastic wastes aggregates (Marzouk et al 2007; Bărbuță and Toma 2015; Alqahtani et al. 2017; Belmokaddem et al. 2020). The density reduction can be related to the lower density of plastic wastes ($0.915\text{--}0.940\text{ g cm}^{-3}$ for LDPE and $0.940\text{--}0.965\text{ g cm}^{-3}$ for HDPE) by comparison to natural aggregates (Hannawi et al. 2010; HDPE 2018; LDPE 2018). Moreover, the average density at different ages of the PWC / MPB was found to be around 2 g/cm^3 considered to be lightweight material based on Rilem classification (RILEM 1978; Saikia and De Brito 2012). This lightening property of PWC and MPB can be of great relevance for saving energy in the field of construction and reduction of the size of various elements in the building. It can also contribute to reduce transport cost and minimize the risk related to excessive weight when failure occurs.

Both curing conditions showed similar behaviour, with the density varying with time and hardened conditions of the PWC/MPB specimens. The thermal shock does not seem to have significant impact on the PWC/MPB density. This fact can be related to the hydrophobic behaviour of plastic paste and the absence of mass loss when the PWC/MPB samples are placed in water.

The absorption (by immersion and capillarity) values for PWC/MPB were found to be lower than the ones obtained for conventional concrete/mortar. This fact can be related to the hydrophobic behavior of plastic used as binder for PWC/MPB. Also, for the conventional concrete, the initial water content contributes to the creation of voids during the drying stage of the sample. In addition, the PWC/MPB samples with lower strength values were found to have higher rates of absorption.

The absorption values are higher for MPB that was subjected to thermal shock, confirming its higher porosity and pores interconnectivity, which subsequently results in lower strength compared to the specimen cured at ambient temperature in controlled laboratory conditions.

6.6 Microstructural properties of PWC and MPB

The SEM images from previous sections provide clear view of the composition (BEC) and topography (SEI) of various PWC and MPB samples with different plastic contents and/or H/L ratios. Based on the images, it was shown that these new materials (PWC and MPB) are porous material with the presence of voids/pores in the samples bodies and their porosity can affect various engineering properties such as permeability and strength of the products. Moreover, by analyzing the MIP of various PWC and MPB, clear difference has been observed in the cumulative pore volume for various formulations of PWC and MPB, confirming the fact that the new materials were found to be porous and MIP tests allowed to better understand the porosity and the connectivity of the pore structure. The samples with the high values of porosity were found to have the lowest strengths. Similar to the conventional concrete, the strength of PWC/MPB is inversely proportional to the porosity of the corresponding specimen. Thus, the samples with higher porosity were found to have higher absorption/permeability and lower compressive strength.

Imagej software analysis, a public domain Java image processing program, was used to determine the area occupied by the pores as well as the average pore diameter for various ecological materials samples. The obtained results from imagej analysis were found to be in line with the MIP results and confirmed the porousness of the ecological materials made of melted plastic wastes.

From the thermal (TG/DTG) analysis, a lag with delay in thermal degradation of PWC/MPB was observed when compared to the pure plastics (HDPE and LDPE) wastes, which indicates that the TG/DTG results for PWC/MPB is not cumulative of the individual polymer degradation. It is evident that the mixing process and heat transfer during the melting phase of plastic wastes influence in some ways the thermal behaviour of the new materials from the constituents binding elements. In addition, 465°C was the temperature required to decompose 80% of the PWC, which is higher than that of plastic wastes (HDPE and LDPE) in the range of 360°C to 460°C. Thus, the inorganic material (sand and gravel) and melting process enhance the thermal stability of the PWC material (Barbara et al. 2014).

Unlike the new cement-less materials, the peak decomposition of the conventional concrete (733°C) was found to be higher than that obtained for PWC samples (432 °C and 482 °C). Also, more residue was left for the conventional concrete than the PWC.

6.7 Large-scale application of PWC and MPB

Previous studies in the field have shown that concrete and mortar with plastic waste as substitute or replacement of natural aggregates may be used for structural construction (Saika and de Brito, 2012; Silva et al. 2013). Therefore, to reinforce our understanding of the applications of the PWC and MPB materials made of melted plastic wastes (HDPE and LDPE) as the only binder in real life conditions, some pavers were prepared and tested in a large-scale realization in two cities in Mali, namely Bamako and Bougouni.

6.7.1 Large-scale applications of the MPB for house backyard and sidewalk

Figure 6-6 shows large-scale pavement constructions using the MPB in two towns in Mali, including Bougouni (sidewalk of a motel) and Bamako (interior backyard of a house).



a) Sidewalk of a motel located in Bougouni, one of the regional capitals of Mali



b) MPB pavers on the courtyard of a house, supporting light loads in Bamako

Figure 6-6: Large-scale application of MPB pavers for a) sidewalk and b) house yard rehabilitation in Mali.

According to the users, these new pavers clearly meet their needs. The MPB material provides good drainage after a heavy rain and it only takes a simple sweep to keep the surface very clean and dry. In addition, from their experiences, during summer the heat is significantly less than what they are used to observe with similar conventional cement-based pavers. They usually have to regularly spray water on the upper side of cement-based pavers for cooling during the hot weather, which is not the case with the ecological pavers.

According to the mason in charge of the large-scale realization, the MPB pavers have interesting advantages and could be appealing to costumers. During transportation and installation, less than 1% of the MPB pavers were broken, as opposed to 3 - 6% for the commercial pavers available on Bamako's market.

Thus, the MPB material offers economic advantages through cost saving by substituting cement paste with the cheap plastic paste. Furthermore, the MPB pavers are lightweight, resistant and above all involves less risk of work interruptions during construction even for sites that are far from the production site.

Before applying the product at large scale, strength tests were performed not to compare the MPB pavers to the commercial cement-based pavers, but rather to have a better understanding of their behaviour when using commercial molds with small thickness different from the standard ones. Compressive strength and splitting tensile tests were carried out on MPB pavers from this study and conventional cement-based pavers sold on the market in Bamako.

Figure 6-7 (a and b) presents some construction pavers made of MPB (4 cm thick) and commercial cement concrete pavers (7 cm thick) before and after the compression tests.



a) MPB pavers



b) Conventional cement-based pavers from Bamako

Figure 6-7: a) MPB and b) Conventional cement-based pavers before and after strength tests

Figures 6-8 and 6-9 present the compressive strength and splitting tensile strength results for the load supported as a function of the deformations for MPB and conventional cement-based pavers

As it can be observed from the results, the MPB samples are able to support heavy loads similar to what is supported by the commercial cement-based pavers. After the peak stress value, full disintegration with brittle failure was observed for conventional cement products while ductile behaviour with gradual deformation capable of supporting loads for a certain period of time after failure was observed for MPB. This finding will be of great interest when using MPB for large-scale applications such as pavements for house backyard or sidewalks (Figure 6-6).

For the same load, the compressive and tensile displacements are higher for the MPB pavers than cement-based pavers, due to the high plasticity of the MPB pavers. This means that an MPB structures take longer time before full disintegration by resist to cracks in the structure body.

These interesting properties make the use of MPB pavers promising, especially for secondary roads with the specific requirements with respect to the fatigue and deformation to ensure better

infrastructural sustainability. The ductile behaviour of MPB pavers will be of great benefit towards the prevention of cracks and improvement of the durability of road structures. Further studies are needed to fully understand the long-term behaviour of this new product in order to ensure its optimal use for future large-scale commercial applications. It is also vital to study the life cycle and cost analysis of the MPB pavement for a large production. Its wider acceptance in the construction industry will help towards getting rid of plastic wastes.

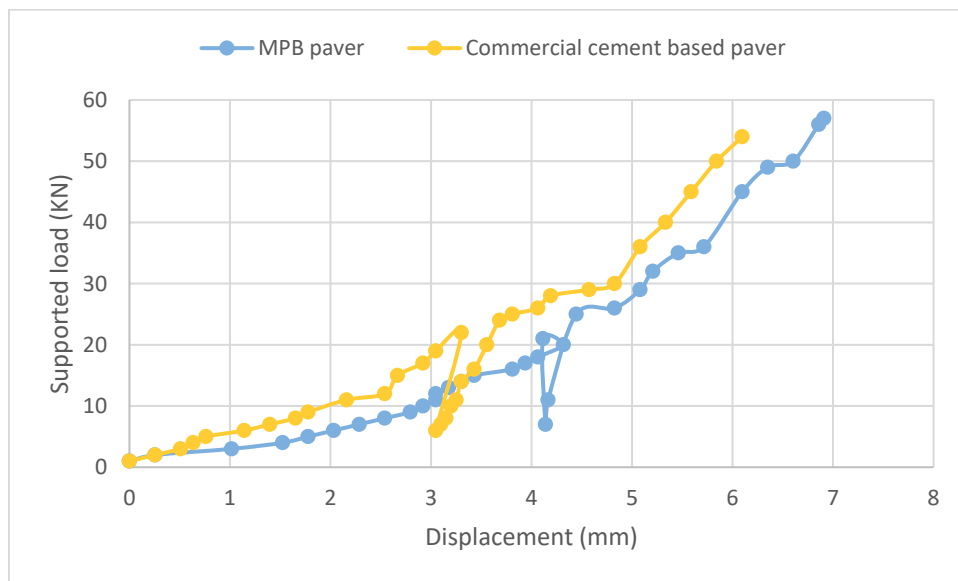
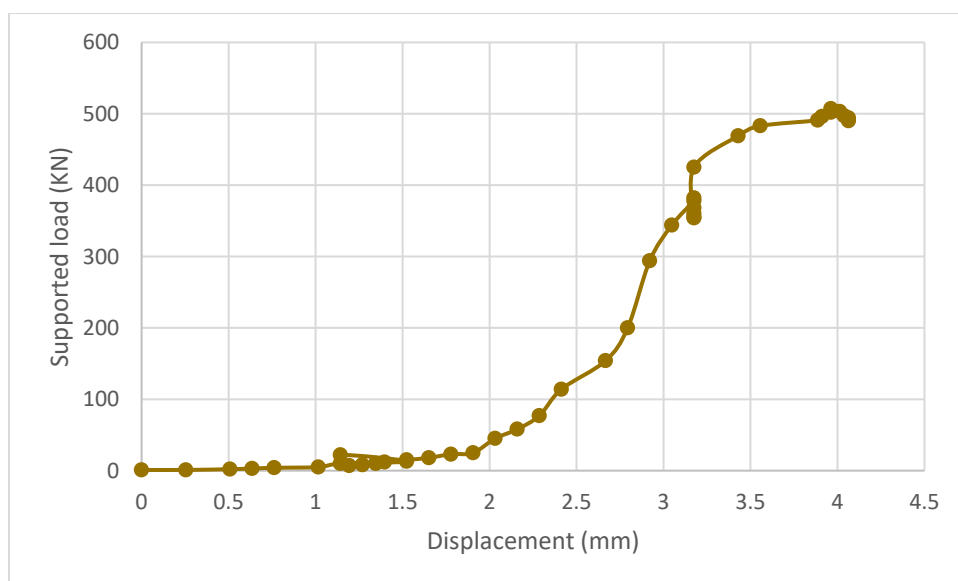
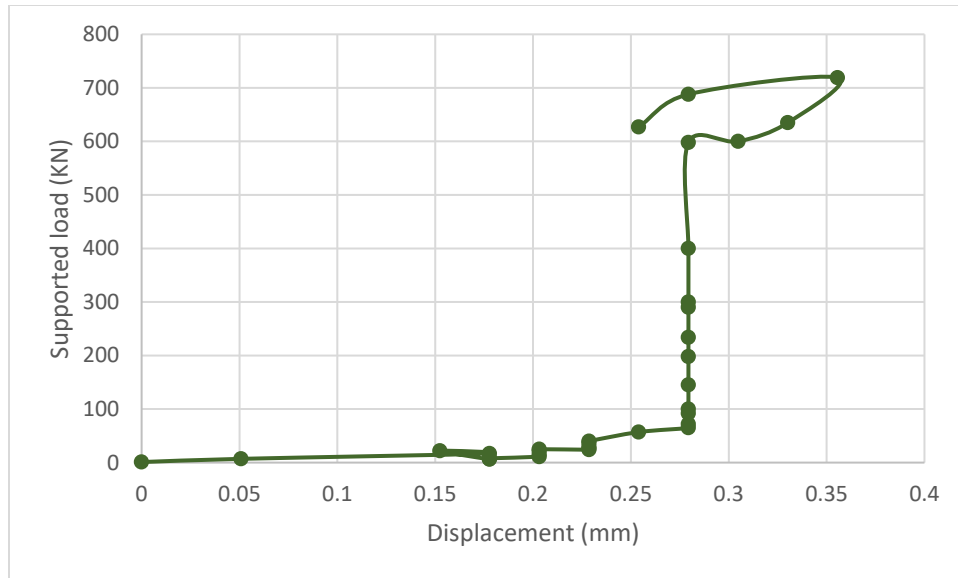


Figure 6-8: Splitting tensile stress-strain behaviour of MPB and conventional cement-based pavers



a) MPB paver



a) Conventional cement-based paver

Figure 6-9: Compressive stress-strain behaviour of MPB and conventional cement-based pavers

6.7.2 Large-scale applications of the PWC for house backyard and sidewalk

Similarly, large-scale experiment was conducted by making roads pavers using the PWC optimal formulations and observing their behaviour in order to improve our understanding of the product before expanding to large projects in practice. Figure 6-10 presents PWC pavers from our research and some commercial conventional cement pavers from Bamako's market before and after the strength tests.



a) PWC pavers from our large-scale experiments.



b) Conventional cement pavers from Bamako's market

Figure 6-10: PWC and conventional cement pavers before and after strength determination tests.

The weight of a single PWC paver is 2235 g, while the two types of conventional cement pavers X1 and Y1 weighed 3735g and 3914 respectively, as shown by the Figure 6-10. Thus, the PWC pavers are lighter than the conventional cement pavers, which can translate to the reduction of cost and pollution rate during the transportation of the products (Silva and de Brito, 2018). In addition, the lightweight properties mean that, when the PWC pavers are used for secondary roads surface layer, the structural self-weight supported by the foundation layers would be lower. Also, the PWC products with its higher plasticity and ductile behaviour will have an appreciable resistance to wear, which will subsequently improve the durability of the roads. Moreover, as opposed to the brittle failure mode with full disintegration for conventional cement pavers, the ductile and higher plasticity nature of the PWC pavers will ensure that broken parts are kept together and will still be capable of supporting loads certain period of time after failure.

Figure 6-11 shows a large-scale realization of PWC pavers from this study for testing purpose inside the national engineering school of Mali in order to gain a better understanding of its properties. A pavement section was built in order to observe the deformations undergone by the PWC pavers when subjected to the loads of heavy and light vehicles in a trafficked public institution.

After more than two years, no significant deformations were observed as shown in Figure 6-11. The PWC pavers appear to undergo ductile plastic deformation against brittle deformation for conventional cement pavers.



Figure 6-11: Large-scale realizations inside the National Engineering School of Mali using the PWC from our research (Bamako, Mali).

From students and professors' opinions, the damaged section of commercial cement pavers, which has been replaced by the PWC pavers, really meets their needs. Thus, that portion covered with the PWC pavers has helped to reduce the risks of vehicles damages and injuries to people. Also, it has contributed to have a smooth flow of vehicles to the parking lots.

To build on the opinions from users and technicians about the PWC products, tests were carried out on the PWC pavers and commercial cement pavers sold at the Malian market. Figures 6-12 and 6-13 present the results obtained for the load supported vs displacement/deformation for the two types of pavers under splitting tensile and compressive forces.

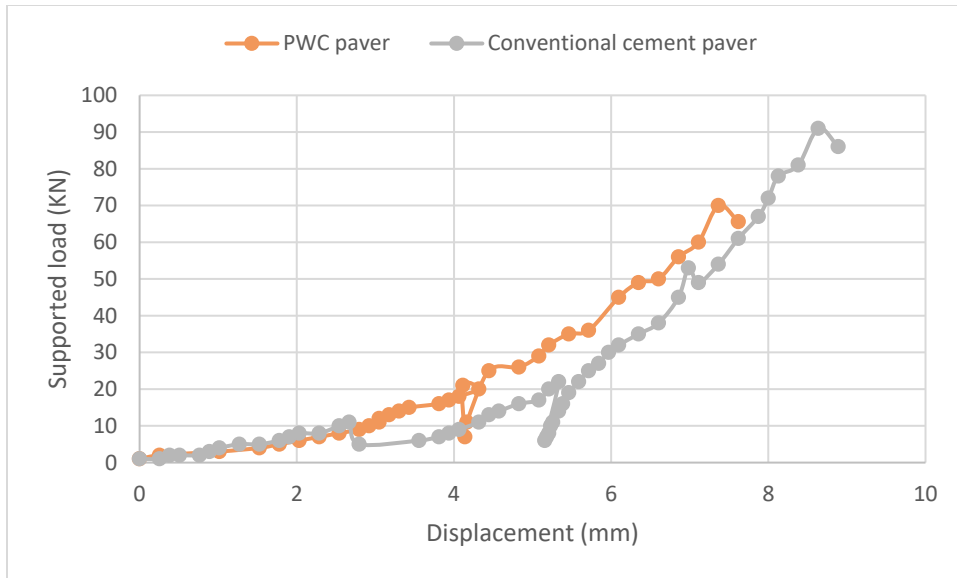
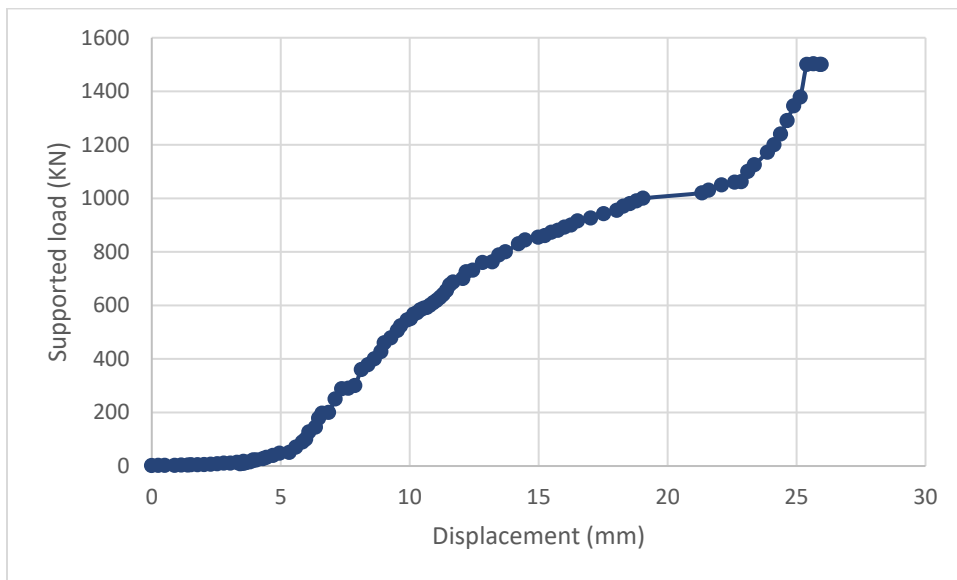
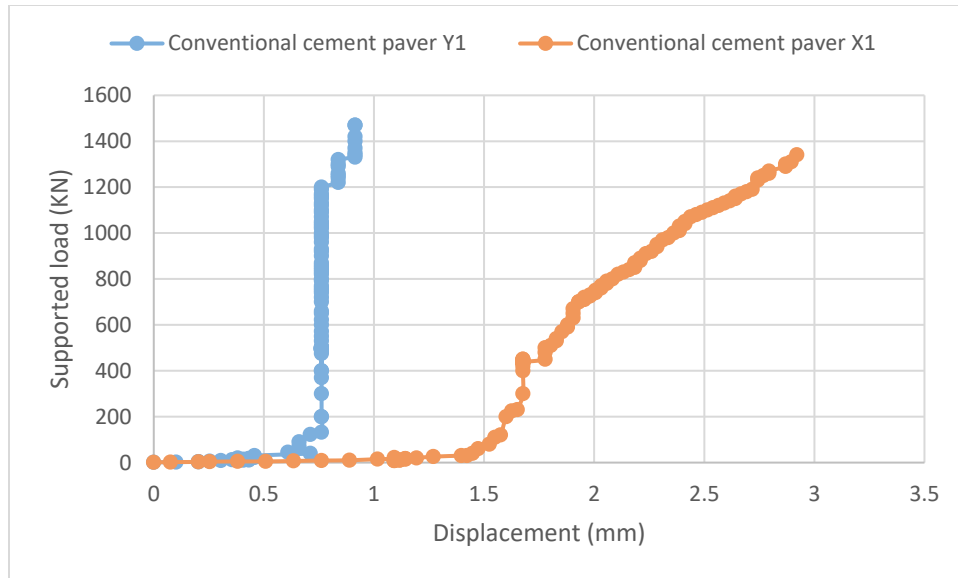


Figure 6-12: Splitting tensile load-displacement behaviour of PWC and conventional cement concrete pavers



a) Compressive load-displacement behaviour of PWC



b) Compressive load-displacement behaviour of conventional cement concrete pavers

Figure 6-13: Compressive load-displacement behaviour of PWC and conventional cement-based pavers.

For the same applied load, the displacement/deformation is lower for conventional cement pavers and the failure is sudden. PWC pavers have a ductile behavior and withstand loads for a long period of time after failure, which can be of great benefits especially for road construction with the loading-unloading cycle as well as the deformations and fatigue behavior of infrastructures to ensure good durability.

Chapter 7. Conclusions and recommendations for future works

7.1 General conclusions

A series of experimental campaigns have been performed in the course of this PhD research on the development of new construction materials, MPB and PWC, using melted plastic wastes as binding materials. The following remarks can be drawn from the obtained results.

- A method to make cemented construction materials (MPB, PWC) with melted plastic waste as the only binder has been developed. The manufacturing process of the conventional cementitious materials is different from that of the MPB and PWC, which is conducted at high temperature without the use of water and cement.
- The compressive strength of the proposed construction materials can be as high as 18 MPa, while the splitting tensile strength is approximately 20% to 25% of the compressive strength. The strengths are a function of the plastic waste content and curing time. Irrespective of the plastic content, the strengths increase with time due to the solidification of the plastic binder. The MPB samples with plastic contents of 50% and 60% and an H/L ratio of 50/50 show the highest COMPRESSIVE STRENGTH values, whereas the PWC60 has higher compressive and splitting tensile strengths than that the PWC50. This higher strength is related to a finer pore structure of the material and better bonding properties at its interfacial transition zone. The MPB and PWC samples reach 60 to 80% of their final strength after just one day of curing. This rapid curing is desirable and important in precast applications.
- A linear relationship has been developed between splitting tensile and compressive strength.. This relationship may allow a simple, but consistent use in practical applications.
- Deformation cones, longitudinal and localized deformations are the commonly observed types of deformations for the MPB and PWC under compressive and splitting tensile forces from experimental tests. The PWC and MPB show interesting post peak strength capable of supporting loads and the deformation is more ductile than that of conventional concretes or mortars. Even after the break, the MPB and PWC are able to sustain load for a period of time before complete disintegration.
- The MPB and PWC made of plastic wastes were found to be lighter than the traditional cemented materials containing cement. The values found for the density of the MPB and PWC are close to 2 g/cm³, thus they can be considered as lightweight concrete according to RILEM classification.
- The thermal analysis results reveal that there is a delay in the thermal degradation of the PWC and MPB in comparison to the pure plastic wastes, which suggests that the thermal degradation or behaviour of MPB and PWC is not cumulative of the individual polymer degradation. From zero to 360°C, no mass change was observed for all the MPB and PWC samples. This means the PWC and MPB specimens are stable up to 360°C.
- The MIP results indicate that the PWC60 (60% plastic waste content) has finer pore structure and smaller porosity than PWC50 due to the difference in plastic content. The SEM analysis results show that the melted plastic paste binds the sand and gravel particles

with the presence of voids/pores, especially at the interfacial transition zone between melted plastic waste and the granular materials.

- The curing conditions and granular material size has a significant effect on the physical and mechanical properties of MPB and PWC.
- The findings of this research indicate the potential of using molten HDPE and LDPE plastic wastes as the only binder to develop construction materials, MPB and PWC. The preparation method of these construction materials needs only a small amount of energy. Furthermore, no water is required to produce these construction materials, which is a valuable benefit in regions of the world that are facing water scarcity. The interesting engineering properties of the proposed MPB and PWC would make it suitable for many construction and buildings applications, such as pavers, secondary roads, non-load bearing partitions, and retaining walls.

7.2 Future work proposal

Development of MPB and PWC materials for construction as an alternative to the traditional cementitious materials is highly encouraged by decision makers and during the past decade, many researchers worked on various techniques integrating plastic in concrete and mortar for construction. The development of the materials required the understanding of various properties at macro and microstructural levels that have significant impacts on their behaviour and performance in practice. Various tests were performed, and promising results were obtained in terms of strength (compressive and splitting tensile), density, permeability, etc. Some comparison between various properties of the conventional cementitious materials and the ecological materials developed during this PhD research were made. Based on the findings, design concepts for constructions using the new ecological concrete and mortar made of plastic wastes were proposed. The following recommendations can be considered for future works.

1. Study the products under flexural forces to define the ideal operating conditions when they are subjected to large-scale loadings.
2. Collaborate with mechanical engineers to automate the furnace (oven) used in the preparation of the new materials to help reduce the production time and improve the mechanical strengths.
3. Design an automatic compaction press adapted to the system for the improvement of the degree of compactness of the products and improve their mechanical properties.
4. Study the impact of the temperature variability and curing conditions on the mechanical and microstructural properties of MPB and PWC products by using a mold insulation system.
5. Study the physico-chemical transformations in the plastic paste binder during melting phase as well as the hardening process of MPB and PWC in order to better understand the evolution of mechanical characteristics and thermal properties.
6. Study in more detail the chemical compositions and microstructural characteristics of MPB and PWC with different formulations containing various plastic contents and HDPE/LDPE ratios.
7. Study the degradation parameters of the MPB and PWC products when used at large-scale as well as investigate their durability.
8. Carry out a life cycle study (LCA) and cost analysis on MPB and PWC by using conventional concrete and mortar as references.
9. Carry out cost analysis for industrial production and analyze the profitability of the product.
10. Study the properties of the plastic binder to better understand the main characteristics (thermal, mechanical, melting, etc.) according to the types of plastics used by performing various tests (ball and ring test, abrasion, etc.).
11. Explore the thermal and electrical conductivity of these materials to have better understanding of their properties when used at large scale (road layers, bearings insulators, etc.).
12. Prepare MPB and PWC formulation by volume of various constituent elements to see the impact on the mechanical and physical properties of ecological concrete and mortars.

13. Conduct extensive large-scale experimental investigations of the behavior of the proposed new construction materials.

Chapter 8. Appendix A

A1- Materials, equipment's, some steps or stages of the waste collection stream



A1-1: Some images of Bamako landfills



A1-2: Awareness campaign and plastic wastes collection with students from Bougoni public high school



A 1-3: Images from certain stages of wastes collection in Bamako



A 1-4: Samples of some a) HDPE and b) LDPE plastic wastes used during the preparation of the MPB and PWC materials.



A1-5: Images of the granular materials (sand and gravel) used during the experimental works as well as their collection point in Bamako



A1-6: Furnace (oven) used for large-scale production of MPB and PWC materials





A 1-7: Molds used for the production of MPB and PWC





A 1-8: Manual press system

A2- Some operational steps for large-scale production, testing and applications of MPB and PWC materials



A 2-1: Melting and preparation of MPB and PWC products in the manual oven under high temperature



A 2-2: Liquid MPB before pouring in molds





A 2-3: Conditioning the mold by injecting the lubricant, pouring of the liquid products (MPB and PWC) in the mold, compaction with the manual press

A3) Some stages of large-scale applications



A 3-1: Prototypes of pavers using MPB (interior backyard) and PWC (bearing heavy load) made from plastic wastes before and after demolding



A 3-2: Samples of MPB (interior backyard) and PWC (bearing heavy load) made from plastic waste after compression tests



A 3-3: Some samples of pavers sold on Bamako's market (Mali, before and after compression tests)



A 3-4: Sidewalk of a motel located in Bougouni, one of the regional capitals of Mali using our research products



A 3-5: MBP pavers for house courtyard supporting light loads in Bamako.

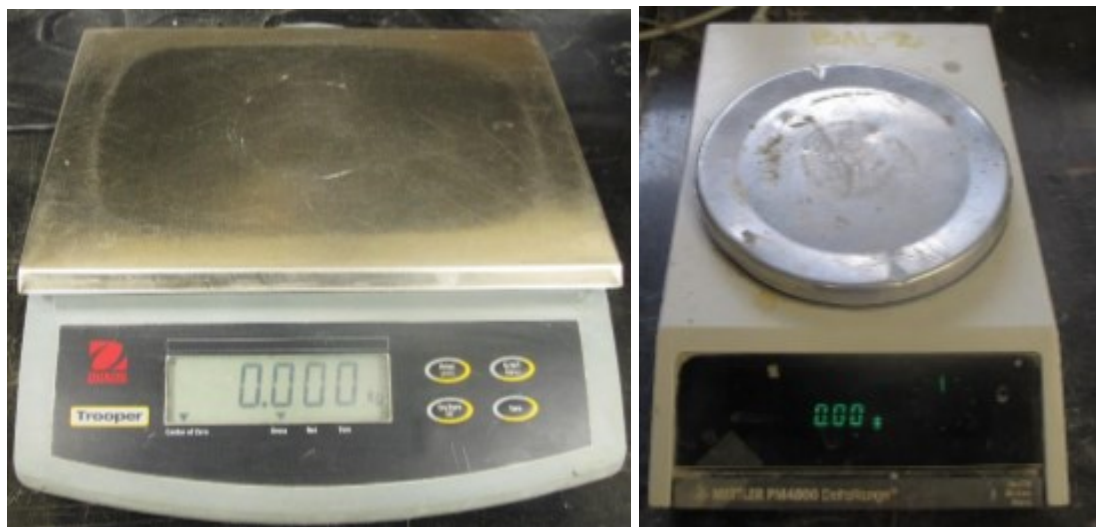


A 3-6: Large-scale construction of PWC in the courtyard of the national engineering school (ENI-ABT) of Mali, with paving stones supporting heavy loads

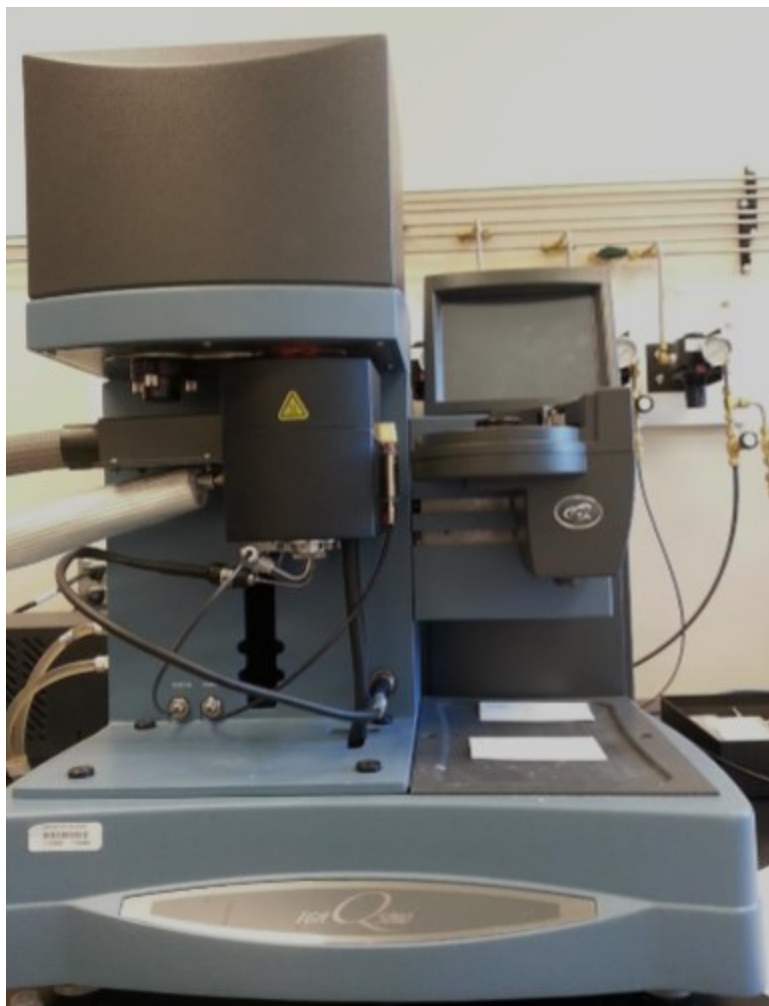
A4) TEST SET-UP AND EQUIPMENT USED IN THE RESEARCH



A 4-1: Performing COMPRESSIVE STRENGTH test on PWC sample



A 4-2: Trooper Ohaus TR15RS (15 kg×5g) balance (left) and Mettler PM4800 (4100×0.01g) used in experiments



A 4-3: Thermogravimetric analysis (TGA) equipment (Q 5000 IR instrument) used to perform thermal analysis on samples



A 4-4: SEM equipment (JEOL 6610LV SEM) located in ARC building at University of Ottawa used to perform SEM analysis on samples in load cell experiments



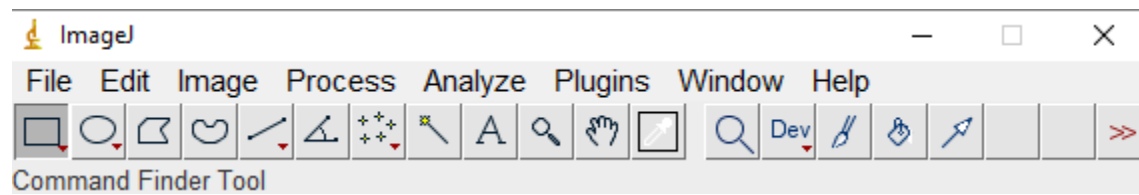
A 4-5: PMI Mercury/Nonmercury Intrusion Porosimetry instrument used to determine pore size distribution, total pore volume and surface area of the samples



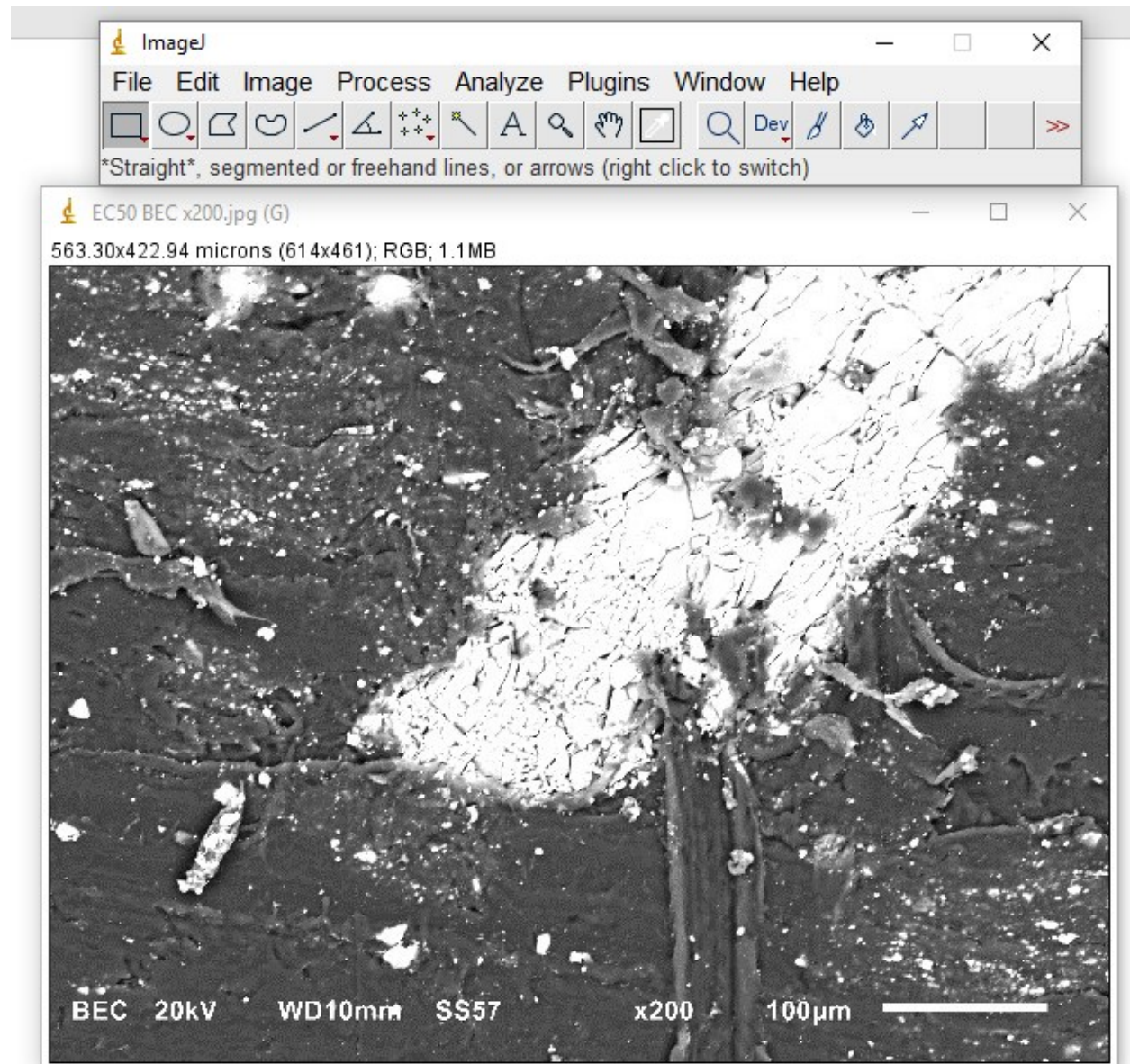
A 4-5: Multi-meter used to record temperature during the experimental program

A5) The steps for using Imagej software (Imagej results)

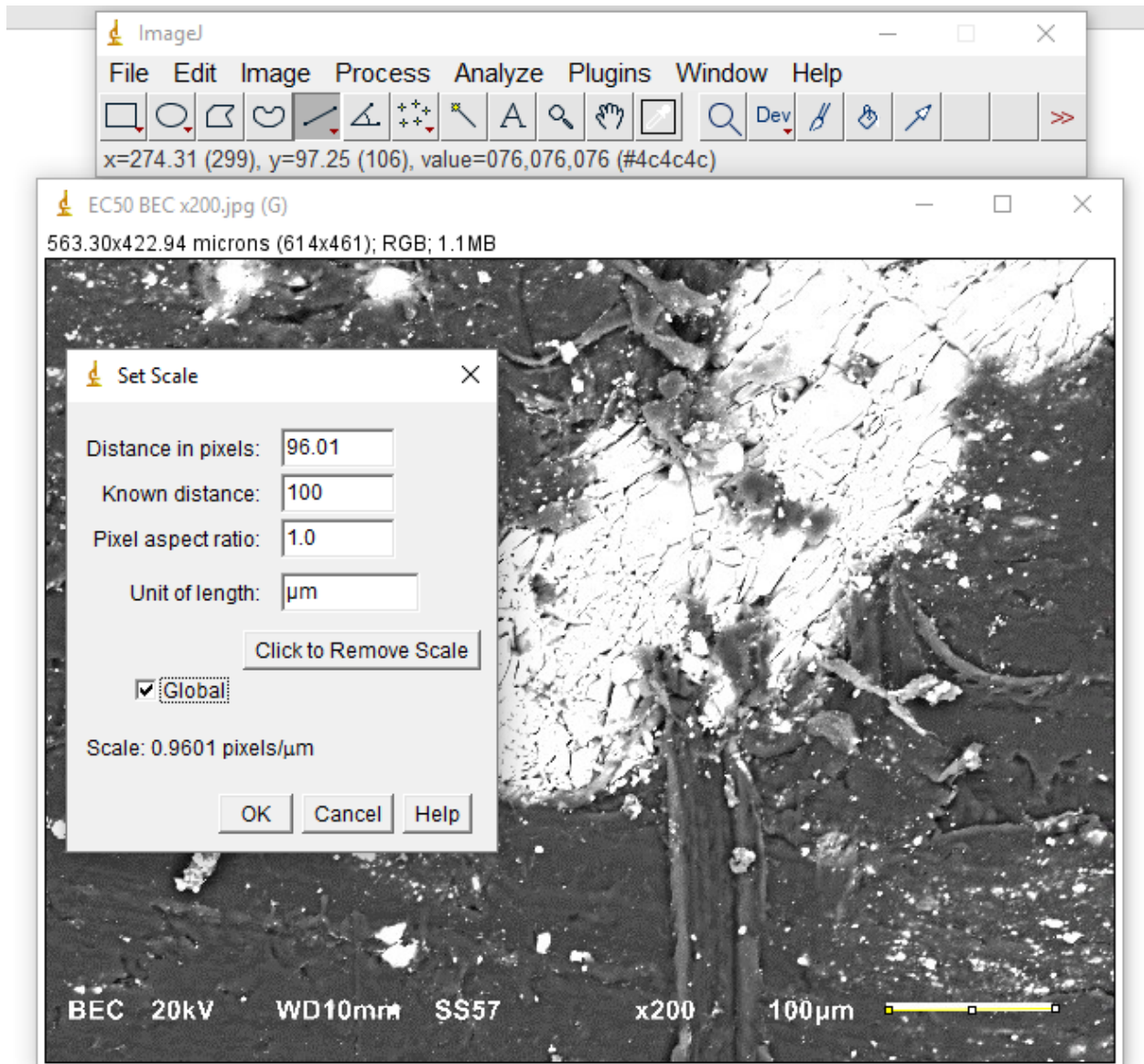
- ✓ Opening of Imagej software interface



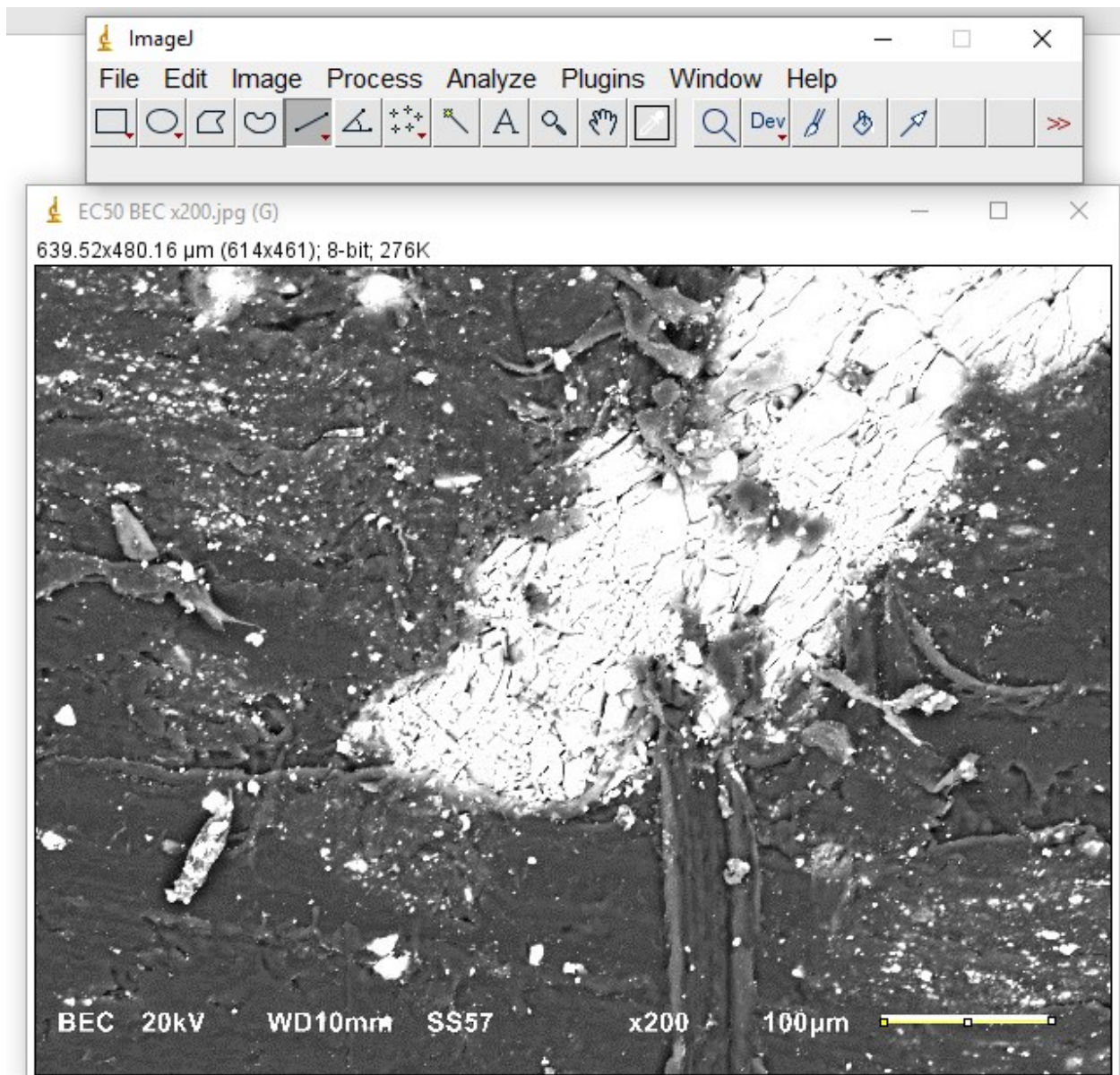
- ✓ Opening of the specific image



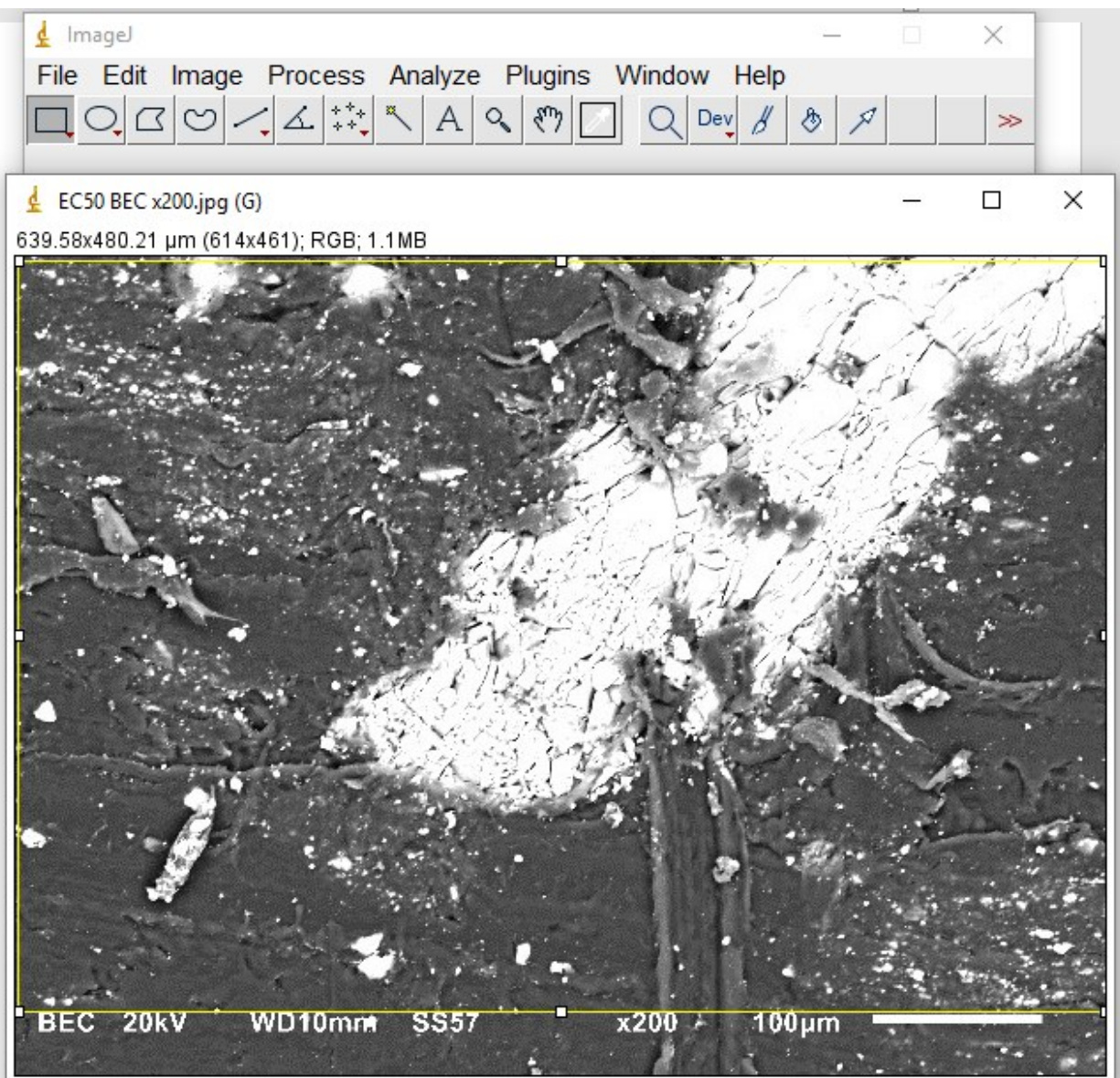
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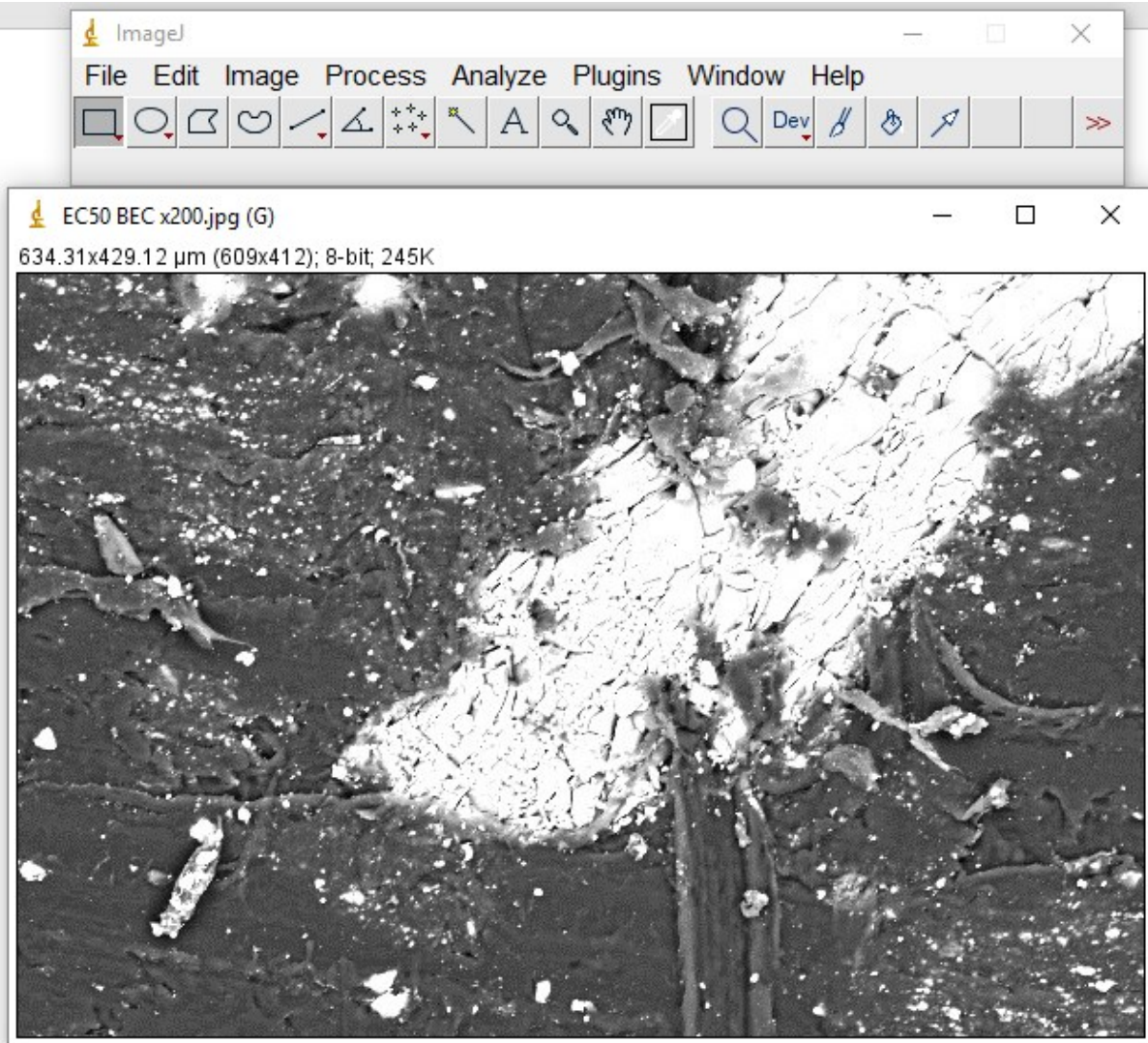


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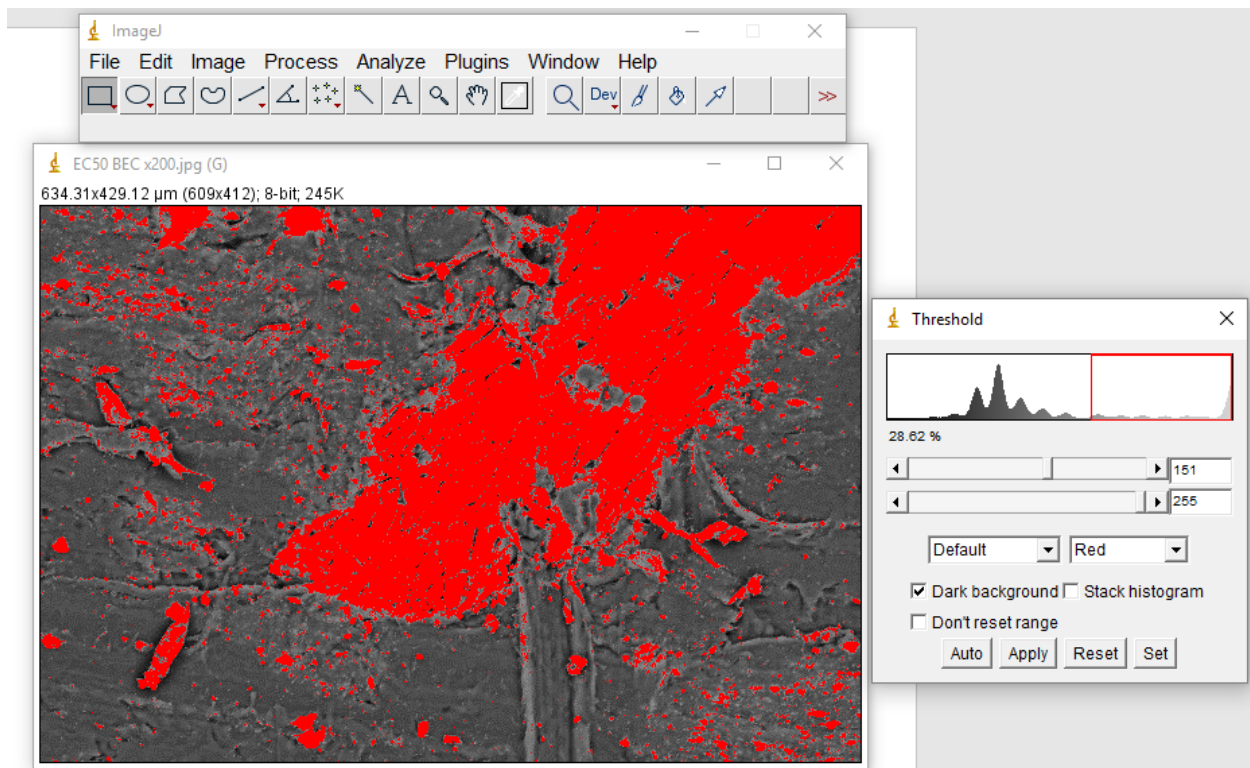


✓ Crop the image to be focus on it without scale bar

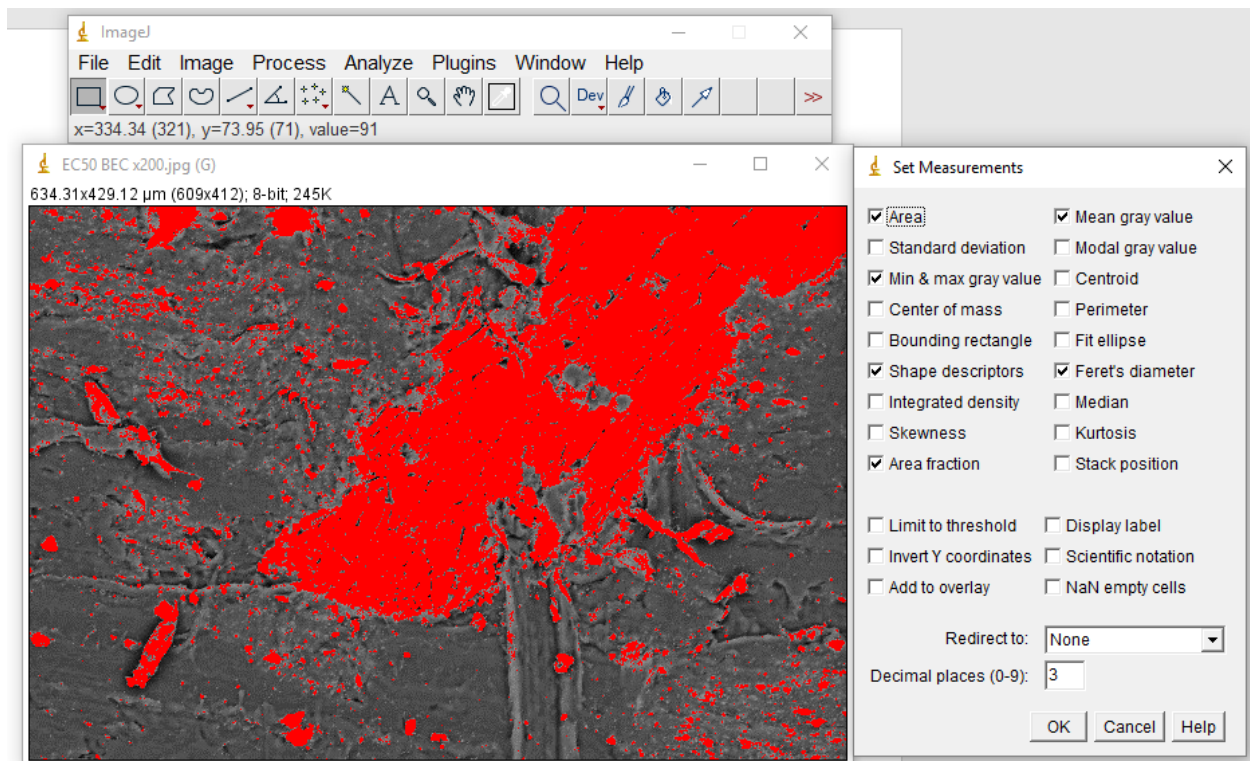




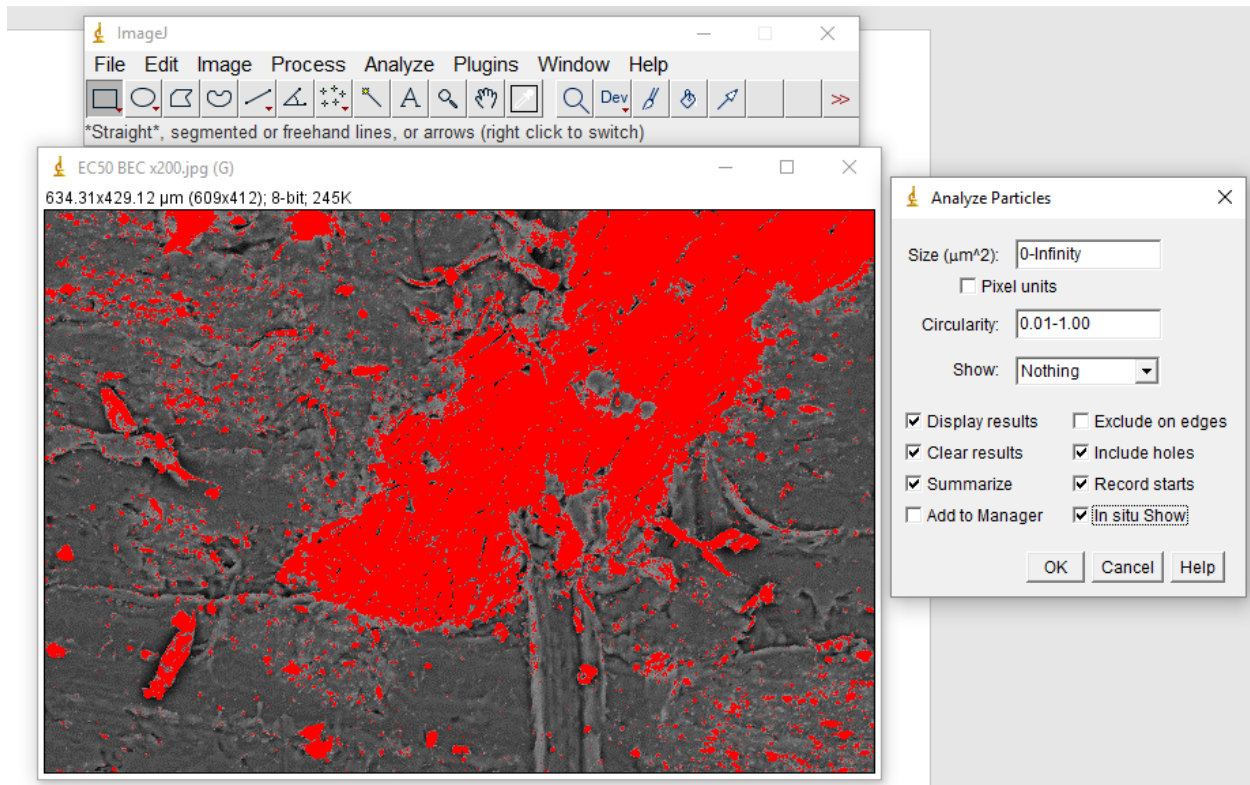
- ✓ Choose adjust Image option and then threshold, to color pores in the material



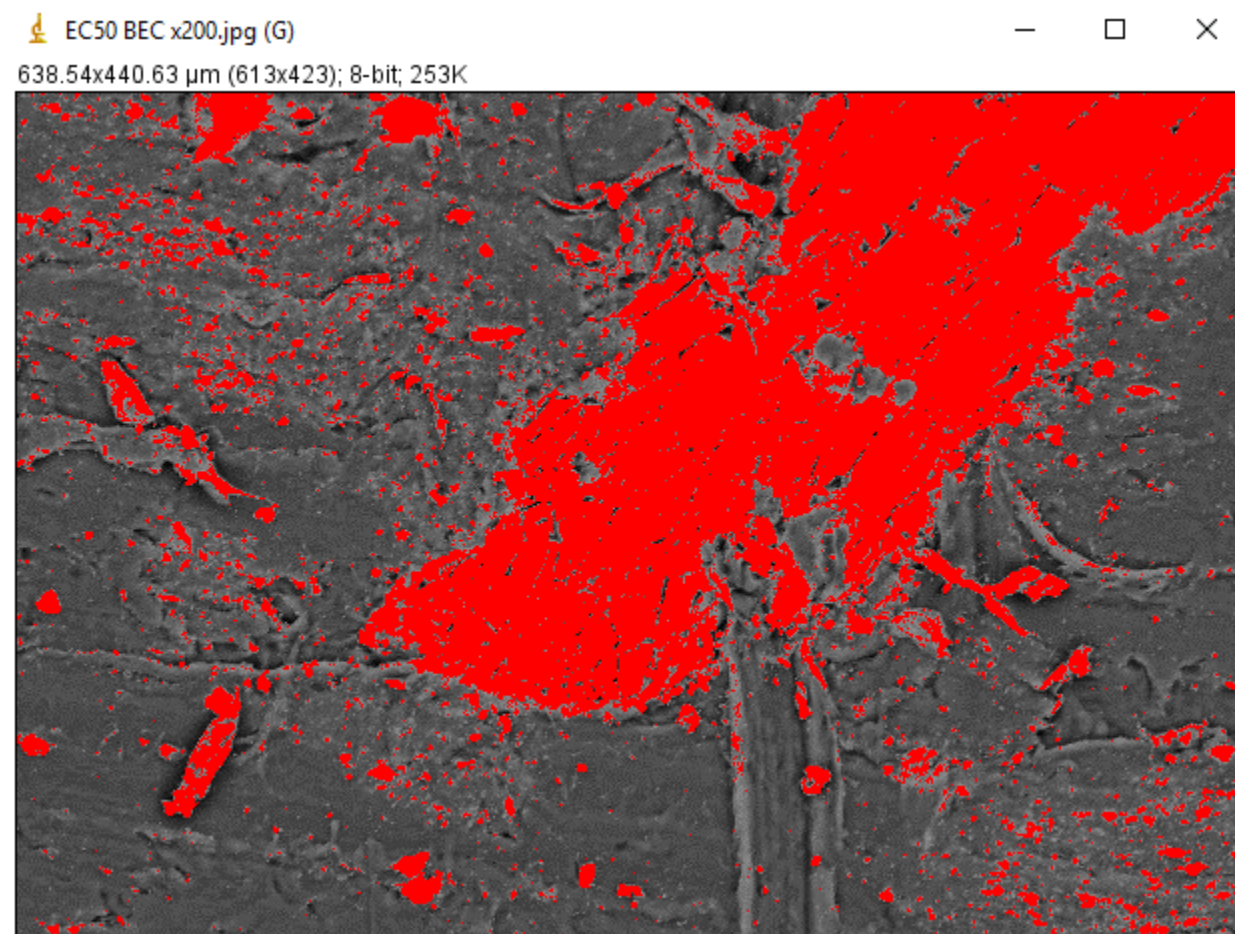
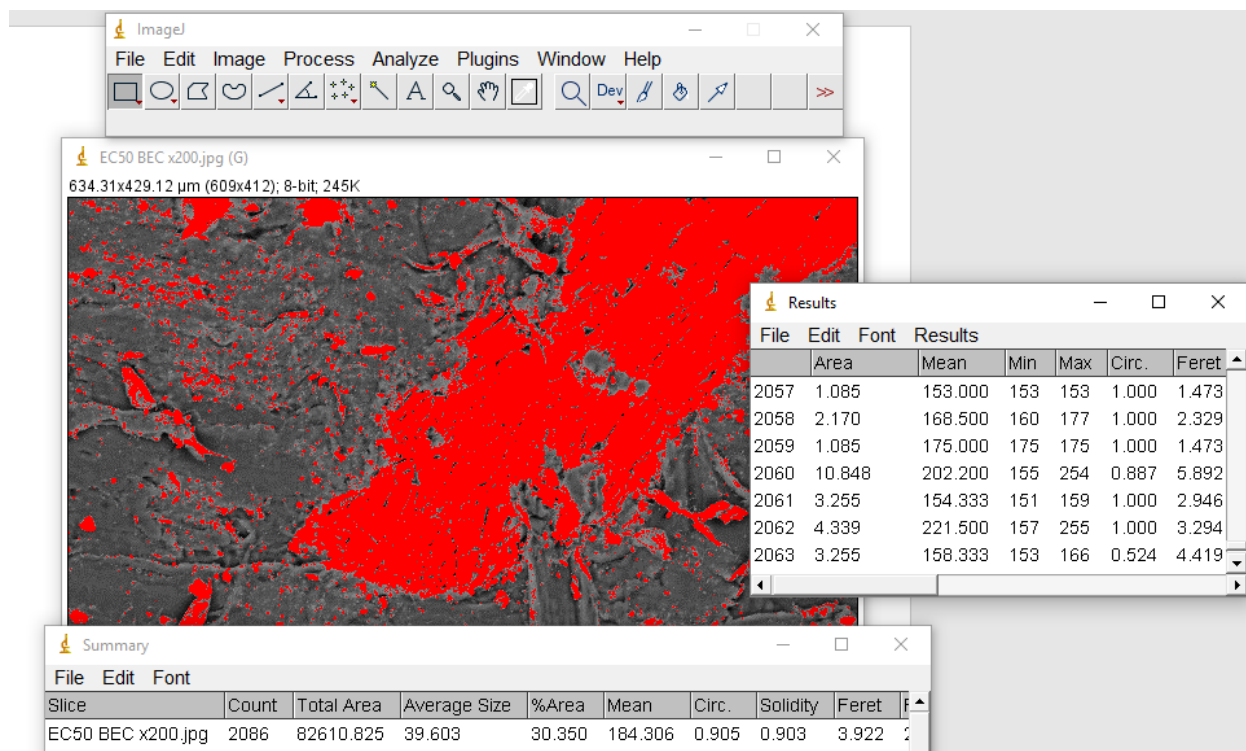
✓ Take the Analyze option from the software interface, then set measurements



- ✓ Choose Analyze option from Imagej, then particle analyze for setting the pores sizes and the output results parameters/options



- ✓ Presentation of the results from Imagej analysis and the final image colored from the software



A6) Results of tests on MPB and PWC (density, traction, compression, capillary absorption, SEM with the chemical composition of certain samples, etc.)

A6-1: COMPRESSIVE STRENGTH of MPB

Samples	Time, days	Strength MPa	Average, MPa	Standard Deviation
		5.61		
45%P – H/L 50/50	1	5.10	5.35	0.25
		5.35		
		6.62		
	3	6.62	6.62	0.00
		6.62		
		7.64		
	7	9.17	8.49	0.78
		8.66		
		8.92		
	28	8.66	8.92	0.25
		9.17		
		7.64		
50%P – H/L 40/60	1	7.54	7.52	0.13
		7.39		
		9.17		
	3	9.17	9.00	0.29
		8.66		
		12.23		
	7	11.72	11.55	0.78
		10.70		
		16.15		
	28	17.02	14.54	3.57
		10.45		
		7.13		
50%P – H/L 50/50	1	6.11	6.62	0.51
		6.62		
		7.13		
	3	10.19	8.66	1.53
		8.66		
		8.66		
	7	8.92	8.78	0.13
		8.76		

		9.58		
	28	9.27	9.55	0.26
		9.78		
		6.47		
50%P – H/L 60/40	1	6.62	6.49	0.13
		6.37		
		8.66		
	3	9.17	10.58	2.89
		13.91		
		10.19		
	7	15.54	13.91	3.23
		16.00		
		16.36		
	28	15.80	17.19	1.94
		19.40		
		8.66		
60%P – H/L 40/60	1	9.43	9.60	1.03
		10.70		
		11.21		
	3	9.68	10.53	0.78
		10.70		
		10.19		
	7	10.55	10.46	0.24
		10.65		
		10.96		
	28	9.17	10.72	1.44
		12.03		
		7.90		
60%P – H/L 50/50	1	9.17	8.58	0.64
		8.66		
		9.17		
	3	8.15	8.65	0.51
		8.61		
		9.43		
	7	8.92	9.17	0.25
		9.17		
		9.83		
	28	9.17	9.65	0.42
		9.94		

		10.45		
60%P – H/L 60/40	1	10.70	9.94	1.11
		8.66		
		9.43		
	3	10.70	10.02	0.64
		9.94		
		10.96		
	7	10.45	10.50	0.44
		10.09		
		10.70		
	28	12.28	11.06	1.09
		10.19		
		5.61		
65%P – H/L 50/50	1	7.64	7.30	1.56
		8.66		
		10.19		
	3	6.62	7.98	1.93
		7.13		
		8.66		
	7	7.64	8.48	0.76
		9.12		
		10.70		
	28	8.66	9.68	1.02
		9.68		

A6-2: Density of MPB

Samples	Time, days	Density g/cm ³	Average, g/cm ³	Standard Deviation
		2.08		
45%P – H/L 50/50	1	2.08	2.01	0.12
		1.87		
		2.01		
	3	2.25	2.14	0.12
		2.15		
		2.27		
	7	2.13	2.20	0.07
		2.22		
		2.09		

	28	2.15	2.12	0.03
		2.14		
		2.05		
50%P – H/L 40/60	1	1.96	2.14	0.24
		2.41		
		1.92		
	3	1.93	1.91	0.03
		1.88		
		1.92		
	7	1.91	1.92	0.01
		1.94		
		2.10		
	28	2.22	2.09	0.14
		1.95		
		2.00		
50%P – H/L 50/50	1	1.94	1.94	0.07
		1.87		
		2.00		
	3	2.02	2.01	0.01
		2.03		
		2.17		
	7	2.25	2.12	0.16
		1.95		
		2.14		
	28	1.92	2.04	0.11
		2.05		
		1.89		
50%P – H/L 60/40	1	1.89	1.90	0.01
		1.90		
		1.86		
	3	1.89	1.96	0.14
		2.12		
		2.00		
	7	2.07	2.05	0.04
		2.07		
		2.21		
	28	2.12	2.07	0.17
		1.88		
		1.82		

60%P – H/L 40/60	1	1.80	1.83	0.05
		1.89		
		1.82		
	3	1.83	1.83	0.01
		1.84		
		1.76		
	7	2.10	2.03	0.24
		2.23		
		1.93		
	28	1.86	2.02	0.22
		2.27		
		1.90		
60%P – H/L 50/50	1	1.87	1.89	0.02
		1.89		
		1.94		
	3	1.95	1.99	0.07
		2.07		
		1.85		
	7	1.85	1.93	0.14
		2.10		
		2.20		
	28	1.78	2.03	0.22
		2.10		
		1.75		
60%P – H/L 60/40	1	1.74	1.76	0.04
		1.81		
		1.81		
	3	2.18	1.97	0.19
		1.93		
		1.83		
	7	1.89	1.89	0.06
		1.95		
		1.80		
	28	2.05	1.93	0.13
		1.95		
		1.87		
65%P – H/L 50/50	1	1.76	1.79	0.06
		1.76		

		1.78		
	3	1.85	1.82	0.04
		1.84		
		1.78		
	7	1.86	1.80	0.04
		1.77		
		1.87		
	28	2.01	1.95	0.07
		1.97		

A 6-3: Split tensile strength of MPB

Samples	Time, days	Split tensile strength , MPa	Average, MPa	Standard Deviation
		2.52		
50%P – H/L 40/60	1	2.41	2.41	0.11
		2.31		
		2.32		
	3	2.42	2.42	0.10
		2.51		
		3.53		
	7	3.48	3.48	0.05
		3.43		
		3.77		
	28	3.63	3.63	0.13
		3.50		
		1.40		
50%P – H/L 50/50	1	1.45	1.45	0.04
		1.49		
		1.81		
	3	1.86	1.86	0.05
		1.91		
		2.24		
	7	2.31	2.31	0.07
		2.38		
		2.78		
	28	2.81	2.81	0.03
		2.83		
		3.22		

50%P – H/L 60/40	1	3.17	3.17	0.05
		3.12		
		3.17		
	3	3.81	3.49	0.32
		3.48		
		4.08		
	7	4.45	4.26	0.18
		4.25		
		4.46		
	28	4.68	4.56	0.11
		4.54		
		2.68		
60%P – H/L 40/60	1	2.80	2.80	0.12
		2.92		
		2.80		
	3	2.89	2.89	0.08
		2.97		
		2.93		
	7	2.93	2.93	0.01
		2.92		
		3.36		
	28	3.10	3.23	0.13
		3.22		
		1.61		
60%P – H/L 50/50	1	1.53	1.53	0.08
		1.45		
		1.69		
	3	1.66	1.66	0.03
		1.64		
		1.72		
	7	1.67	1.67	0.04
		1.63		
		1.64		
	28	1.71	1.71	0.06
		1.77		
		2.29		
60%P – H/L 60/40	1	2.22	2.22	0.08
		2.14		

		2.36		
	3	2.42	2.42	0.06
		2.47		
		2.78		
	7	2.89	2.89	0.11
		2.99		
		2.90		
	28	3.22	3.22	0.31
		3.53		

A 6-4: COMPRESSIVE STRENGTH of PWC

Samples	Time, days	Strength MPA	Average, MPA	Standard Deviation
		10.85		
PWC50	1	10.50	10.85	0.36
		11.21		
		11.11		
	3	10.96	11.11	0.15
		11.26		
		12.54		
	7	12.18	12.54	0.36
		12.89		
		13.91		
	28	13.81	13.86	0.05
		13.86		
		12.89		
PWC60	1	12.54	12.89	0.36
		13.25		
		13.50		
	3	13.35	13.50	0.15
		13.66		
		14.83		
	7	14.73	14.83	0.10
		14.93		
		14.27		
	28	16.05	15.15	0.89
		15.13		

A6-5: Density of PWC

Samples	Time, days	Density g/cm ³	Average, g/cm ³	Standard Deviation
		2.25		
PWC 50	1	2.23	2.25	0.03
		2.29		
		2.24		
	3	2.25	2.24	0.02
		2.22		
		2.27		
	7	2.26	2.27	0.01
		2.28		
		2.26		
	28	2.25	2.26	0.01
		2.26		
		2.16		
PWC 60	1	2.18	2.16	0.02
		2.13		
		2.15		
	3	2.15	2.15	0.00
		2.15		
		2.15		
	7	2.13	2.15	0.02
		2.17		
		2.04		
	28	2.14	2.09	0.05
		2.09		

A 6-6: Split tensile strength of PWC

Samples	Time, days	Split tensile strength, MPa	Average MPa	Standard Deviation
		1.94		
PWC 50	1	1.97	1.94	0.04
		1.90		
		2.68		
	3	2.65	2.68	0.03
		2.71		
		2.74		
	7	2.69	2.74	0.06
		2.80		

		3.55		
	28	3.52	3.55	0.04
		3.59		
		2.88		
PWC 60	1	2.92	2.88	0.03
		2.85		
		2.96		
	3	2.97	2.96	0.01
		2.96		
		3.68		
	7	3.71	3.68	0.03
		3.66		
		4.08		
	28	4.05	4.08	0.03
		4.11		