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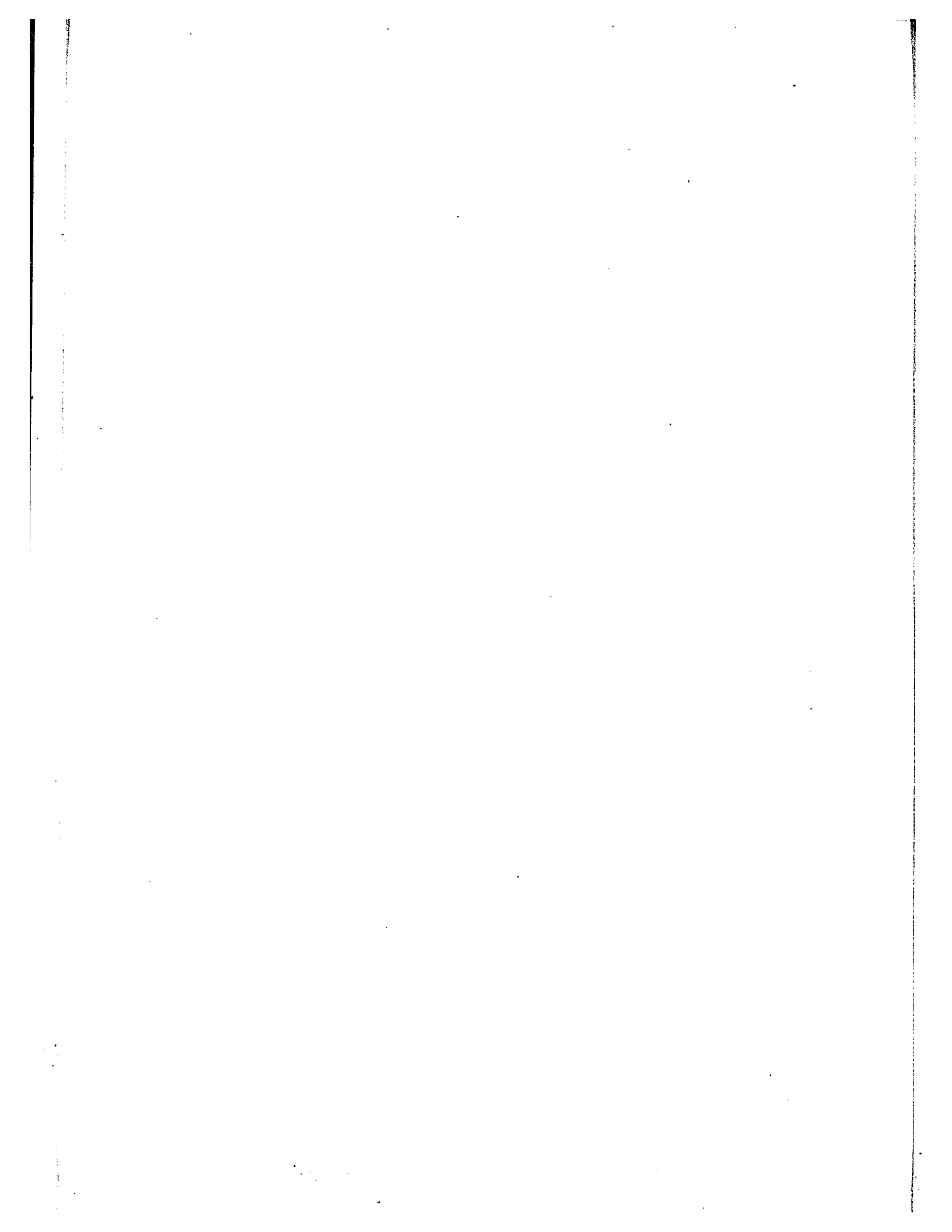
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A STUDY ON THE EFFECT OF CASTING AND CURING TEMPERATURE ON
THE
MECHANICAL PROPERTIES OF CONCRETE

by

Fak-Lok Sau

A thesis
presented to the University of Ottawa
in partial fulfillment of the
requirements for the degree of
Master of Engineering
in
Civil Engineering

OTTAWA, Ontario, 1984

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ABSTRACT

Conventional winter concreting practice in Canada recommends concrete to be mixed and placed at 10°C or above and be cured for seven days (not necessarily consecutive) at which the air temperature is above 10°C. However, construction of offshore Arctic structures will usually take place at temperatures close to that of the sea at approximately 0 to 4°C; and hence information on the influence of temperature during mixing, placing and curing on the development of concrete strength is essential. Previous research has shown conflicting results on the effect of casting and curing temperature. Since the economic benefits of being able to place and cure concrete at low temperature without any strength penalty are significant, this study was undertaken to examine the effect of casting and curing temperature on the mechanical properties of concrete.

Standard concrete cylinders made of type 10 Portland cement were cured extensively at 0°C, 16°C and 45°C after holding the specimens at various casting temperatures for 3 to 12 hours to separate the effect of casting temperature and curing temperature. Concrete prisms were also cast and cured at 0°C, 16°C and 45°C to determine

the dynamic modulus of elasticity. The tests on compressive strength, indirect tensile strength, static and dynamic modulus of elasticity were carried out at the ages of 3, 7, 14, 28 and 90 days.

In general, the compressive strength increased with increasing time and decreasing water-cement ratio. The lower the water-cement ratio, the faster the concrete gained its strength. The effect of temperature on the strength development was found to be depended upon the water-cement ratio of the concrete. The study showed that casting and curing at 0°C or 45°C would not damage the concrete strength but conversely increased the strength if the water-cement ratio was kept below 0.35. Concrete cast and cured several hours at 0°C or 45°C and subsequently cured at 16°C received no damage but benefits to its strength providing water-cement ratio was as low as 0.45. However, extreme casting or curing temperature should be discouraged for water-cement ratio above 0.55.

Tensile strength, static and dynamic modulus of elasticity increased with increasing compressive strength but at a different rates depending on the casting and curing temperature. Tensile strength, static and dynamic modulus of elasticity were related to the power of 0.60, 0.65 and 0.31 of the cylinder strength, respectively.

ACKNOWLEDGEMENTS

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Chapter I

INTRODUCTION

Concrete is by far the most versatile construction material in the building industry and in related structural construction. Besides its low material cost, low thermal conductivity and its capability to mold into various shapes, its high resistance to corrosion and abrasion make it superior to steel, ceramics and timber. In addition, its ability to resist intense local pressure and its non-brittle behaviour at low temperature also gives it an expanding role in the construction of offshore Arctic structures. However, the performance of concrete is very dependent on various stages starting from the manufacturing of cement to the mixing and placing of the fresh concrete and to the curing environment. Either one of these could drastically affect the strength and serviceability of the concrete. Although improved construction practices and techniques have added greatly to the ability to produce good concrete, it is the responsibility of those in charge of construction work to become familiar with these practices and techniques and to make sure that they are being used effectively. However, the continuous efforts to explore and develop new concrete that has more strength, more workability, more durability

and concrete that is more economical to produce rest on the shoulders of many concrete researchers. The capability of concrete is limited only by the ingenuity and imagination of engineers and researchers.

In addition, the recent rapid development of the Arctic mineral and hydrocarbon resources will need significantly large civil engineering infrastructures for docks, platforms and foundations which are usually constructed in reinforced concrete. Conventional wisdom is that concrete should be mixed and placed at temperatures of 10°C or above depending on the dimension of the concrete element and cured for seven days (not necessarily consecutive) at which the air temperature is above 10°C. Moreover, winter concreting in Canada⁽¹⁾ has identified three important stages in winter protection and curing: concrete should attain sufficient initial strength (7-10 MPa) to protect against early frost damage, concrete should then attain sufficient strength to support its own weight and the construction loads, and finally, concrete should be properly cured to reach its specified strength and for better durability. However, Arctic construction in the sea will usually take place at temperature close to that of the sea at approximately 0 to 4°C; and hence the information on the influence of temperature during mixing, placing and curing on the development of concrete strength is essential.

1.1 SCOPE

The aim of this study is to provide a better understanding of the effect of temperature on the mechanical properties of concrete. Attention is drawn to the casting and initial curing temperature which are believed to have significant effects on the concrete strength in its early age and in its long term performance. Research and development on this subject is essential if more specific guidance is to be provided in the future. At the present^t stage, guidance in these areas is mostly confined to the advice from various sources ranging from the cement manufacturer to the Code regulatory committee. Some of these information sources are Portland Cement Association, American Concrete Institute, American Society for Testing Materials and Canadian Standard Association. Guidelines are provided for selecting proper concrete materials, mixing and placing of the concrete, and the curing environments in order to ensure a satisfactory concrete performance at adverse temperature condition. Previous researches have generally indicated that concrete which mixed, placed and cured under low temperature attained higher ultimate strength in spite of its low initial strength. While on the other hand, concrete that cast and cured at elevated temperature has a higher initial strength but a lower ultimate strength. However, knowledge on this subject is still limited and in many cases, the lack of certainty makes

it necessary to recommend further research to explore and explain some of the uncertainties.

Considerable information on the compressive strength development under varying temperature conditions is available. This information indicates that the compressive strength can be predicted if the curing history, in terms of temperature and age, is known. However, other mechanical properties of concrete such as tensile strength and stiffness at early age and the durability of concrete under varying curing conditions are still not fully understood. It is well established that all concrete properties increase with an increase in compressive strength and it is usually assumed that they are related to some empirical functions of the compressive strength. In North America, common practice is to relate these strength parameters to the square root of the compressive strength. However, there are no substantial facts to reinforce this assumption especially when the concrete is exposed to adverse temperature conditions at early age. This information is needed for the construction industry in determining the appropriate shoring methods and time to strip the formworks in Arctic construction. Therefore, this study also examined the relationship between the compressive strength and other mechanical properties and to examine the validity of the common assumptions.

1.2 BACKGROUND

Early research by Price⁽²⁾ showed that concrete mixed, placed and cured at low temperature developed strength at a significantly slower rate than at room temperature; while on the other hand, the highest mixing, placing and curing temperature developed the highest 28-day strength. For instance, concrete specimens that were mixed, placed and cured at 4°C had a 28-day compressive strength 22 percent lower than the specimens that were cast and continuously cured at 21°C as shown in figure 1.1. Concrete specimens that were cast and cured at 46°C developed a 28-day strength 5 percent higher than those cast and cured at 21°C. Price also investigated the effect of initial temperature on the strength of concrete. He tested the specimens which cured at 21°C after holding the specimens at various casting temperatures for two hours and the results indicated that concrete attained slightly higher ultimate strength if it was mixed and placed at low temperature and subsequently cured at normal temperature. The specimens that were mixed, placed and cured continuously at 21°C has a 28-day compressive strength of 33 MPa while the specimens that were cast and initially cured at 4°C for two hours and subsequently cured at 21°C has a 28-day compressive strength of 36 MPa which is 10 percent higher as shown in figure 1.2. By studying these test results, it could be concluded that it was the curing temperature rather than the casting temperature that was responsible for the strength variation.

Klieger⁽³⁾ also investigated the significance of the casting and curing temperature on strength development. He tested concrete specimens that were mixed, placed and cured at the same temperature. The 28-day compressive strength of the specimens that were mixed, placed and cured at 4°C was about 20 percent lower than the specimens that were mixed, placed and cured at 23°C. In addition, the specimens that were mixed and placed at 4°C and then immediately transferred and continuously cured at -4°C had a 28-day compressive strength 30 percent lower than the specimens that were mixed and continuously cured at 23°C, as shown in figure 1.3. Therefore, Klieger's results gave the same conclusion that it was the low curing temperature responsible for the strength reduction.

In contrast, more recent work by Gardner and Poon⁽⁴⁾, Aitchin and Finsonneault⁽⁵⁾ lead to a different conclusion. Gardner and Poon cast concrete specimens at 22°C, cured at 22°C for a defined time and then continued curing at 2°C. The test results from these specimens have indicated that the 28-day compressive strengths were practically the same as shown in figure 1.4. Moreover, these compressive strengths were slightly higher than the 28-day strength of the specimens that were cast and cured at 22°C. This implied that the low curing temperature has no detrimental effect to the strength of concrete except it was the casting and initial curing temperature that has played an important role.

A similar work was done by Aitchin and Pinsoaneault. They tested the concrete specimens which were cast at uncontrolled temperature, cured at 4°C for a defined time and then continued curing at 0°C . The results shown in figure 1.5 have indicated that the longer the concrete was kept at 4°C before being exposed to 0°C , the lesser the influence on the relative 28-day strength.

The economic benefits of being able to place and cure concrete at low temperature without any strength penalty are significant. Therefore, it is necessary to verify the difference in conclusions amongst the earlier and more recent researchers.

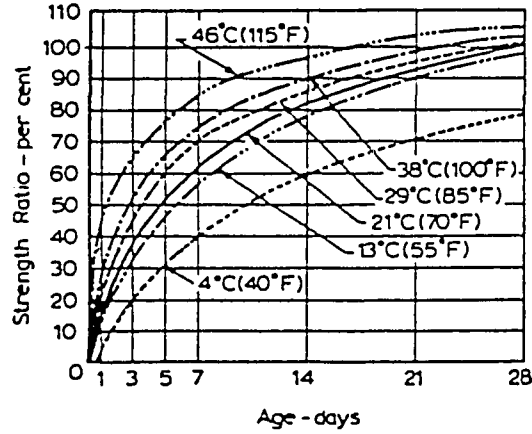


FIGURE 1.1 : DEVELOPMENT OF CONCRETE STRENGTH WITH TIME⁽²⁾
(W/C is 0.5, Cast/Cured at indicated temperature)

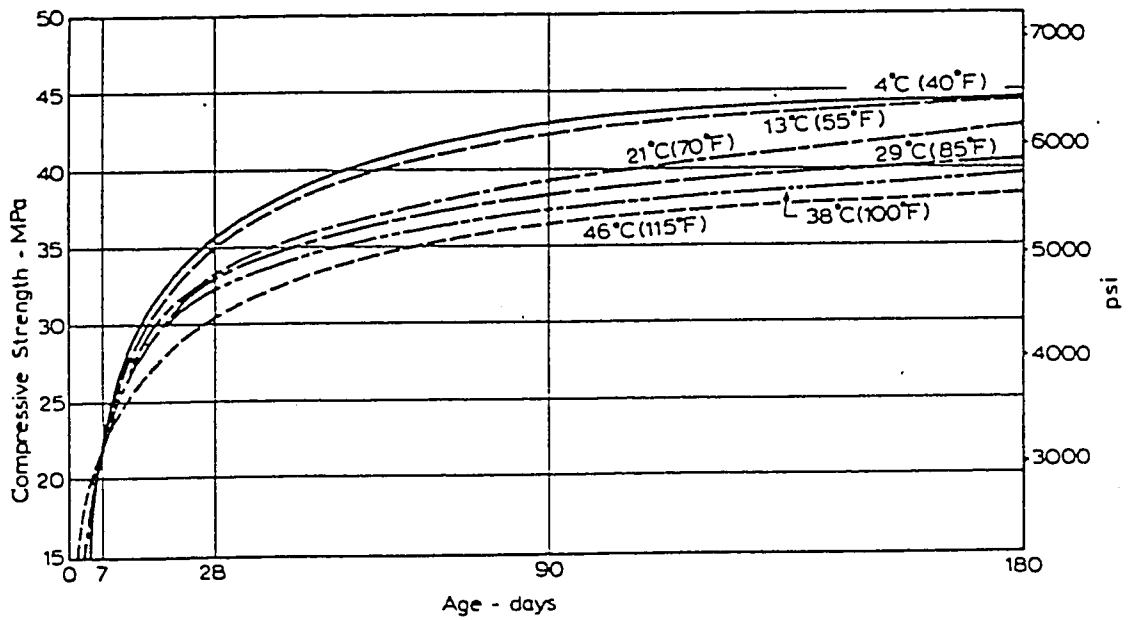


FIGURE 1.2 : STRENGTH OF CONCRETE WITH EXTENDED CURING AT 21°C⁽²⁾
(W/C is 0.5, Cast/Cured 2 hours at indicated temperature)

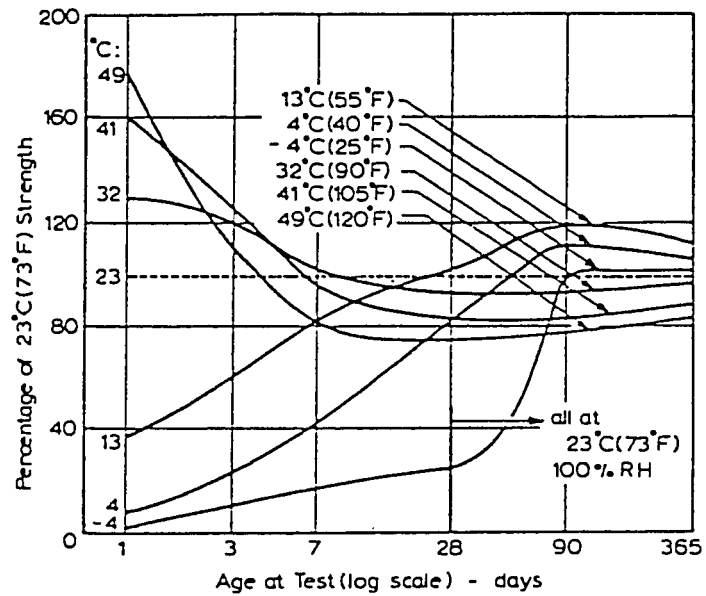


FIGURE 1.3 : EFFECT OF TEMPERATURE ON THE STRENGTH OF CONCRETE⁽³⁾
 (Cast/Cured at indicated temperature)
 (Specimens cured at -4°C were casted at 4°C)

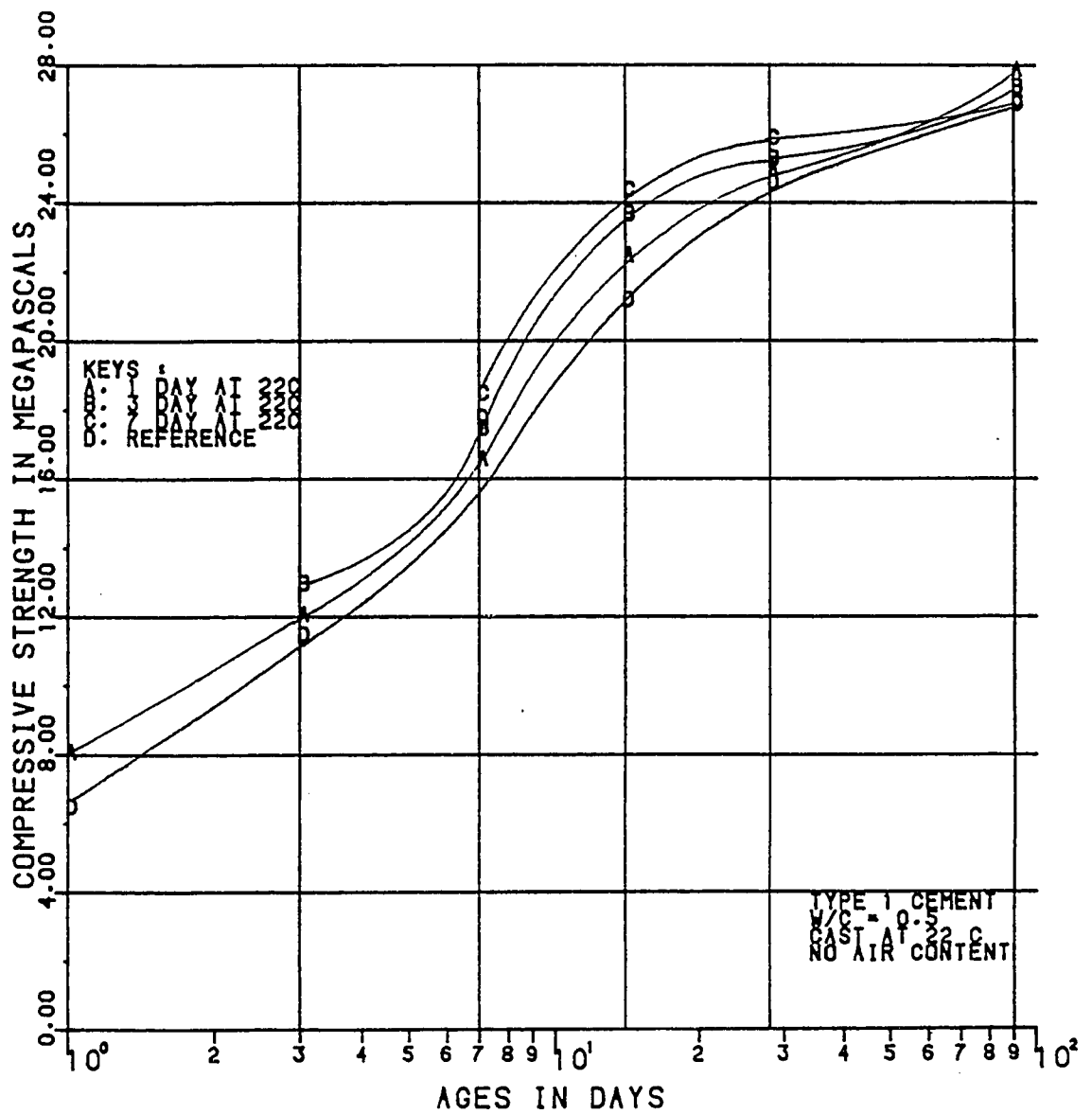


FIGURE 1.4 : STRENGTH OF CONCRETE WITH CURING TEMPERATURE 2°C (a)

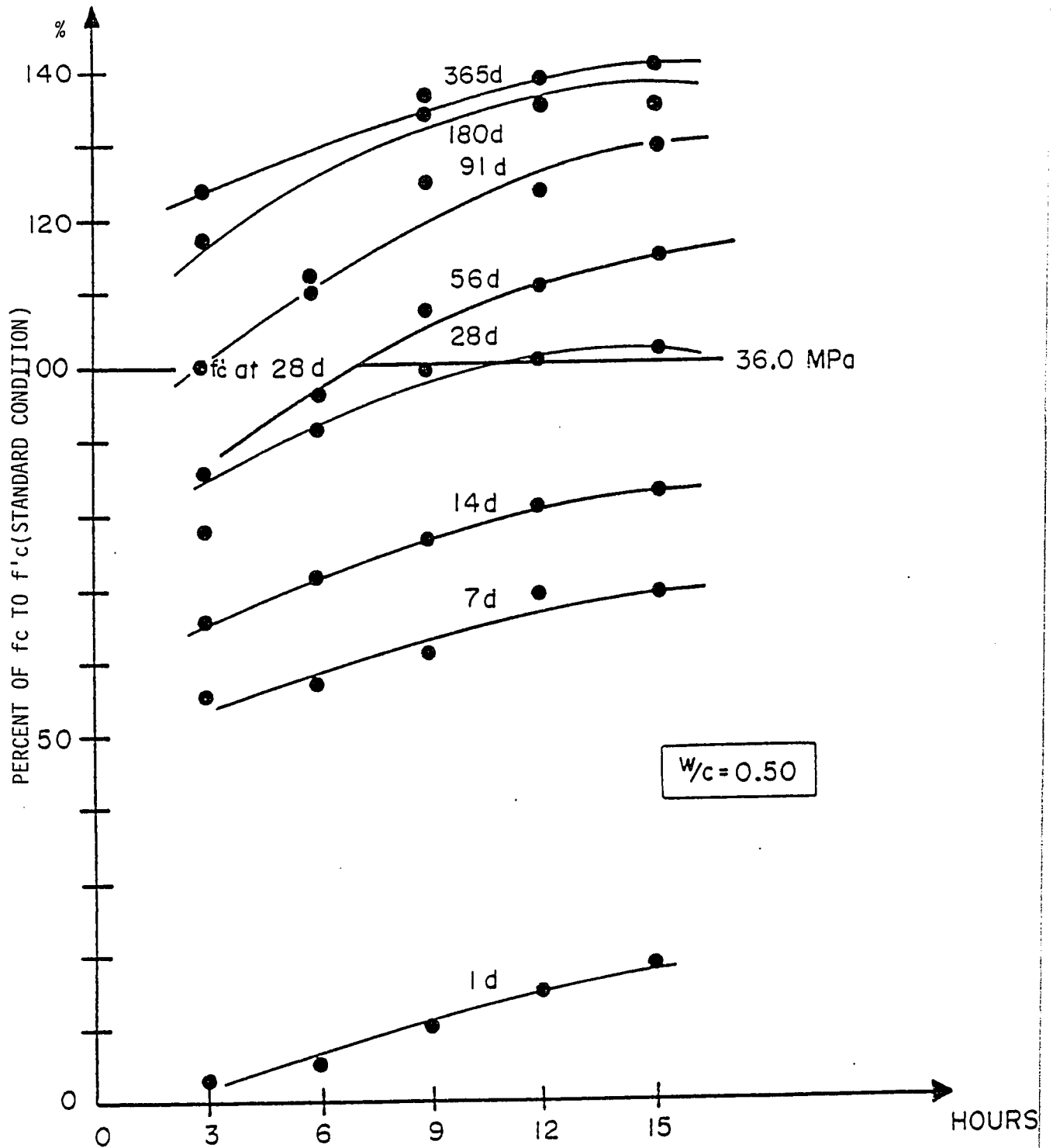


FIGURE 1.5 : CONCRETE STRENGTH WITH EXTENDED CURING AT 0°C ⁽⁵⁾
 (Cast/Cured at 4°C for the indicated duration)

Chapter II

HYDRATION PROCESS OF PORTLAND CEMENT

It is well established that concrete gains strength through hydration. However, this hydration process which is essentially a series of chemical reactions amongst the cement constituents is sensitive to temperature. At low temperature, the chemical reaction is retarded and hence the rate of strength development is slower than at elevated temperature. Early research^(*) has indicated that hardened concrete continued to gain strength at a temperature as low as -12°C . To examine this temperature effect, knowledge on the cement compositions and their hydration processes is essential.

2.1 CHEMICAL COMPOSITIONS OF PORTLAND CEMENT

The chemical compositions of an ordinary Portland cement can be considered as comprising four major compounds namely tricalcium silicate, dicalcium silicate, tricalcium aluminate and tetracalcium aluminoferrite. Amongst these, the two calcium silicates, which account for almost three-quarters by weight of the cement, are the main constituents related to strength contribution. Tricalcium silicate reacts with water fairly rapidly forming silicate hydrates and

calcium hydroxides. It hardens rapidly and is largely responsible for the initial setting and the high early strength of the concrete. Dicalcium silicate is also responsible for the strength development; but because of its low steady reaction rate, the strength contribution comes in rather late, normally at ages beyond one week. Tricalcium aluminate is the most reactive compound which reacts with water violently and liberates vast amount of heat during reaction; but it contributes little to strength. The same is also true for tetracalcium aluminoferrite. It contributes very little strength; however, this compound is essential in the cement manufacturing process rather than in the hydration process.

In brief, when water is first added to the cement, a violent dissolution and reaction of the cement compounds begin to take place. This lasts for several minutes before it enters the dormant period. In the dormant period, the dissolution and reaction proceed at a very slow rate. The cement grains slowly build up the initial coating of reaction products. It is this dormant period which lasts for several hours, usually 2 to 3 hours, enabling the fresh concrete to remain in a plastic condition. This is essential for the construction industry because it allows fresh concrete to be transported and placed into forms. The rupture of the initial gel coating on the crystals of the tricalcium silicate compound enables water to react with a

fresh reactive surface of tricalcium silicate; a progressive process of breakup and resealing is postulated, resulting finally in the formation of calcium silicate gel of sufficient amount that the paste begins to exhibit increasing rigidity. This activity lasts for about 6 hours before the process of hardening begins.

2.2 EFFECT OF TEMPERATURE ON PORTLAND CEMENT

Hydration is an exothermic process. By measuring the amount of heat evolved at a period of time, the rate of hydration can be determined. However, it is not easy to examine microscopically the effect of temperature on the hydration process; it requires precision instruments and representative samples. In addition, the temperature effects on pure tricalcium silicate or dicalcium silicate, etc., cannot fully represent the actual behaviour of the cement because the interaction amongst the cement compounds is also important. However, this does provide some information on the temperature sensitivity of each individual component. Perhaps, the best way is to examine specimens made of various types of Portland cements. In this way, the significance of each cement compound in the concrete as influenced by the temperature could be studied by comparing the results and the relative amount of each cement compound in that particular type of Portland cement. But in view of large quantity of specimens required in this project, only type 10 Ordinary Portland Cement is used.

There is evidence⁽⁷⁾ that the hydration of cement is retarded at low temperature. As shown in figure 2.1, the heat evolved from hydration over the first 3 days at 0°C dropped 60 percent comparing to hydration at 20°C. This could explain why concrete has a low initial strength while cured at low temperature. On the other hand, the heat evolved from hydration at 50°C increased 25 percent comparing to 20°C. Copeland and Kantro⁽⁸⁾ illustrated the effect of temperature on the hydration of tricalcium silicate. Tricalcium silicate is important because it is largely responsible for the high early strength of the concrete. From figure 2.2, it could be seen that the hydration of tricalcium silicate was very sensitive to low temperatures at the first 24 hours after mixing with water and this temperature effect drastically reduced at age beyond 24 hours. From the same figure, it could also be seen that tricalcium silicate was less affected by high temperature. In contrast, dicalcium silicate is very much sensitive to high temperature. Verbeck⁽⁹⁾ studied the cement hydration reactions at early ages and his results indicated that dicalcium silicate was sensitive to both high and low temperature as shown in figure 2.3. During the first 24 hours after mixing with water, the dicalcium silicate specimens which were cured at 50°C showed a 100 percent increase in hydration comparing to specimens cured at 24°C. Furthermore, the amount of dicalcium silicate hydrated at

4°C during the first 28 days decreased 60 percent comparing to those at 24°C.

Unfortunately, there is no available information on the effect of temperature on the hydration of mixed compounds. However, the hydration of pure compound as described earlier does provide some information on the temperature sensitivity of each individual compound.

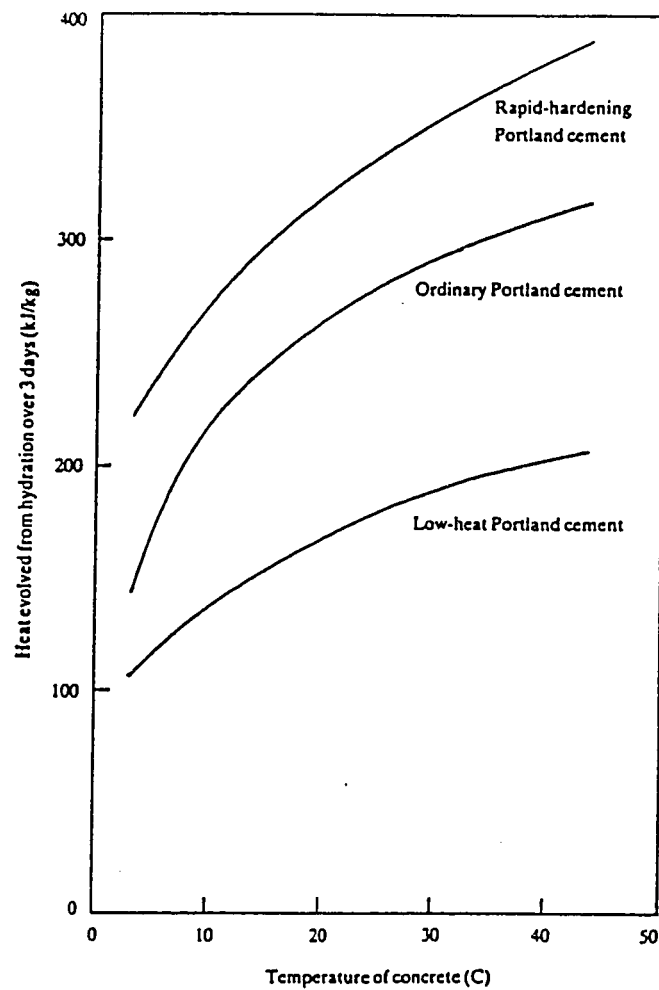


FIGURE 2.1 : EFFECT OF TEMPERATURE ON THE HYDRATION OF CEMENT⁽⁷⁾

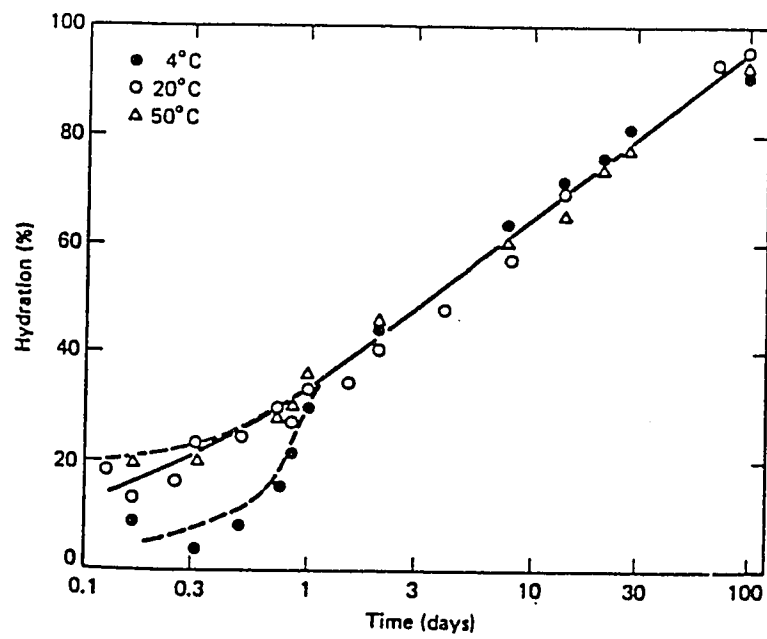


FIGURE 2.2 : EFFECT OF TEMPERATURE ON TRICALCIUM SILICATE⁽⁸⁾

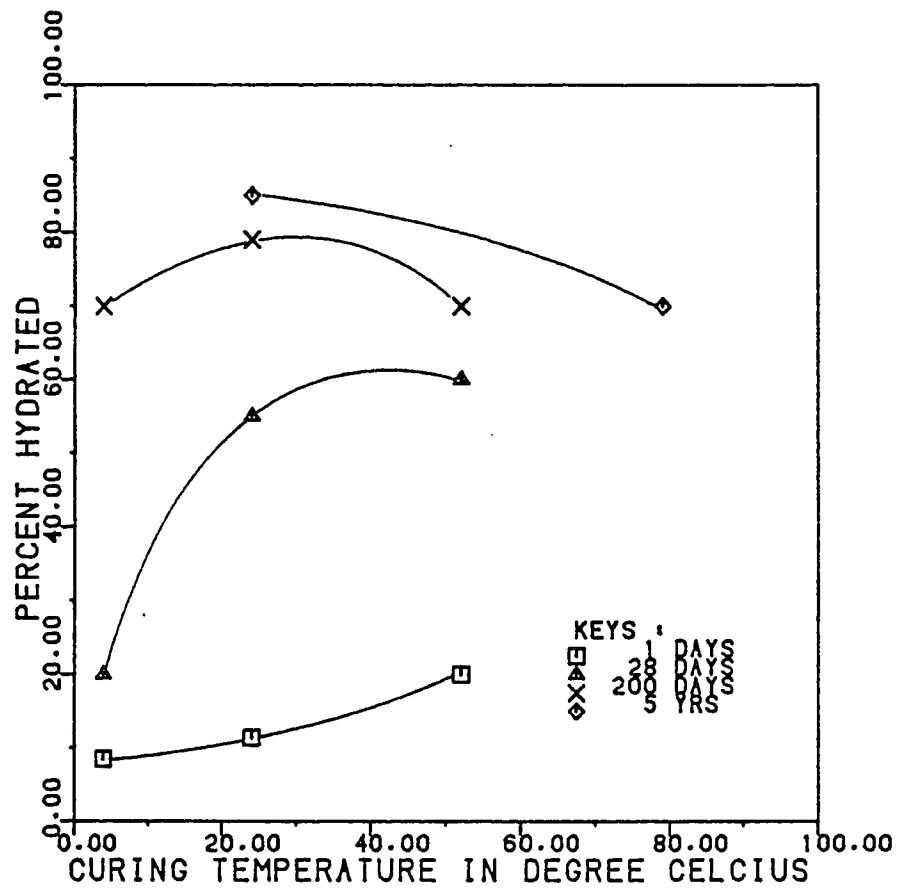


FIGURE 2.3 : HYDRATION OF DICALCIUM SILICATE WITH TIME & TEMPERATURE (9)

Chapter III

EXPERIMENTAL WORK

Since the purpose of this study was to investigate the effect of casting and initial curing temperature on the strength and stiffness properties of the concrete, the type of specimens and tests were chosen to be as representative as possible. Crushing strength, tensile strength, stiffness and durability of the concrete were measured at varying ages after casting. The dynamic modulus of elasticity was chosen as a means of determining the durability of the concrete. However, because of time limitations, this report included only the test results up to 90 days. The tests on compressive strength and tensile strength were carried out using standard 150mm x 300mm concrete cylinders cast in single-use plastic molds. The plastic cylinder molds were supplied by M&L Testing Equipment Company Limited, Hamilton. For the test of dynamic modulus of elasticity, 75mm x 75mm x 300mm prisms were cast using reusable metal molds.

A total of nine series of specimens, three cast at 0°C, three cast at 16°C, and the remaining three cast at 45°C, were made using type 10 Ordinary Portland Cement. Each three series of specimens were cast with water-cement ratio of 0.35, 0.45, and 0.55, respectively. To examine the

significance of casting and initial curing temperature on the concrete, some of the compression test cylindrical specimens were later removed to another curing environments. The descriptions are as follow:-

1. Series one had a total of seventy-eight 150mm x 300mm cylinders and two 75mm x 75mm x 300mm prisms having a water-cement ratio of 0.35. The casting temperature was 0°C. Thirty-six of these cylinders were later cured at elevated temperatures; twelve cured at 16°C after a 3-hour delay, twelve cured at 16°C after a 12-hour delay and the remaining twelve cured at 45°C after a 3-hour delay at casting temperature. The rest of the specimens were then cured at 0°C.
2. Series two was essentially the same as series one except the water-cement ratio was 0.45.
3. Series three was essentially the same as series one except the water-cement ratio was 0.55.
4. Series four had a total of seventy-eight cylinders and two prisms having a water-cement ratio of 0.35. The casting temperature was 16°C. Thirty-six cylinders were later removed to another curing environment; twelve cured at 0°C after a 3-hour delay, twelve cured at 0°C after a 12-hour delay, and the remaining twelve cured at 45°C after a 3-hour delay at 16°C. The rest of the specimens were then cured at 16°C.

5. Series five was essentially the same as series four except the water-cement ratio was 0.45.
6. Series six was essentially the same as series four except the water-cement ratio was 0.55.
7. Series seven had a total of sixty-six cylinders and two prisms having a water-cement ratio of 0.35. The casting temperature was 45°C. Twelve cylinders were later cured at 0°C after a 3-hour delay and twelve cylinders cured at 16°C after a 3-hour delay at 45°C. The rest of the specimens were then cured at 45°C.
8. Series eight was essentially the same as series seven except the water-cement ratio was 0.45.
9. Series nine was essentially the same as series seven except the water-cement ratio was 0.55.

The tests on compressive strength, tensile strength, static and dynamic modulus of elasticity were made on specimens cured at the casting temperature. The various casting temperatures were 0°C, 16°C and 45°C, and the specimens were tested at ages of 3, 7, 14, 28, 90, 180 and 360 days after casting. For the cylindrical specimens which cured at a temperature different from casting, only compressive strengths were measured and the test ages were 7, 28, 90 and 360 days, respectively. A total of 666 concrete cylinders and 18 concrete prisms were cast.

3.1 MATERIALS

Natural sand and crushed limestone were supplied locally by Dufferin Concrete Products, Ottawa. Material testing was carried out following the guidelines recommended by ASTM⁽¹⁰⁾ and CSA⁽¹¹⁾ standards. The gradings and physical properties of the aggregates were given in figures 3.1, 3.2, and tables 3.1, 3.2 and 3.3. The coarse aggregate used in this project was a combination of two aggregate sizes (14mm and 20mm), in order to meet the grading requirements of CSA standards. The type 10 Ordinary Portland Cement was a product of Canada Cement Lafarge Limited.

3.2 CASTING PROCEDURE

Two properly insulated rooms were borrowed from the Department of Mechanical Engineering, University of Ottawa. One refrigeration unit with the addition of a backup unit was installed and the room temperature was adjusted to 0°C. An electric furnace was installed to the other room in which the temperature was adjusted to 45°C. The cement, aggregates and water were stored at the required temperature prior to casting.

A small concrete mixer having a volume capacity of 0.035 cubic meters was purchased for the purpose of this project. The mixing drum which was driven by a 0.5 horsepower motor was inclined at an angle of 30°, rotating at a speed of 23 revolutions per minute. However, in order

to ensure a proper concrete mix, the mixing volume was reduced to 0.032 cubic meters. The air entraining admixture and superplasticizers were first mixed with the water before it was added to the mix. The mixing regime was three minute initial mixing followed by a two minute rest and the concrete was then remixed again for a duration of two minute before it was dumped into a flat pan. Each batch contained sufficient concrete to cast six standard cylinders. Slump, air content by the pressure method, and concrete temperature were measured immediately after mixing. Roding was used to consolidate the freshly mixed concrete. Slump (ASTM C143) was found varying from 60mm to 68mm and the air content (ASTM C231) varied from 5% to 6%. The temperature of the fresh concrete was measured by inserting a thermometer into the mix. The mix proportions and the properties of the fresh concrete were listed in tables 3.4, 3.5 and 3.6.

For concrete that was cast at 0°C or 45°C, three extra cylinders were made in which thermocouples were installed so that the curing temperature history of the specimens could be traced. These temperature were monitored by an Electronik 15* Strip Chart Multipoint Recorder, a product of Honeywell Controls Limited.

3.3 CURING PROCEDURE

After filling, the molds were covered by a polyethylene sheet to minimize evaporation. Special cautions were taken for the specimens that were cast at 45°C. A combination of wet burlap and polyethylene sheet was used to cover the molds and the burlap was wetted every 12 hours. The molds were left undisturbed for a period of 24 to 48 hours prior to stripping. The specimens in the cold room took a longer period to attain sufficient stiffness to allow stripping without damaging the specimens. This usually took 48 hours.

In the cold room, the specimens received further curing in several large galvanized steel tanks filled with salt water. The salt water was made by diluting 35 grams of commercial deicing salt in every liter of fresh water. The chemical constituents of the deicing salt was given in table 3.7. A similar curing environment was provided in the hot room except the specimens were cured in hot fresh water rather than salt water. The specimens that were cured at room temperature were stored in a fog chamber where specimens were continuously kept moist by water spraying. The temperature inside the chamber was also monitored.

3.4 STRENGTH TESTS

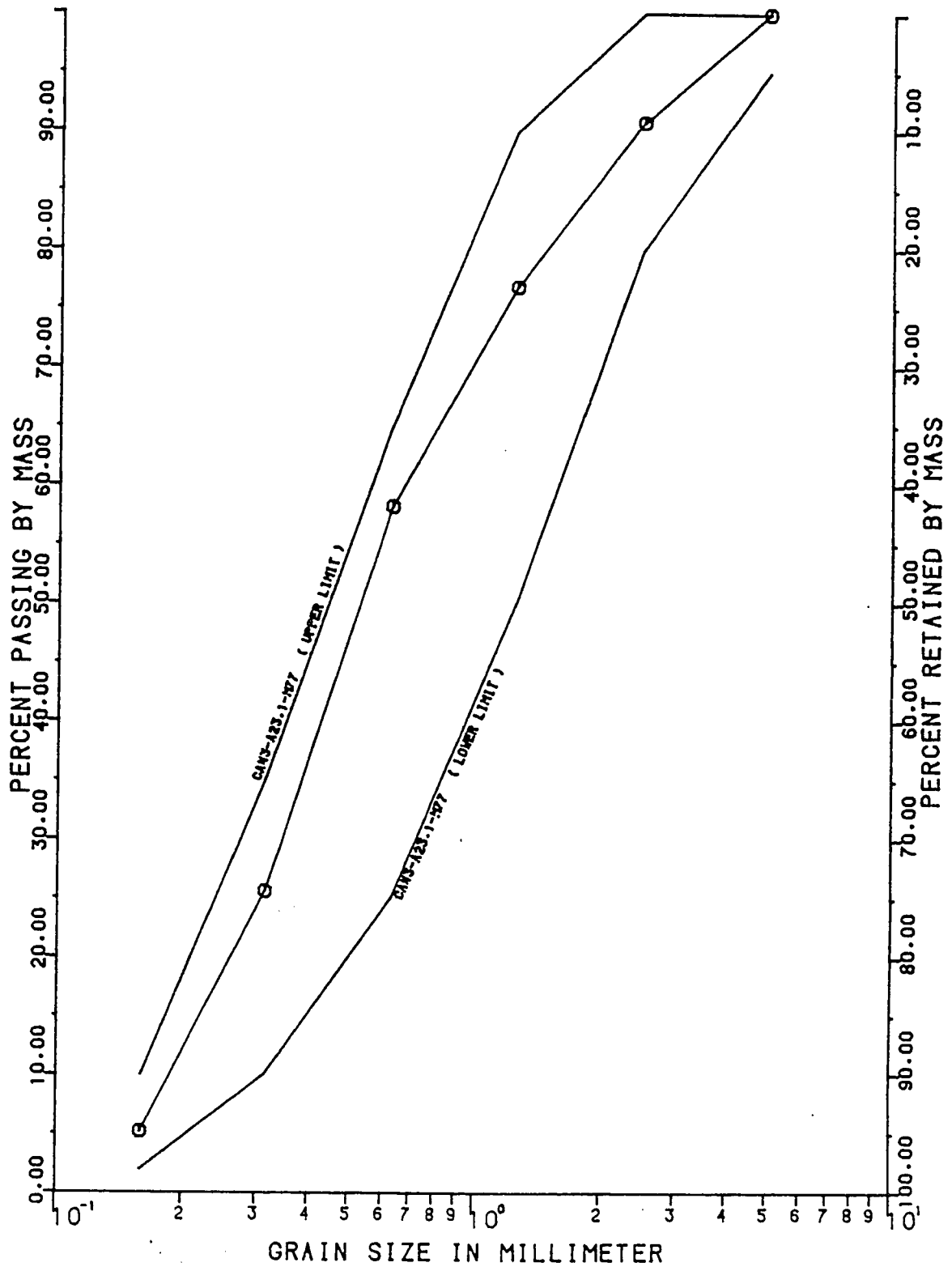
The compressive strength tests were carried out in a hydraulic testing machine capable of exerting a compressive force of 300,000 Pounds. Three 150mm x 300mm cylinders were capped and tested each time; the crushing strength of the concrete was taken as the average of the three results. The applicable testing standard was ASTM C39. In addition, deformation of the specimen over a gage length of 200mm in the direction of loading was also measured during the compression tests using a compressometer equipped with two dial strain gauges essentially as described by ASTM C469.

The splitting tensile strength test in accordance with ASTM C496 was chosen as the indicator of tensile strength of the concrete. The tests were carried out in a Tinius Olsen Universal Testing Machine of 500,000 Newtons capacity. Three 150mm x 300mm cylinders were split each time and the tensile strength was taken as the average of the three results.

In the case of determining the dynamic modulus of elasticity, two 75mm x 75mm x 300mm prisms were tested on an EWEFCO Electro Dynamic Material Tester (type SCT5) as essentially described by ASTM C215. The specimen was supported at the center with frequency driving and pickup unit attached to the ends. The fundamental longitudinal frequency was then determined by measuring the maximum

oscillation of the specimen. The weight of the specimen was also recorded. The dynamic modulus of elasticity was then computed using the empirical equation as stated in ASTM C215. This equation stated that the dynamic modulus of elasticity was related to the weight and geometry of the specimen, and also the fundamental longitudinal frequency. The average of two was taken as the target value. Since the sonic test was non-destructive, the prisms were put back to its curing environment after testing so that it could be reused again.

All the specimens mentioned above were tested at a surface dry condition.



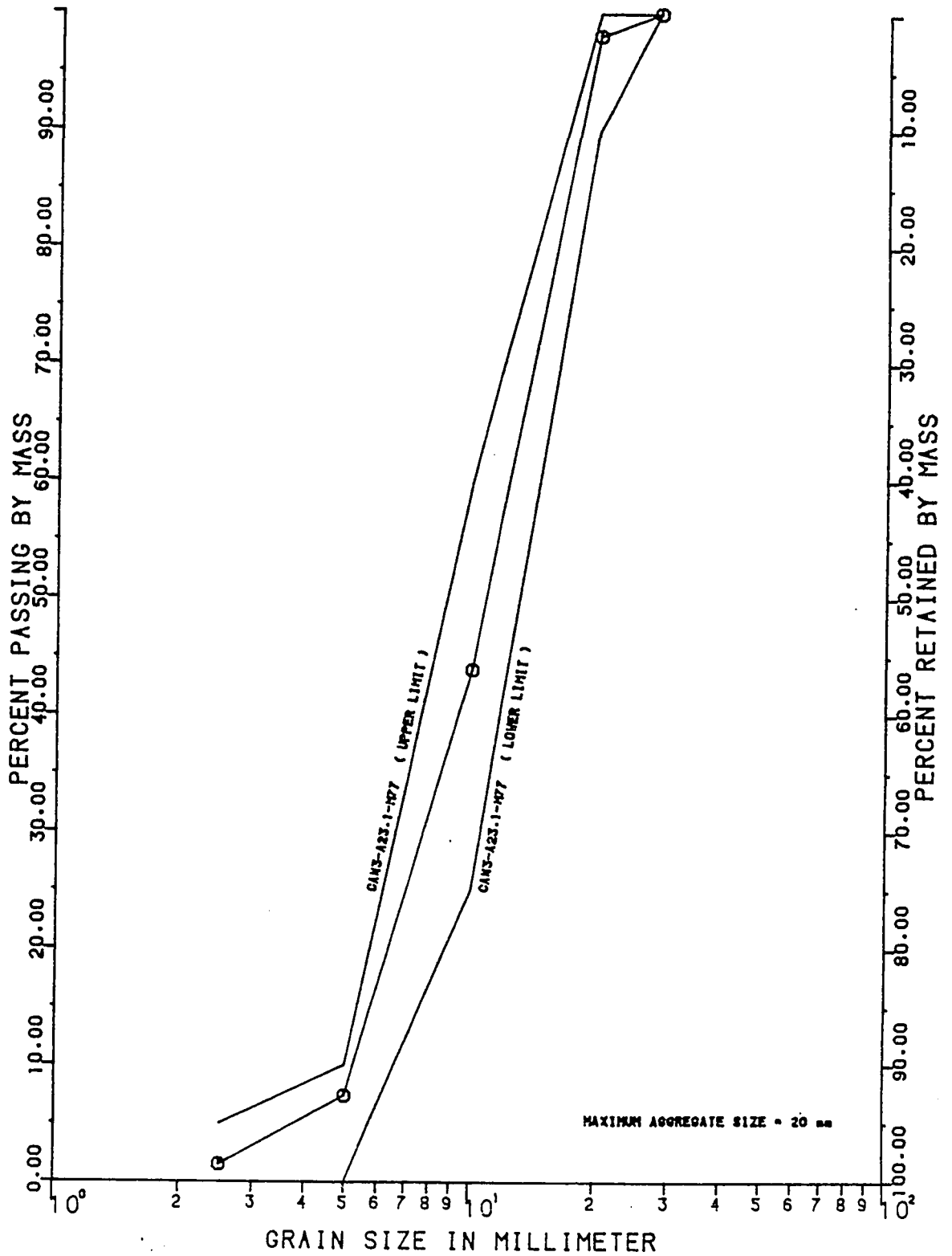


FIGURE 3.2 : GRAIN SIZE DISTRIBUTION OF COARSE AGGREGATE

TABLE 3.1
GRADING OF FINE AGGREGATE

Sieve Size (mm)	Percent Passing by Mass	
	Fine	CSA Limits
9.50		100
4.75	100.0	95 - 100
2.36	90.8	80 - 100
1.18	76.8	50 - 90
0.60	58.2	25 - 65
0.30	25.6	10 - 35
0.15	5.2	2 - 10

TABLE 3.2
GRADING OF COARSE AGGREGATE

Sieve Size (mm)	Percent Passing by Mass			
	14mm (35%)	20mm (65%)	Combined CSA	Limits
25.00		100.0	100.0	100
19.00	100.0	97.0	98.1	90 - 100
9.50	96.7	15.5	43.9	25 - 60
4.75	17.5	2.0	7.4	0 - 10
2.36	2.5	1.0	1.5	0 - 5
1.18	0.0	0.0	0.0	0

TABLE 3.3
 PROPERTIES OF CONCRETE MATERIALS

Cement

Type 10 Portland Cement

Combined Aggregate

Maximum Size	20 mm
Dry Rodded Mass	1600 Kg/m ³
Relative Density	2.65
Absorption	0.70%
Moisture Content	0.50% (Laboratory)
	0.50% (Cold Room)
	0.0 % (Hot Room)

Fine Aggregate

Fineness Modulus	2.43
Relative Density	2.61
Absorption	1.15%
Moisture Content	0.92% (Laboratory)
	0.92% (Cold Room)
	0.0 % (Hot Room)

TABLE 3.4
 PROPERTIES OF COLD CAST CONCRETE

	Water-Cement Ratio		
	0.55	0.45	0.35
(Kg/m ³)			
Water	169	169	160
Cement	305	370	440
Fine Aggregate	740	684	668
Coarse Aggregate	1110	1110	1110
Superplasticizer	none	none	3.1
Density of Fresh Concrete	2324	2333	2378
Air Content (%)	6.0	6.0	6.0
Slump (mm)	60	60	60
Temp. of Fresh Concrete (°C)	0	0	0
Relative Humidity (%)	80	80	80

TABLE 3.5
 PROPERTIES OF WARM CAST CONCRETE

	Water-Cement Ratio		
	0.55	0.45	0.35
(Kg/m ³)			
Water	167	167	160
Cement	305	370	440
Fine Aggregate	735	684	668
Coarse Aggregate	1105	1110	1110
Superplasticizer	none	none	3.1
Density of Fresh Concrete	2312	2331	2373
Air Content (%)	6.0	6.0	6.0
Slump (mm)	60	64	64
Temp. of Fresh Concrete (°C)	16	16	16
Relative Humidity (%)	20	20	20

TABLE 3.6
PROPERTIES OF HOT CAST CONCRETE

	Water-Cement Ratio		
	0.55	0.45	0.35
(Kg/m ³)			
Water	190	185	175
Cement	315	385	450
Fine Aggregate	755	700	680
Coarse Aggregate	1140	1140	1140
Superplasticizer	none	none	3.2
Density of Fresh Concrete	2400	2410	2445
Air Content (%)	5.0	5.0	5.0
Slump (mm)	64	60	68
Temp. of Fresh Concrete (°C)	45	45	45
Relative Humidity (%)	35	35	35

TABLE 3.7
CHEMICAL CONSTITUENTS OF SIFTO DEICING SALT

NaCl	97.60%
CaSO ₄	1.55%
CaCO ₃	0.58%
CaCl ₂	0.02%
MgCl ₂	0.03%
MgCO ₃	0.20%
Acid Insoluble	0.02%

Information supplied by DOMTAR Chemicals Group, Toronto.

Chapter IV

OBSERVATIONS

In general, the physical tests on the properties of freshly mixed concrete and the mechanical tests on the hardened concrete specimens have carried out successfully. However, there are several remarks that must be mentioned in order to make this report complete. For instance, the cylindrical specimens that have to be transferred to another curing environments after a 3-hour delay at casting temperature required special attention. Practically, the concrete mass of these specimens was still in its dormant period and excessive vibration during transportation could damage the initial chemical bond established within the crystal structure of the cement paste and hence the strength of the concrete. Although concrete with low water-cement ratio hardened rapidly, this was not true for the concrete with a water-cement ratio of 0.35 which took a longer time to set. This was due to the incorporation of superplasticizer into the mix. In this case, special care was taken to minimize vibration during transportation of the specimens.

4.1 EFFECT OF TEMPERATURE ON SUPERPLASTICIZER

Superplasticizer as a high range water-reducing agent has been used successfully in producing high strength concrete by making possible large reduction in water content to achieve the required consistency and workability. A recent study by Malhotra¹² reviewed developments on the effect of superplasticizer on the properties of fresh and hardened concrete. The review has generally indicated that incorporation of superplasticizer into the concrete mix appeared to have no significant adverse effect on initial set and the rate of bleeding of fresh concrete. Furthermore, the strength, shrinkage and creep properties of the hardened concrete were found comparable to concrete without incorporating superplasticizer. In spite of these, the use of superplasticizer in producing high strength concrete has essentially been confined to the precast concrete industry where the duration between mixing and pouring into forms is relatively short. The ready-mix concrete companies were still reluctant to use this simply because of the rapid loss in slump and workability with time and temperature.

A similar problem was encountered in this project during the casting at 45°C. Concrete mix incorporating superplasticizer (i.e. w/c = 0.35) was found to be very sensitive to elevated temperature. While the wet concrete maintained sufficient workability for a long period of time at 0°C and 16°C, the workability was rapidly reduced at

45°C. The wet concrete at this temperature "appeared" flowable but the paste was found to have high adhesion which made shuffling and pouring difficult. Time was a crucial factor here because this adhesion increased with increasing time. A delay of 10 minutes after mixing could induce an adhesion so great that it was difficult to work with.

4.2 EFFECT OF TESTING TEMPERATURE

An interesting problem was to decide at what temperature the specimens should be tested. Obviously, concrete should be tested at the curing temperature because a concrete structure will not wait for the temperature to reach room temperature if it fails. Unfortunately, because of the number of concrete specimens that had to be tested, some of the specimens were exposed to room temperature for a period as long as 2 hours and a small experiment has indicated that the temperature, measured at the center of the specimen, could change 9°C over a 2-hour period as shown in figure 4.4. Klieger⁽³⁾, in his investigation, preconditioned the specimens in a moist room at 23°C for one and half hours prior to test. Other researchers, as mentioned earlier in Chapter I, gave no further details on testing temperature.

Saeman and Washa⁽¹³⁾ investigated the variation of concrete properties with temperature. They cast and cured concrete specimens at room temperature, 100% relative

humidity for 14 days, and then cured at 21°C, 50% relative humidity for 13 days, and finally preconditioned the specimens at the prescribed testing temperature for 24 hours. Their results, as shown in figure 4.1, indicated that the 28-day compressive strength was indeed affected by the testing temperature. The strength was reduced 5 percent if tests were carried out at 45°C and a 10 percent increase in strength if tests were done at 0°C, compared to testing at room temperature. But however, their investigations were more or less dedicated to the fire resistance of the concrete member. A recent study on the effect of temperature at time of testing was conducted by the Cement and Concrete Association⁽¹⁴⁾ and the investigation was more related to this study. They cast and cured cement mortar cubes at prescribed temperature and then tested some of the specimens at the same curing temperature while some of the specimens were tested at 20°C after 2 hours preconditioning prior to test. The results, as shown in figures 4.2 and 4.3, have indicated that the effect of temperature at time of testing were virtually negligible except when the curing temperature was above 65°C. For instance, the specimen cast, cured and tested at 5°C has a 7-day compressive strength of 200 MPa while a similar specimen tested at 20°C has a 7-day compressive strength of 200 MPa which was exactly the same as former. The problem here was to justify whether the results obtained from cement mortar cubes could relate to

the actual behaviour of the concrete cylinders. To further examine the effect of testing temperature, twelve concrete cylinders with water-cement ratio of 0.55 and twelve with water-cement ratio of 0.35 were cast and cured 24 hours at room temperature. The specimens were then demolded and capped. Half of these specimens were later cured at 0°C and the other half were cured at 45°C. The compression tests were done 14 days after casting. For each water-cement ratio, three specimens were tested at the curing temperature and three specimens were tested after a 2-hour delay at room temperature. The results as shown in table 4.1 have indicated that there were practically no variation in compressive strength. However, the only strength variation came from water-cement ratio of 0.55. The results indicated that concrete cured and tested at 45°C has a compressive strength five percent less than a similar concrete which has exposed to room temperature for two hours. From the above information, the effect of temperature at time of testing was believed to be insignificant providing specimens were exposed to room temperature no more than two hours.

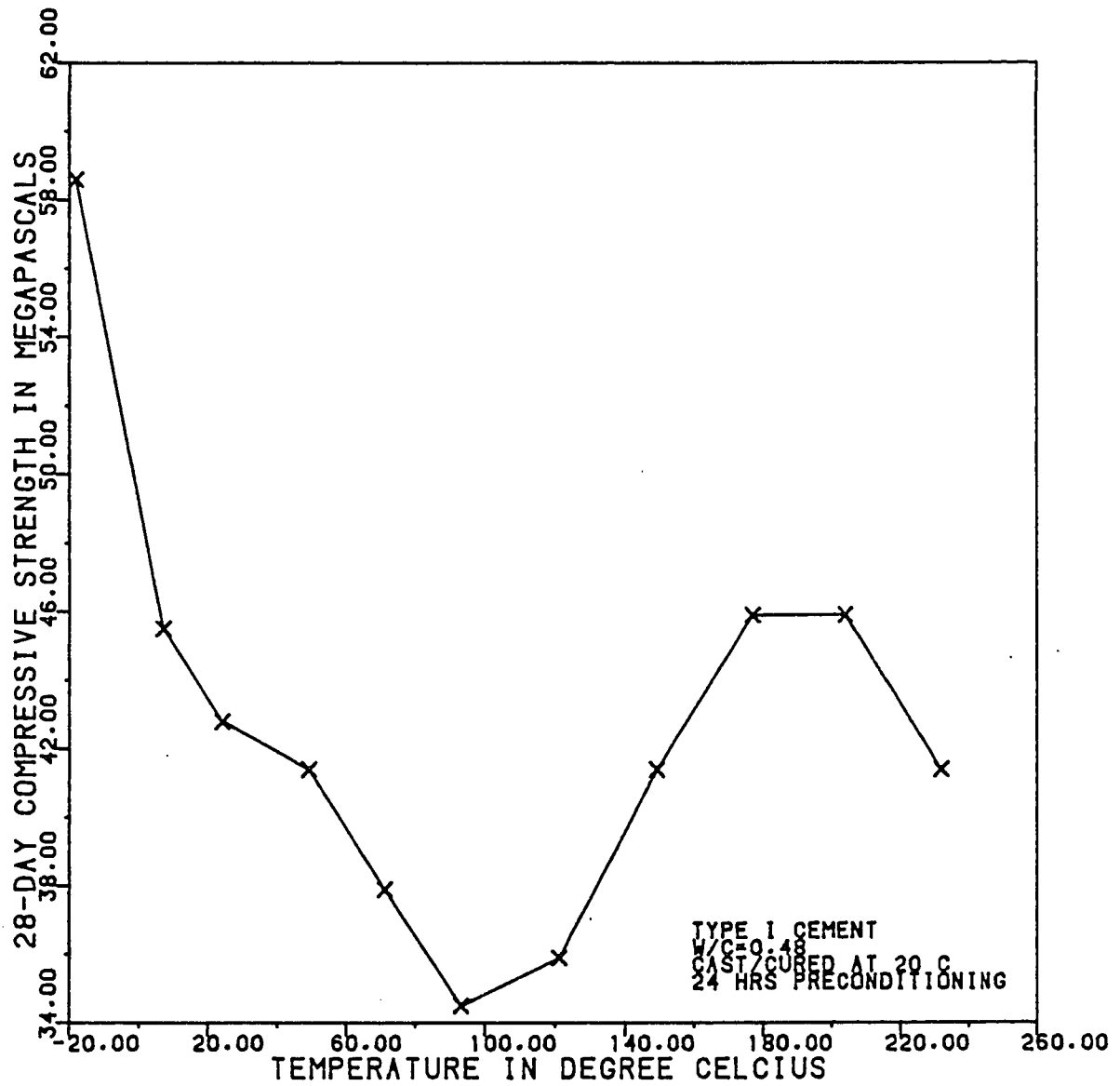


FIGURE 4.1 : VARIATION OF CONCRETE STRENGTH WITH TESTING TEMPERATURE (13)

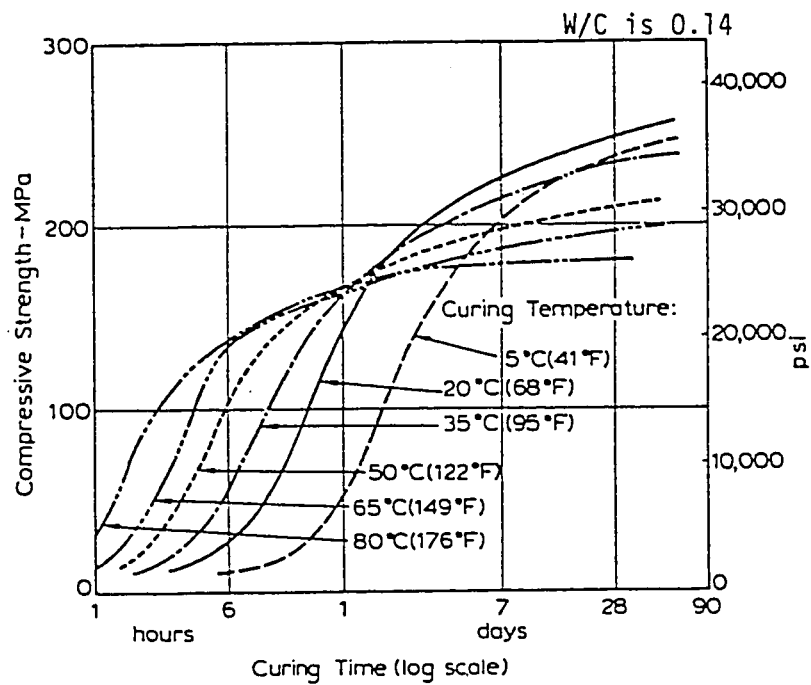


FIGURE 4.2 : EFFECT OF TEMPERATURE ON THE STRENGTH OF CEMENT⁽¹⁴⁾
 (Cast, cured and tested at indicated temperature)

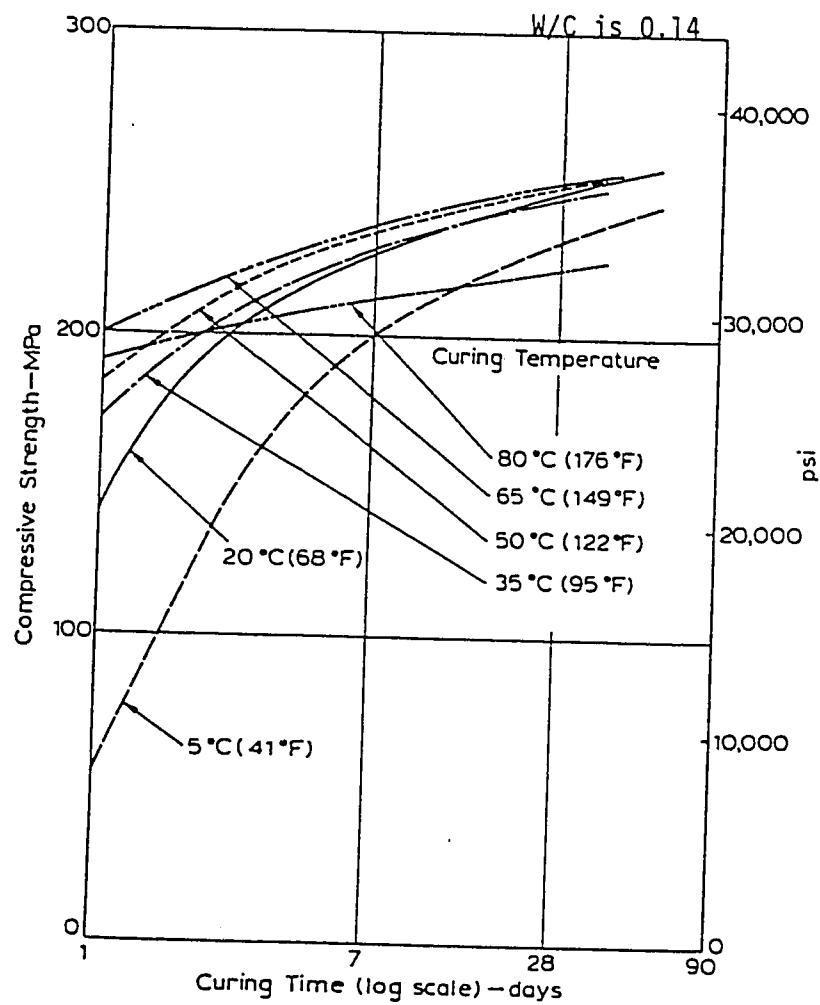


FIGURE 4.3 : EFFECT OF TEMPERATURE ON THE STRENGTH OF CEMENT⁽¹⁴⁾
 (Cast/Cured at indicated temperature)
 (Tested at 20°C after a two-hour period of preconditioning)

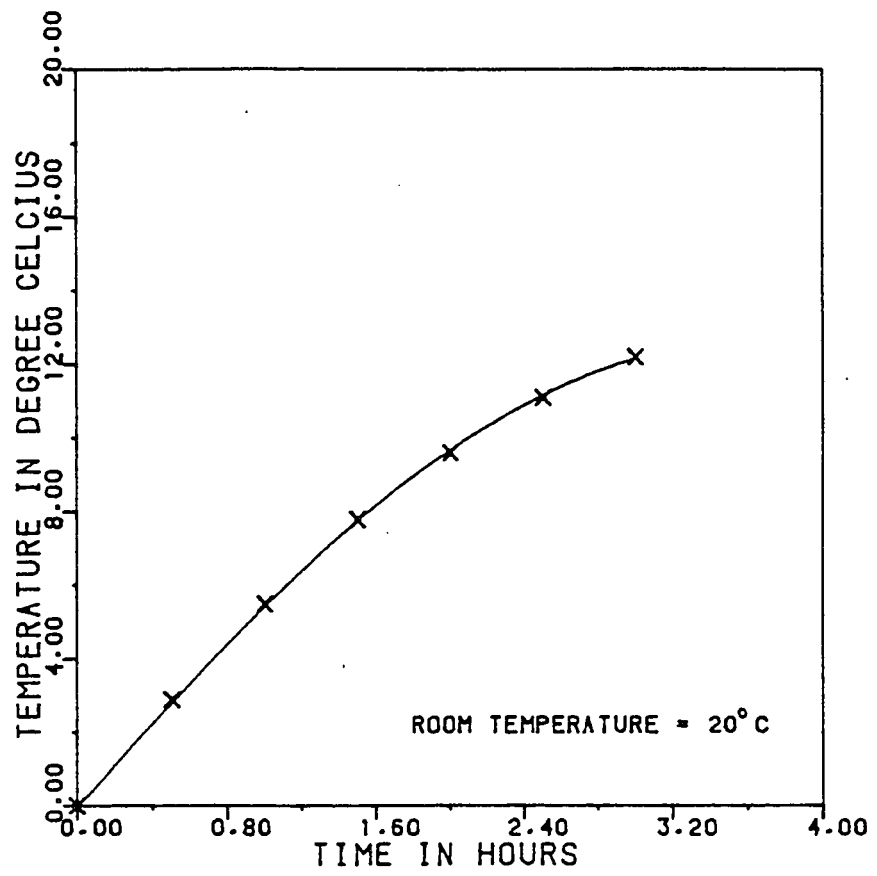


FIGURE 4.4 : CHANGE OF CONCRETE TEMPERATURE WITH TIME

TABLE 4.1
EFFECT OF TESTING TEMPERATURE

Curing temperature (°C)	0	0	45	45
Hours of Delay at FCC@				
Temperature Before Test	0	2	0	2
fc (14 days, w/c=0.55, MPa)	16.2	16.5	18.8	19.8
fc (14 days, w/c=0.35, MPa)	34.2	34.3	31.5	32.0

Chapter V

DISCUSSION

For the sake of clear identification and interpretation of the experimental results, the discussion is divided into two parts. First, the discussion were dedicated to the effect of temperature on the mechanical properties of concrete cast and cured at 0°C, 16°C and 45°C. The relationships between the compressive strength, tensile strength, static and dynamic modulus of elasticity are also examined and elaborated. The second part of the discussion deals with the effect of casting and initial curing temperature on the compressive strength of concrete.

5.1 TEMPERATURE EFFECTS ON THE MECHANICAL PROPERTIES OF CONCRETE

5.1.1 Effect of Temperature and Age on the Compressive Strength

In general, the specimens have failed in a consistent manner in that the compressive strength increased with increasing time and decreasing water-cement ratio. The low-strength specimens went through a considerable amount of elastic deformation before failure occurred. In contrast, specimens having high compressive strength, typically above 40 MPa, took up very little plastic strain and the failure

was both sudden and explosive. The results of the compression tests at varying age, water-cement ratio, casting and curing temperature were given in tables 5.1, 5.2 and 5.3. To examine the test results, the compressive strength versus the age of concrete were also plotted as shown in figures 5.1 to 5.11. A similar trend could be seen from all these figures that compressive strength varied with varying age, water-cement ratio and casting and curing temperature. In addition, concrete continued to gain strength even though it was cast and cured at low temperature. A distinct strength variation was observed by comparing figures 5.2 and 5.3. Attention must be given to the spacing of the curves in figure 5.3 in which the curves were spaced further apart than those in figure 5.2. This indicated that compressive strength was more sensitive to water-cement ratio at elevated temperature where a slight decrease in water-cement ratio could result in a substantial increase in strength. A somewhat similar trend was also observed in figure 5.1 for concrete cast and cured at 0°C. The compressive strength increased rapidly for concrete with water-cement ratios of 0.45 and 0.35 but not the 0.55 water-cement ratio.

As expected, concrete cast and cured at 0°C developed very little strength at its early ages as shown in figures 5.4 to 5.6. Despite these low initial strength, its long-term strength was found comparable to concrete cured at

16°C. Figure 5.4 shows that the 90-day compressive strength of concrete cured at 0°C with water-cement ratio of 0.55 was slightly below the strength of concrete cast and cured at 16°C. However, for water-cement ratio below 0.45, 0°C cured concrete picked up strength rapidly and even exceed that of 16°C at ages beyond seven days. In contrast, concrete cast and cured at 45°C has both high early strength and high long-term strength especially for those with water-cement ratio of 0.35. It showed a much higher strength than those at 16°C at all ages.

Besides the magnitude of concrete strength, attention was also given to the rate of strength development. ACI Committee 209⁽¹⁵⁾ proposed that the compressive strength of concrete made of ordinary Portland cement could be predicted by

$$f_c = f'_c \times t / (a + b \times t) \text{ ----- (5.1)}$$

where $a=4.00$ and $b=0.85$ for normal moist cured concrete and $a=1.00$ and $b=0.95$ for steam cured concrete. This equation simply states that the compressive strength at any time t could be related to the age of concrete and its 28-day compressive strength. However, as shown in figures 5.7 to 5.9, the rate of strength development was also affected by the water-cement ratio and the casting and curing temperature. The lower the water-cement ratio, the faster the concrete gained its strength. Furthermore, concrete that

was cast and cured at 0°C, developed strength slowly at early ages. As shown in figure 5.7, the 3-day compressive strengths were about 20% of its 28-day strength while others at 16°C and 45°C have already reached 60%. Despite these, concrete at low temperature managed to catch up the strength with the others as time proceeded. For instance, figures 5.8 and 5.9 showed that concrete at elevated temperature could reach at least 80% of its 28-day strength within 14 days while figure 5.7 reviewed a similar percentage even though the concrete was cast and cured at 0°C.

Figure 5.10 indicated that concrete cast and cured at 0°C and with an appropriate water-cement ratio could develop a higher compressive strength than a similar concrete cast and cured at 16°C. For instance, the 3-day strength of concrete at 0°C and with water-cement ratio of 0.45 was about one-quarter of the 28-day strength of a similar concrete at 16°C, but then the strength was able to reach 100% at 14 days and 125% at 90 days. Similarly, concrete with water-cement ratio of 0.35 attained 40% at 3 days, 100% at 28 days and 125% at 90 days. In contrast, concrete with water-cement ratio of 0.55 started out with a low initial strength and ended up also with a low 90-day strength comparing to the 28-day compressive strength of a similar concrete at 16°C. Apparently, concrete at low temperature has benefited from low water-cement ratio. The lower the water cement ratio, the higher the long-term

relative strength. However, it could be seen that concrete with water-cement ratio of 0.35 has a lower strength percentage than 0.45 at ages beyond 14 days. Although it still managed to attain high long-term strength percentage, the reason for the variation in the rate of strength development between water-cement ratio of 0.35 and 0.45 is not known. One possible explanation could be the effect of incorporation of superplasticizer into the concrete with water-cement ratio of 0.35. As shown in figure 5.11, concrete cast and cured at 45°C with a water-cement ratio of 0.35 attained 110% of the 28-day strength of a similar concrete at 16°C within 3 days, and this percentage continued to increase and reached 170% at 90 days. Concrete with water-cement ratio of 0.45 developed 100% at 14 days and 120% at 90 days while concrete with water-cement ratio of 0.55 did not yield very good strength at high temperature. Apparently, concrete with low water-cement ratio has received benefits to its compressive strength from both casting and curing at 0°C and 45°C.

5.1.2 Tensile Strength of Concrete

In general, the tensile strength of concrete increased with increasing time and increasing compressive strength as shown in tables 5.1 to 5.3. The Canadian Code for the Design of Concrete Structures for Buildings⁽¹⁶⁾ suggested that the tensile strength could be related to its compressive strength by equation (5.2).

$$f_{ct} = 0.56(fc)^{0.50} \text{ ----- (5.2)}$$

However, when all the experimental results which collected from all different water-cement ratio and all different casting and curing temperatures were plotted as shown in figure 5.12, it could easily be seen that this relationship did not hold for the majority of the test results. Obviously, a better relationship could be established by using the theory of statistics and probability to determine the distribution of the experimental data. To do this, the tensile strength was first expressed as a power function

$$f_{ct} = K(fc)^N \text{ ----- (5.3)}$$

where K and N are the unknown parameters to be determined. Further, by taking natural logarithm on both sides of the equation, equation (5.3) became

$$\log(f_{ct}) = \log(K) + N \log(fc) \text{ ----- (5.4)}$$

$$\text{OR/} \quad Y = A + BX \text{ ----- (5.5)}$$

where $Y = \log(f_{ct})$, $A = \log(K)$, $B = N$ and $X = \log(fc)$. This simply means that a linear relationship could be reached when all the experimental data were plotted on a log-log paper. Using Least Square Regression Method (see Appendix A), the regression coefficients ($K=0.45$, $N=0.60$) were determined as given in table 5.4. The correlation coefficient was found to be 0.86 which indicated that a good linear trend existed

between tensile and compressive strength in log-log scale. As shown in figure 5.13, 44 out of 45 of the given data fell within the 95% confidence limits. In other words, the proposed regression line determined from least square error minimization method was acceptable.

Poon⁽¹⁷⁾ found that $K=0.34$ and $N=0.69$ in his study. Carino and Lev⁽¹⁸⁾ collected previous research data from National Bureau of Standards and the parameters were found to be $K=0.24$ and $N=0.71$ from a series of statistical analysis. Plotting all these in figure 5.14, it could be seen that Poon's result was in good agreement with the present study. A remark must be pointed out that some of the data from Poon's equation were collected from specimens cured at 2°C. Apparently, Carino and Lev's results have given a lower bound solution where only 7% of the data fell below the curve. In addition, the results from Poon, CAN3-A23.3-M77 and the present study were all in good agreement in predicting the tensile strength of young concrete with compressive strength less than 20 MPa. When the compressive strength of concrete increased further, equation (5.2) yielded a conservative result. It underestimated the tensile strength of concrete which has high compressive strength. However, the above equations have presumed that the tensile strength was only related to its compressive strength. When the Least Square Regression method was applied to data which collected from individual

casting and curing regime, the curves in figure 5.15 indicated that tensile strength was also affected by temperature. Low temperature was affecting tensile strength more than compressive strength and hence different relationships between tensile and compressive strength could be derived for different casting and curing temperature.

5.1.3 Static Modulus of Elasticity

Similarly, the static modulus of elasticity increased with increasing compressive strength. Using the same approach as in the previous section, the static modulus of elasticity was once again expressed as a power function in equation (5.6).

$$E_c = K(f_c)^N \text{ ----- (5.6)}$$

The regression coefficients K and N were found to be 3.05 and 0.65, respectively, as given in table 5.4. The correlation coefficient was 0.95 which indicated a strong linear relationship between the Young Modulus and its compressive strength in log-log scale. Figure 5.16 showed that 93% of the given data fall within the 95% confidence limits which further verified the acceptability of the proposed regression line.

The Canadian Code⁽¹⁶⁾ suggested that $K=5.00$ and $N=0.50$ for normal weight concrete. On the other hand, the British Code of Practice⁽¹⁹⁾ suggested that K and N should

be equal to 9.10 and 0.33, respectively. However, when these were plotted as shown in figure 5.17, it could be seen that both the Canadian Code and British Code have overestimated the static modulus of elasticity of the young concrete and underestimated that for the mature concrete.

Figure 5.18 showed that concrete at 45°C yielded a higher Young modulus than those at 0°C for compressive strength below 30 MPa and a lower static modulus of elasticity for strength above 30 MPa. In other words, the static modulus of elasticity increased with increasing compressive strength but the rate varied depending on the casting and curing temperature.

5.1.4 Dynamic Modulus of Elasticity

The dynamic modulus of elasticity increased with increasing compressive strength. From a series of statistical analyses, the correlation coefficient as shown in table 5.4 was found to be 0.94 which indicated a strong linear relationship between the dynamic modulus of elasticity and its compressive strength in log-log scale. Similarly, when the dynamic modulus of elasticity was expressed as a power function of

$$E_d = k(fc)^N \text{-----} (5.7)$$

the regression coefficients k and N from Least Square analysis were determined to be 13.30 and 0.31, respectively.

In addition, as shown in figure 5.19, 96% of the given data fell within the 95% confidence limits which further justified the proposed regression equation.

The British Code of Practice⁽¹⁹⁾ suggested that the dynamic modulus of elasticity could be related to its compressive strength by equation (5.8).

$$E_d = 14.0 + 7.60(f_c)^{0.33} \text{ ----- (5.8)}$$

As shown in figure 5.20, the Code has apparently overestimated the dynamic modulus of elasticity for compressive strength less than 20 MPa while it continued to underestimate the dynamic modulus of elasticity of the concrete having compressive strength exceeding 20 MPa.

Figure 5.21 showed that concrete cast and cured at high temperature attained a higher dynamic modulus of elasticity than a similar concrete having the same strength (below 45 MPa) but cast and cured at low temperature.

5.2 CASTING AND CURING TEMPERATURE EFFECTS ON CONCRETE STRENGTH

As discussed earlier in section 5.1.1, concrete that cast and cured at 0°C could develop much higher long-term strength than those at 16°C if the water-cement ratio was kept to its minimum. In contrast, concrete cast and cured at 45°C developed both high early and long-term strength. The key issue was to keep the water-cement ratio as low as possible so that concrete will suffer no damage to

its strength but conversely benefit from casting and curing at extreme temperature.

Although the strength was affected by temperature, there was no doubt that compressive strength of concrete, as given in tables 5.5 to 5.7, increased with increasing time and decreasing water-cement ratio. The trend applied to all various combinations of casting and curing temperature. Figure 5.22 has shown that curing at 0°C has no adverse effect on concrete strength as long as the water-cement ratio was kept low. The casting temperature was also affecting the strength as well. For instance, the best combination was obviously came from the one that cast and cured 3 hours at 45°C and subsequently cured at 0°C. It has exhibited the highest strength in both 7-day and 90-day. Similarly, casting at 45°C together with low water-cement ratio were also good in producing high strength concrete regardless of the curing temperature. Figures 5.22 to 5.24 all indicated that the best strength, both early and long-term, was obtained from concrete cast at 45°C. However, to justify which casting and curing regime yielded the best results, it is necessary to put up a reference so that direct comparisons could be made. Since common practice was to cast and cure concrete at room temperature, the concrete that cast and cured at 16°C was chosen to be the reference and the compressive strength from various casting and curing regimes would be compared to the 28-day compressive strength

of the reference. The results were given in tables 5.6 to 5.10 and graphically in figures 5.25 to 5.33.

Figure 5.25 showed that casting at 45°C did indeed improve the early strength to a certain degree but the overall picture showed that concrete with water-cement ratio of 0.55 and curing at 0°C yielded poor results. Even though cast at an elevated temperature, it still failed to produce good strength comparing with a similar concrete at 16°C. When the water-cement ratio was reduced to 0.45, some improvements showed. As shown in figure 5.26, concrete cast and cured at 0°C yielded results comparable to the reference. It showed a relative strength percentage of 68% in 7 days, 107% in 28 days and 124% in 90 days. In addition, concrete cast and cured 3 hours at 45°C and continued curing at 0°C also yielded favourable results. It showed a relative strength percentage of 69% in 7 days, 114% in 28 days and 132% in 90 days. In contrast, concrete that cast at 16°C and cured at 0°C showed a little improvement and the strength was low comparing with the reference. For water-cement ratio as low as 0.35, the overall picture definitely improved. As shown in figure 5.27, the best temperature combination was certainly the one that cast and cured 3 hours at 45°C and subsequently cured at 0°C. It showed a relative strength percentage of 102% in 7 days, 145% in 28 days and 169% in 90 days which were extremely good. The second best result came from the concrete that cast and cured 3 hours at 16°C and

subsequently cured at 0°C. It yielded high strength in both its early and later ages. Apparently, three important observations could be drawn from these three figures. First, casting at 45°C did improve the initial and long-term strength of concrete. Next, it was the water-cement ratio that played an important role in low temperature curing. The lower the water-cement ratio, the better the results. Finally, concrete cast and cured 3 hours at 45°C or 16°C and then continued to cure at 0°C yielded very good strength providing water-cement ratio was kept to its minimum.

Figures 5.28 to 5.30 showed the relative concrete strength cured at 16°C but cast at different temperature. For water-cement ratio of 0.55, figure 5.28 showed that casting at elevated temperature or low temperature reduced the concrete strength. In contrast, as shown in figure 5.29, the concrete was actually benefited from casting at 0°C when water-cement ratio reduced to 0.45. The longer the concrete remained at 0°C before receiving extensive curing at 16°C, the higher the strength, both initial and long-term. Although casting at 45°C did not give high strength, the results were found comparable to the reference. Once again, when water-cement ratio reduced to 0.35, the overall picture revealed definite improvements in all various casting and curing regimes. The best result obviously came from the concrete that cast and cured 3 hours at 45°C and continued curing at 16°C. It showed a relative strength percentage of

95% in 7 days, 119% in 28 days and 132% in 90 days. Casting at 0°C and subsequently cured at 16°C also yielded a better strength than those cast and cured at 16°C. The longer the concrete stayed at 0°C, the better the strength. A similar observation was that concrete strength from various casting and curing regimes improved only if the water-cement ratio was kept to its minimum.

Similarly, for extended curing at 45°C, figures 5.31 to 5.33 showed the relative strength of concrete versus time with different water-cement ratio. Figure 5.31 indicated that curing at 45°C would damage the concrete strength for water-cement ratio of 0.55. Some improvements in strength were observed in figure 5.32. Concrete with water-cement ratio of 0.45 showed a higher initial and long-term strength if it was cast and cured at 45°C. Casting at low temperature and then cured at 45°C would damage the strength. For water-cement ratio of 0.35, similar improvement in strength was observed in figure 5.33. The best result came from concrete cast and cured at 45°C continuously. It showed a relative strength percentage of 126% in 7 days, 150% in 28 days and 167% in 90 days. Casting at 0°C and then a period of 3-hour initial curing at 0°C also improved the relative strength of concrete.

The above results were found consistent with the results from previous research. As discussed earlier in section 1.2, Price⁽²⁾ indicated that concrete mixed, placed

and cured at 4°C have a 28-day compressive strength 22 percent lower than those which were mixed and continuously cured at 21°C as shown in figure 1.1. In addition, the compressive strength of concrete that cast and cured 2 hours at 4°C and subsequently cured at 21°C was found higher than the concrete cast and continuously cured at 21°C. However, all concrete specimens in his study were using water-cement ratio of 0.50. Although the present study did not investigate this water-cement ratio, by averaging the experimental results from water-cement ratio of 0.55 and 0.45, the same observations could be made. As shown in table 5.11, Price's results were found comparable to this study. Although an exact correlation is not possible because of the differences in the type of cement that were being used in the studies, the overall picture has shown a similar result with this study. Price was using ASTM type II cement which has a higher percentage of tricalcium silicate and a lower percentage of dicalcium silicate than the type I ordinary Portland cement. Klieger⁽³⁾ was using water-cement ratio of 0.42 and his results indicated a slight deviation in conclusion. For instance, as shown in figure 1.3, concrete cast and cured at 4°C developed a 28-day strength 20 percent lower than a similar concrete cast and cured at 23°C. However, the quality of cement has improved over the last 25 years. As shown in table 5.12, the chemical compositions of CSA type 10 Portland cement was roughly equal to the average

of the chemical compositions of ASTM type I and type III cement that Klieger used in his study. The compressive strength of type 10 cement was also found comparable to the average of the strength of type I and type III cement. Therefore, by averaging the results as shown in table 1.3, the relative 28-day concrete strength was found comparable to this study. However, it should be pointed out that averaging the concrete strength of type I and type III cement might lead to a conclusion different from the actual concrete made of type 10 cement.

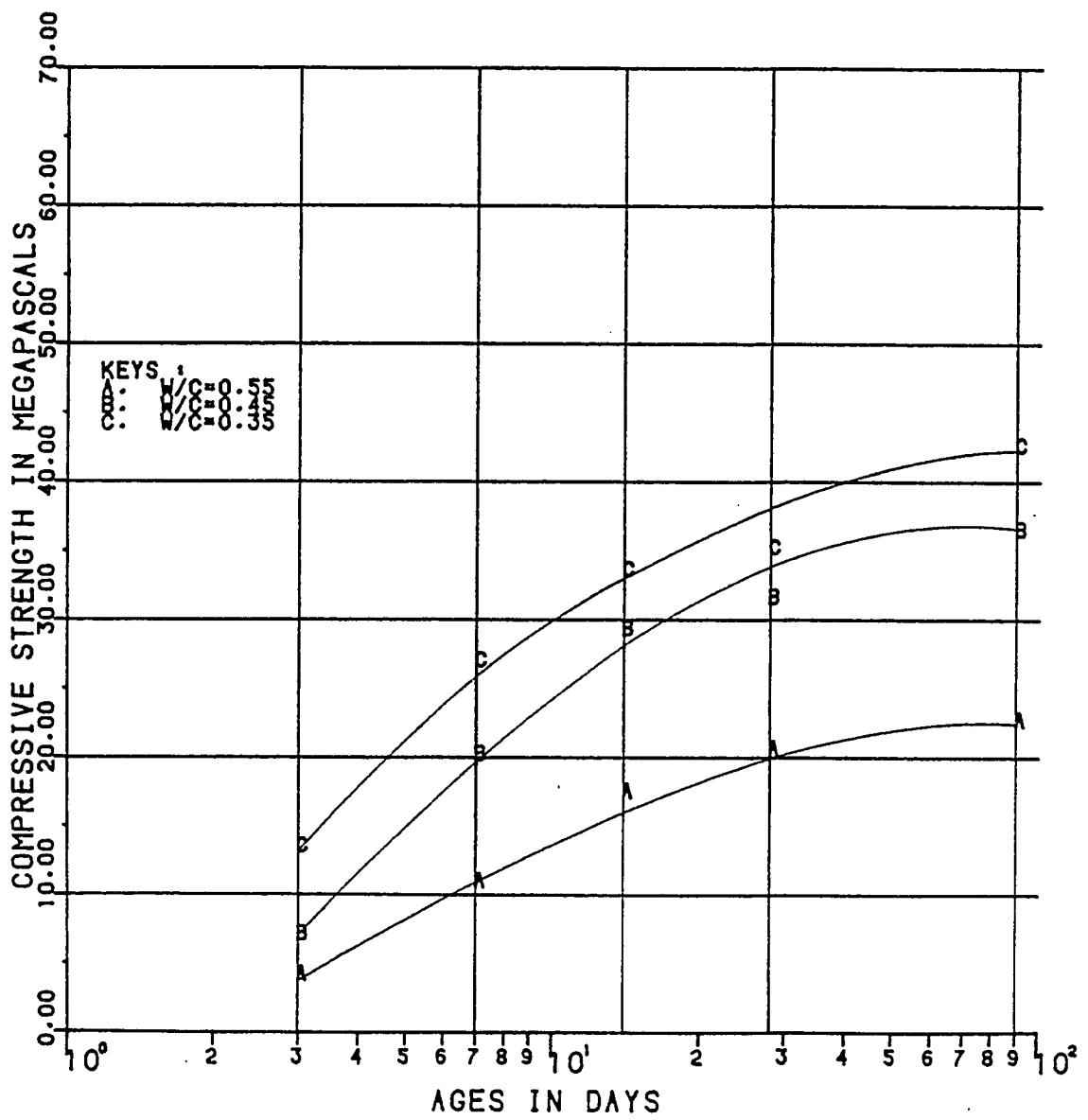


FIGURE 5.1 : COMPRESSIVE STRENGTH OF CONCRETE CAST/CURED AT 0°C

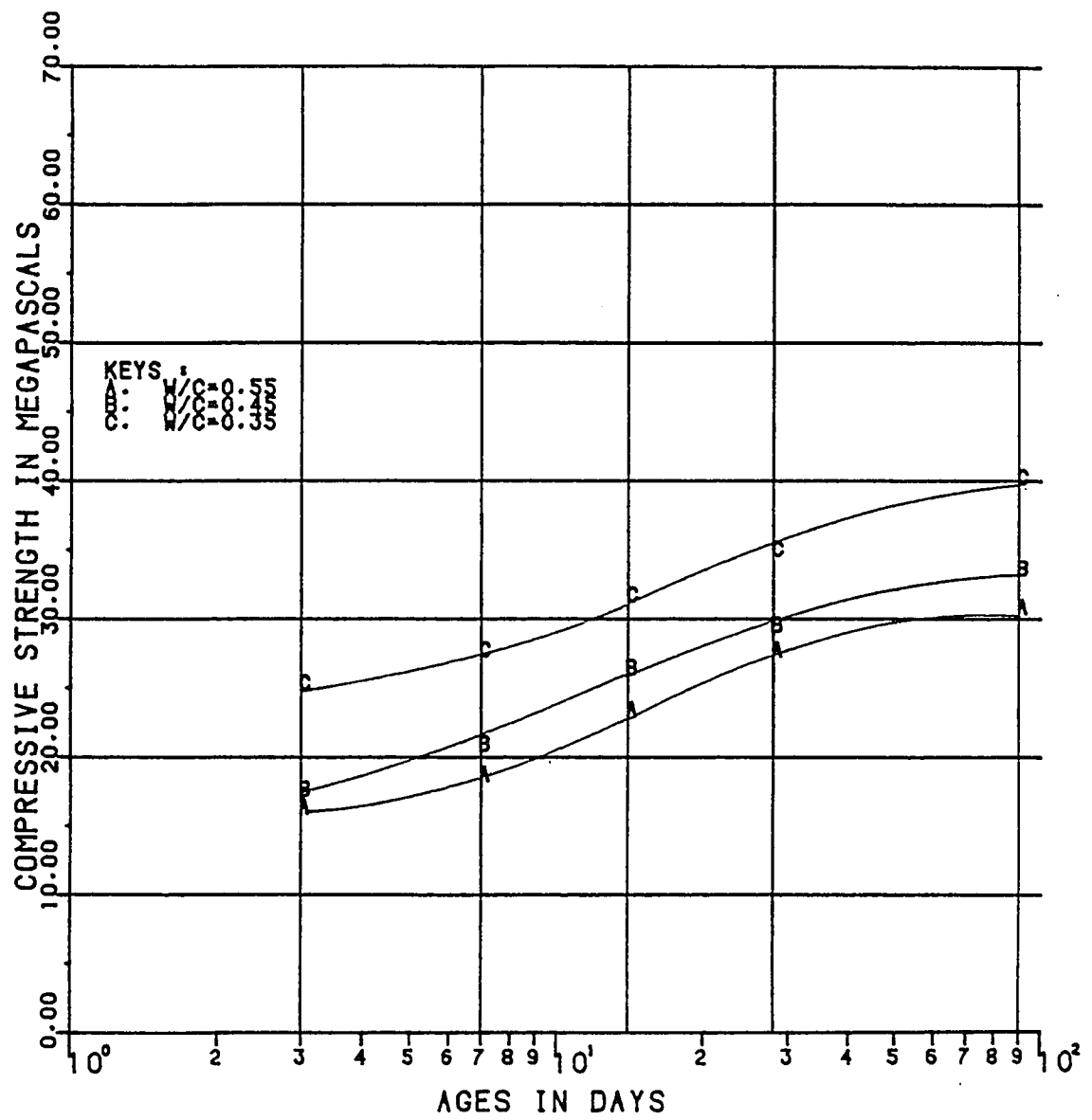


FIGURE 5.2 : COMPRESSIVE STRENGTH OF CONCRETE CAST/CURED AT 16°C

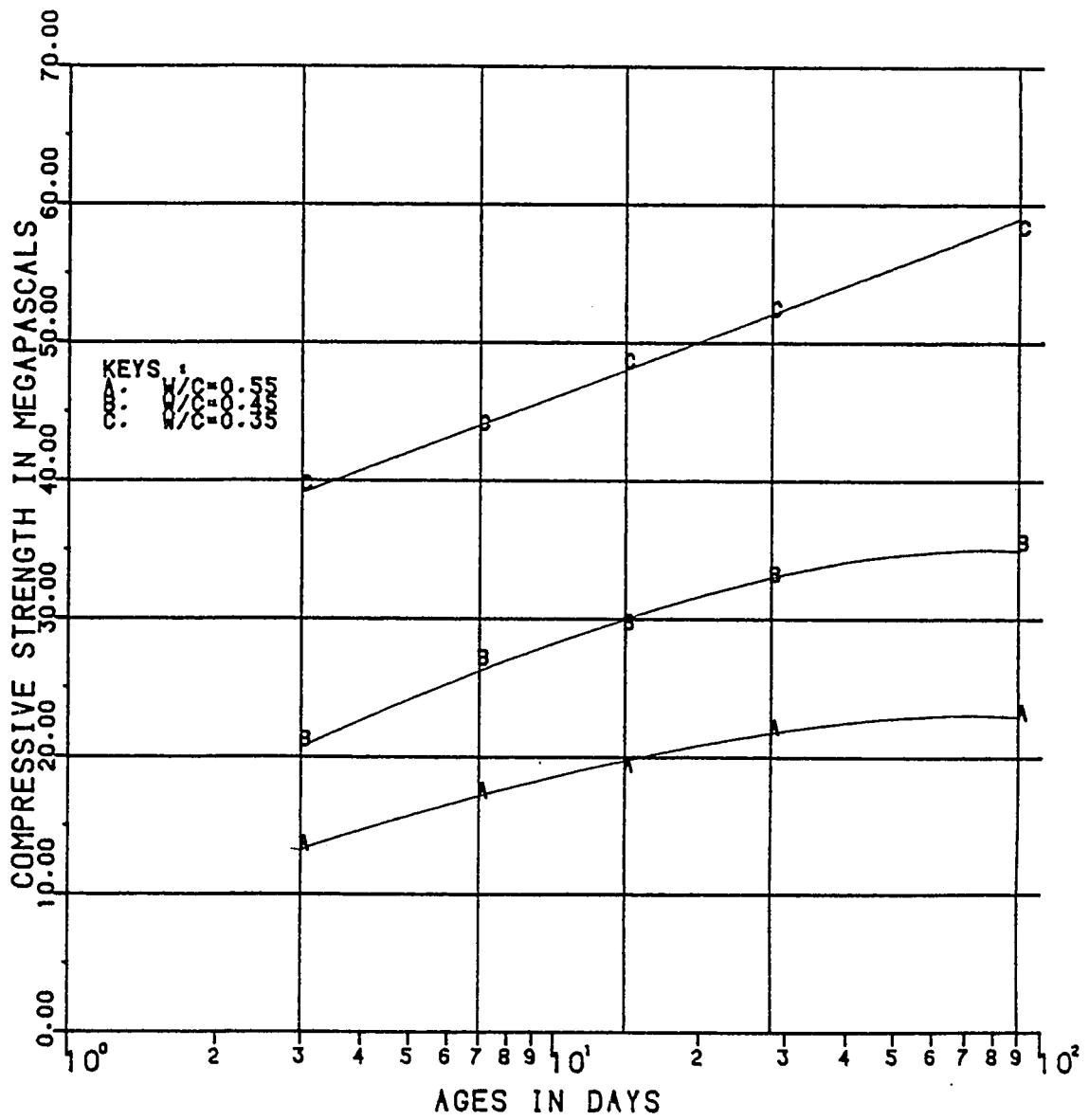


FIGURE 5.3 : COMPRESSIVE STRENGTH OF CONCRETE CAST/CURED AT 45°C

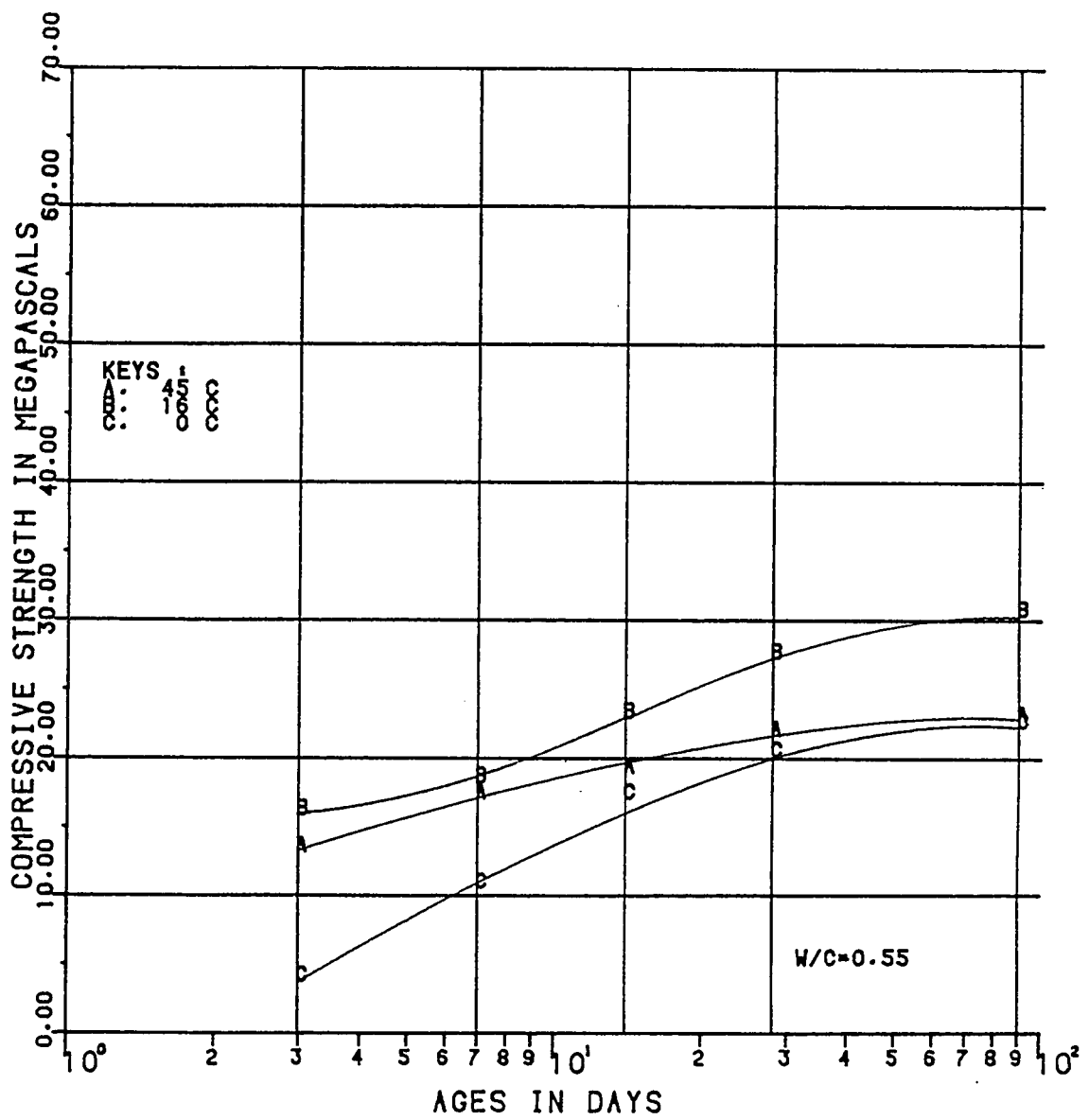


FIGURE 5.4 : VARIATION OF CONCRETE STRENGTH WITH TEMPERATURE

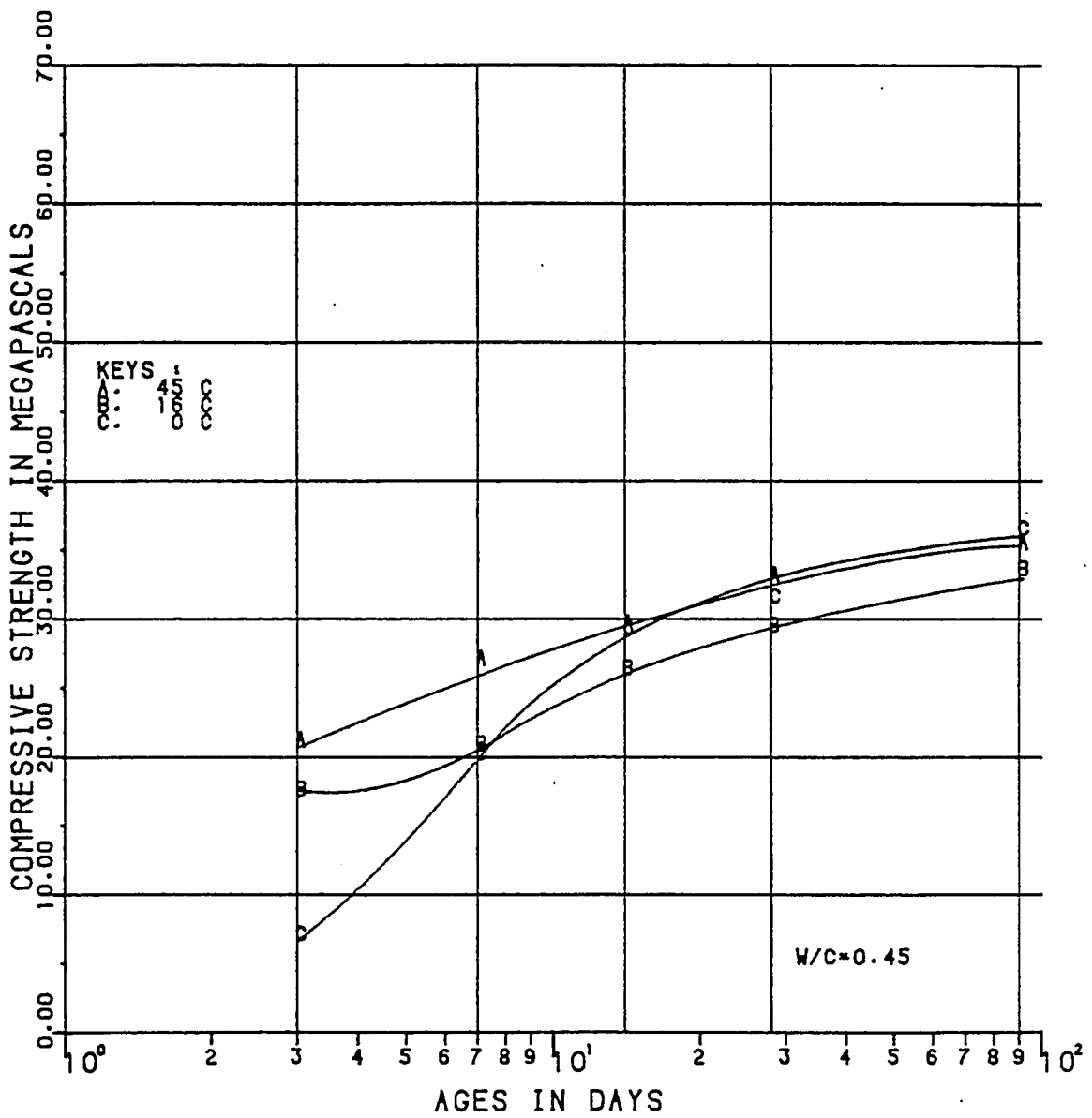


FIGURE 5.5 : VARIATION OF CONCRETE STRENGTH WITH TEMPERATURE

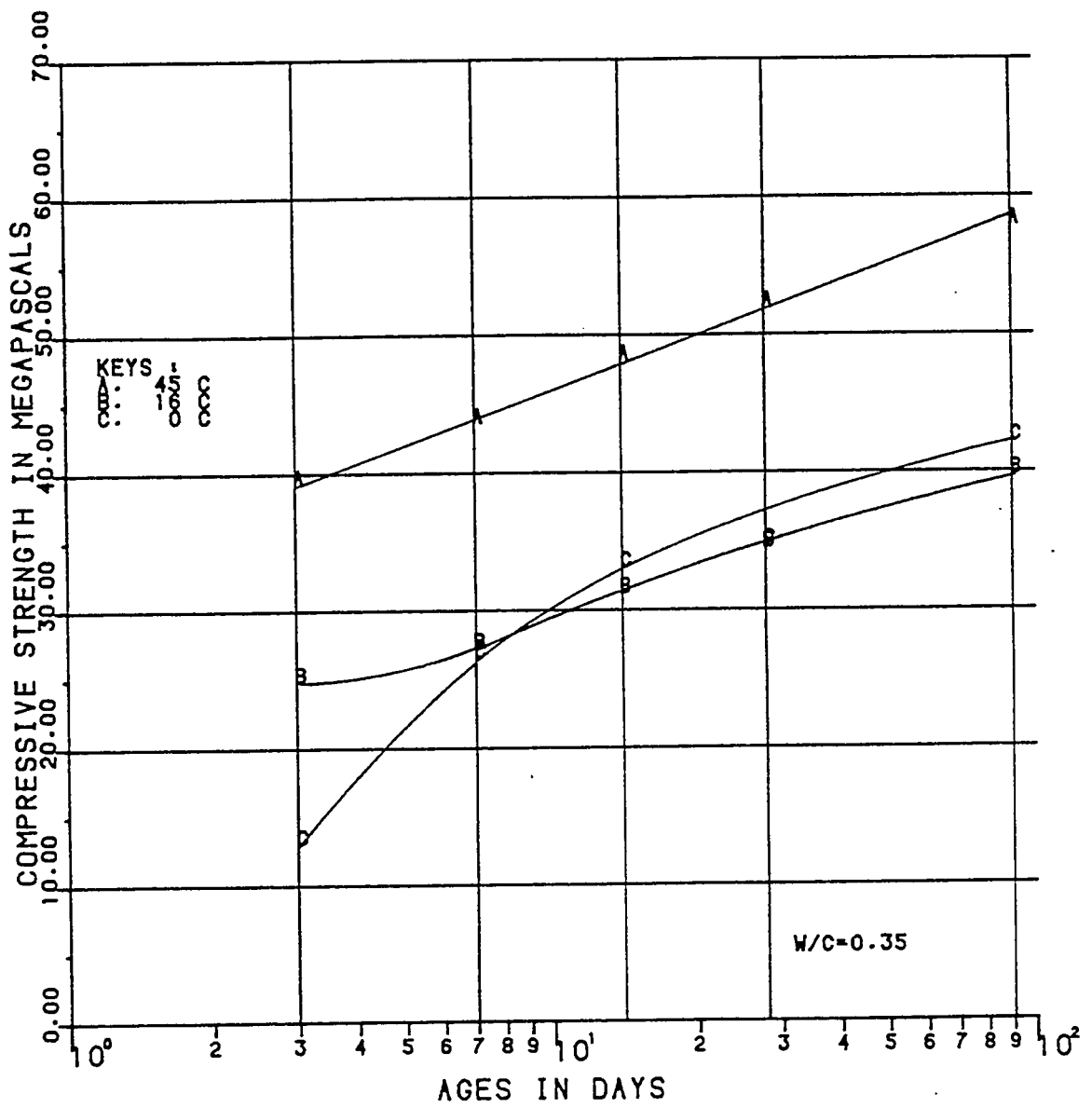


FIGURE 5.6 : VARIATION OF CONCRETE STRENGTH WITH TEMPERATURE

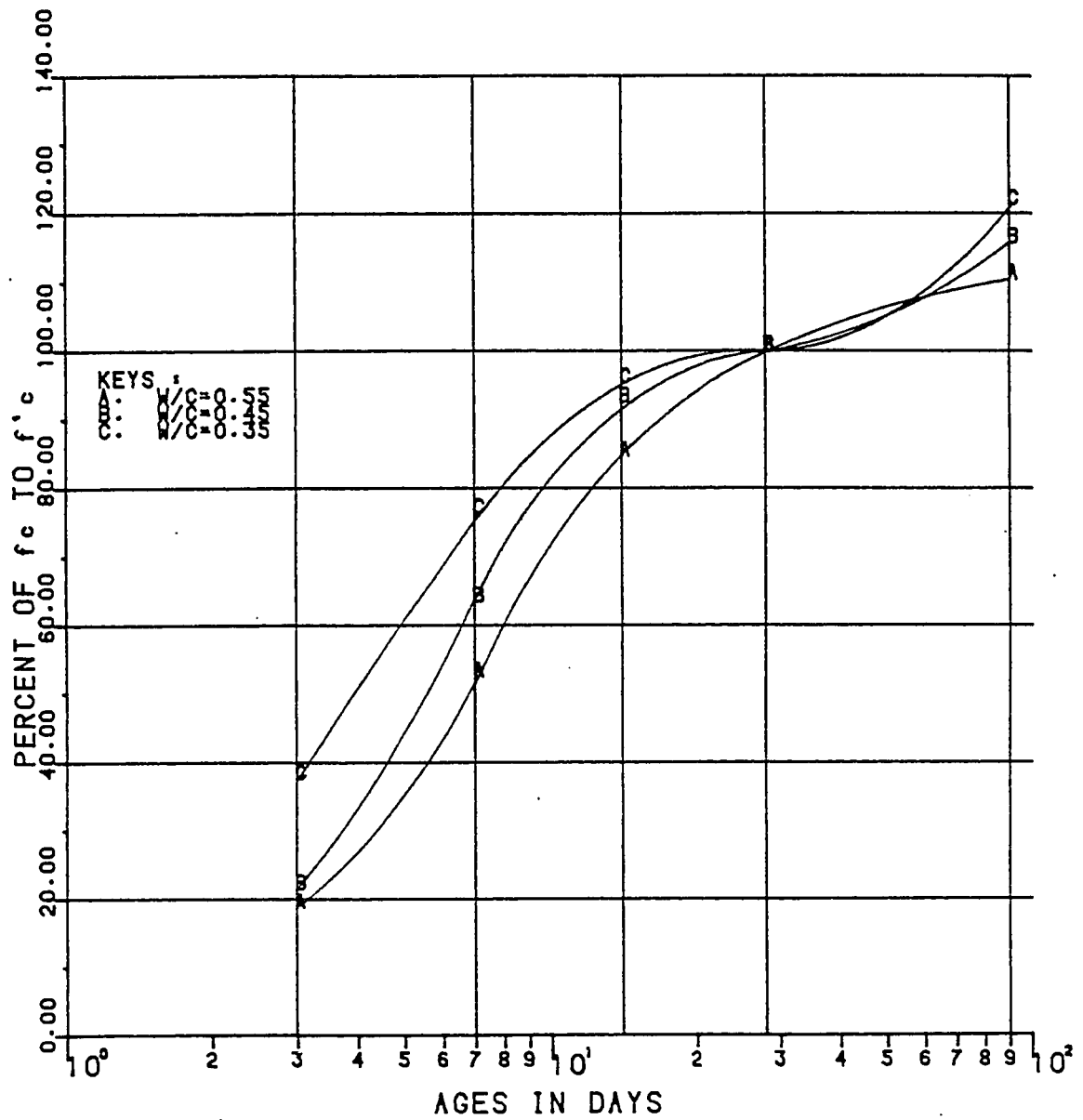


FIGURE 5.7 • DEVELOPMENT OF CONCRETE STRENGTH CAST/CURED AT 0°C

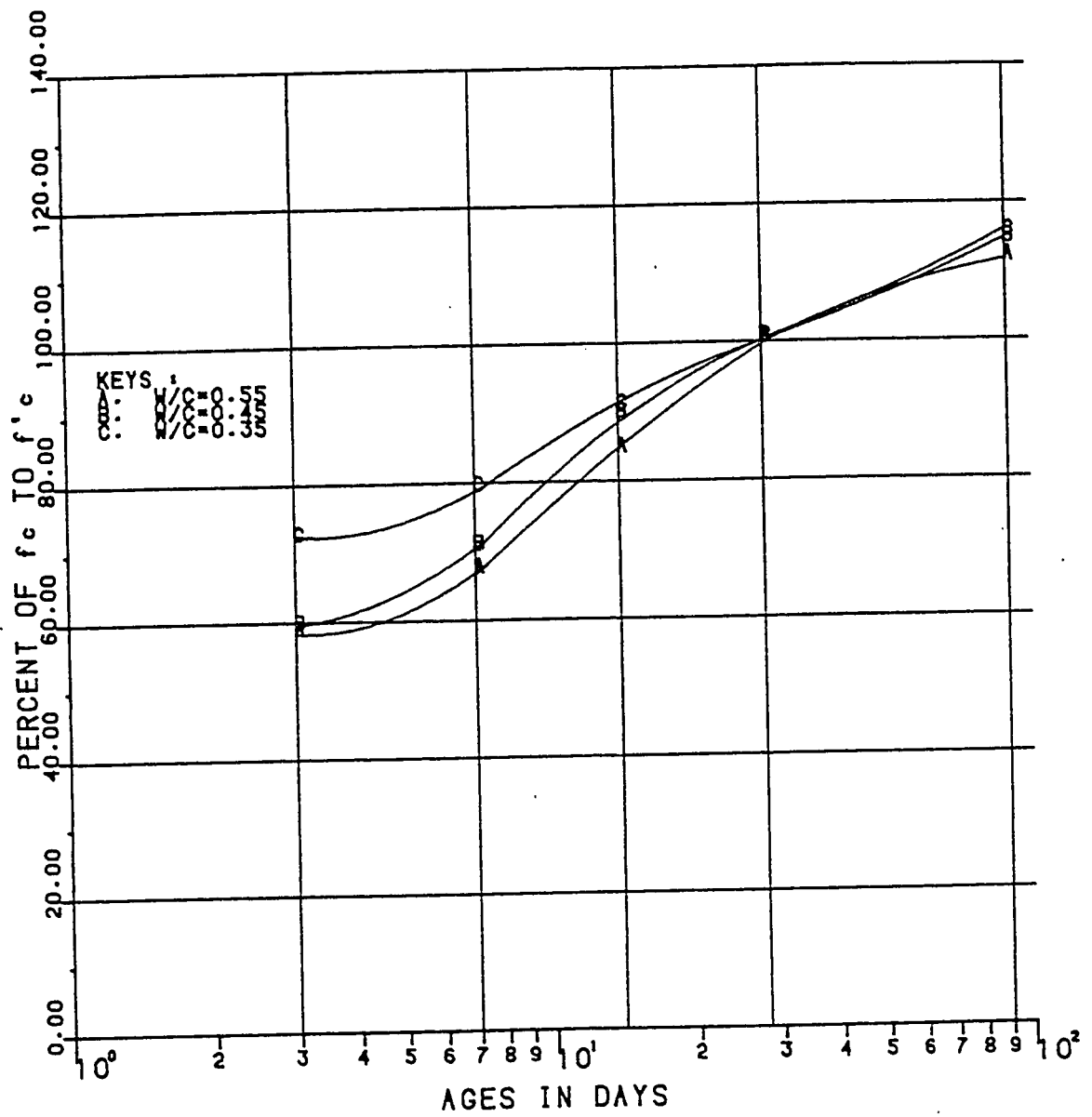
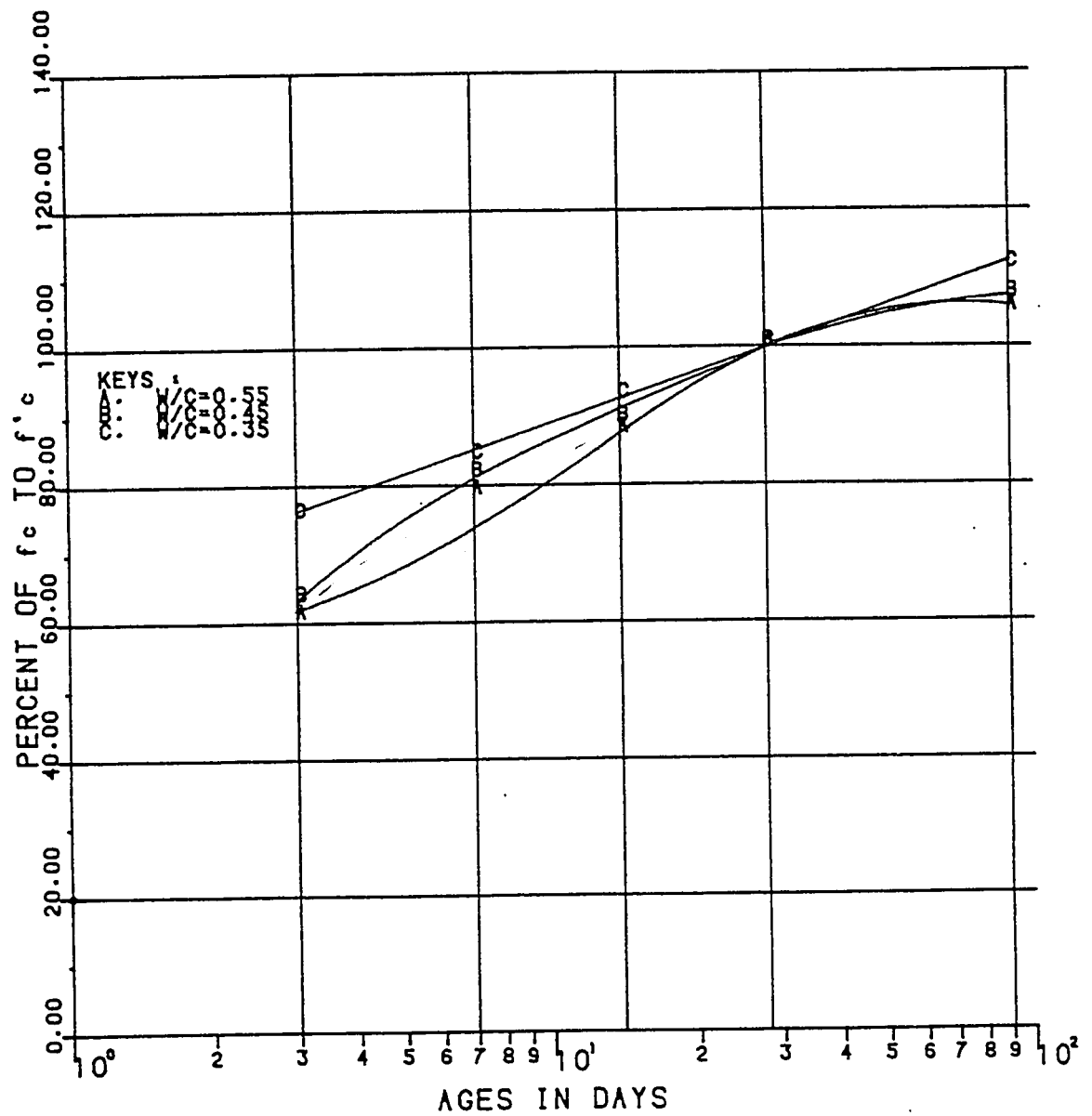


FIGURE 5.8 : DEVELOPMENT OF CONCRETE STRENGTH CAST/CURED AT 16°C



* FIGURE 5.9 : DEVELOPMENT OF CONCRETE STRENGTH CAST/CURED AT 45°C

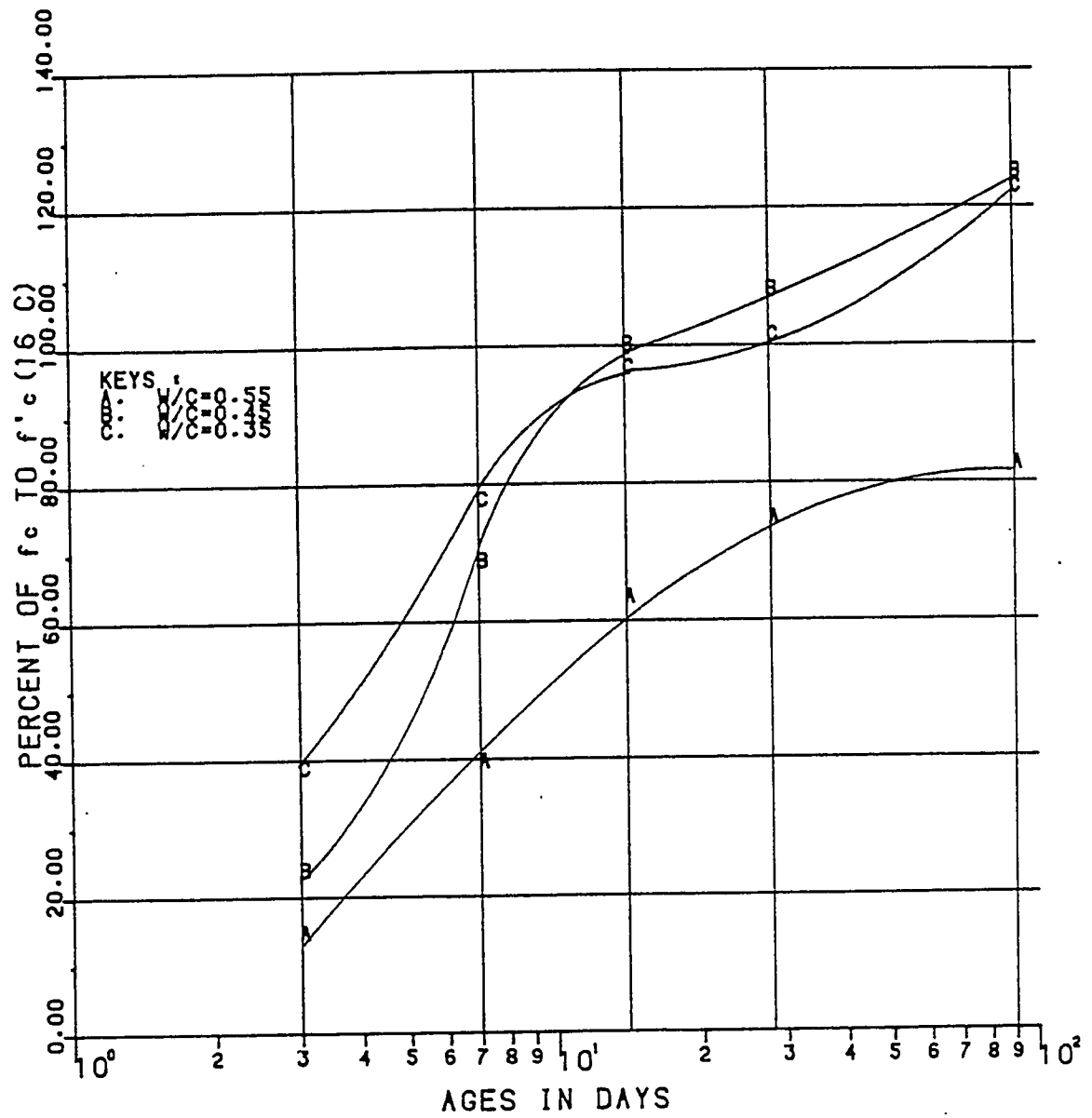


FIGURE 5.10: DEVELOPMENT OF CONCRETE STRENGTH CAST/CURED AT 0°C

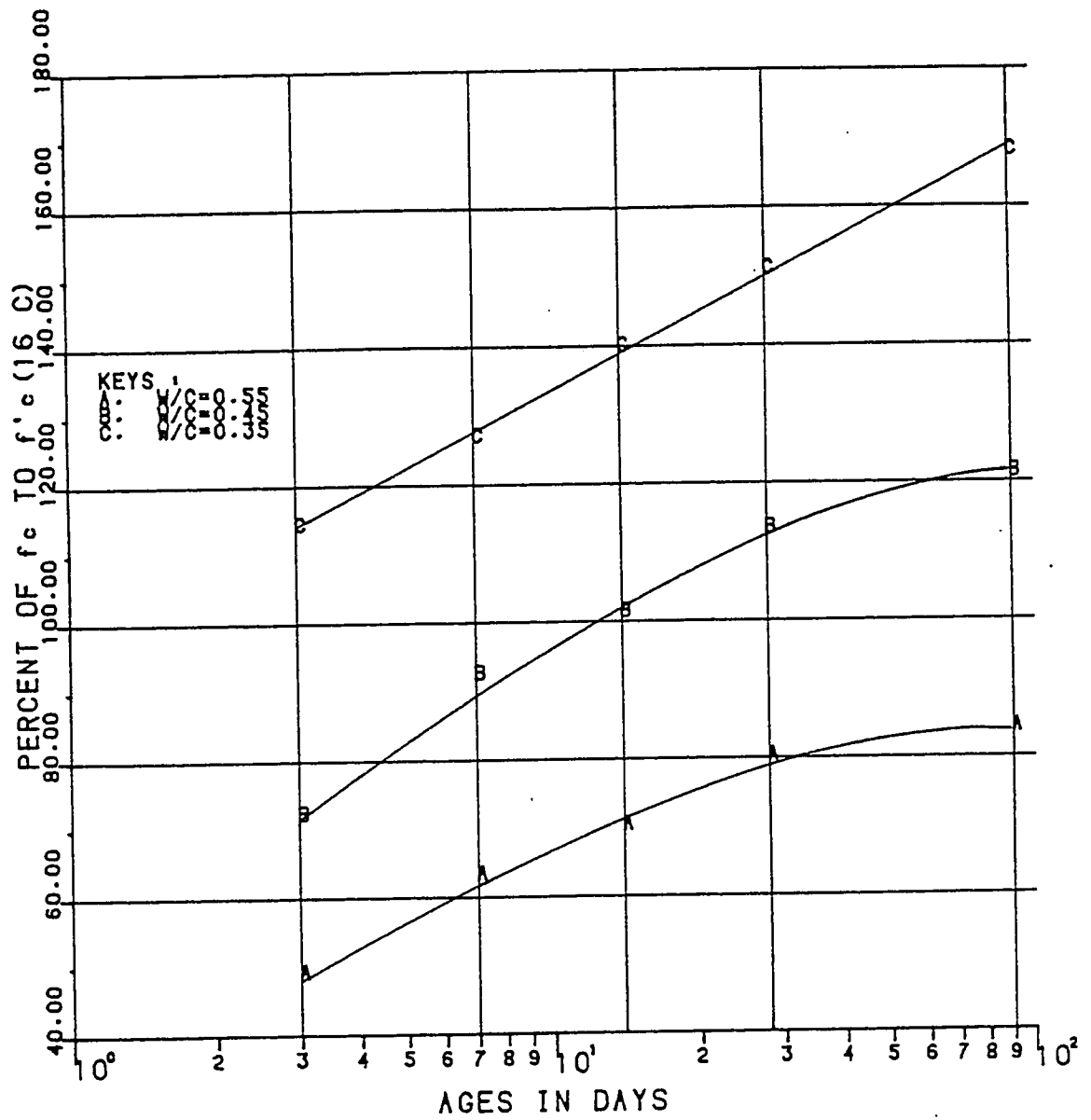


FIGURE 5.11: DEVELOPMENT OF CONCRETE STRENGTH CAST/CURED AT 45°C

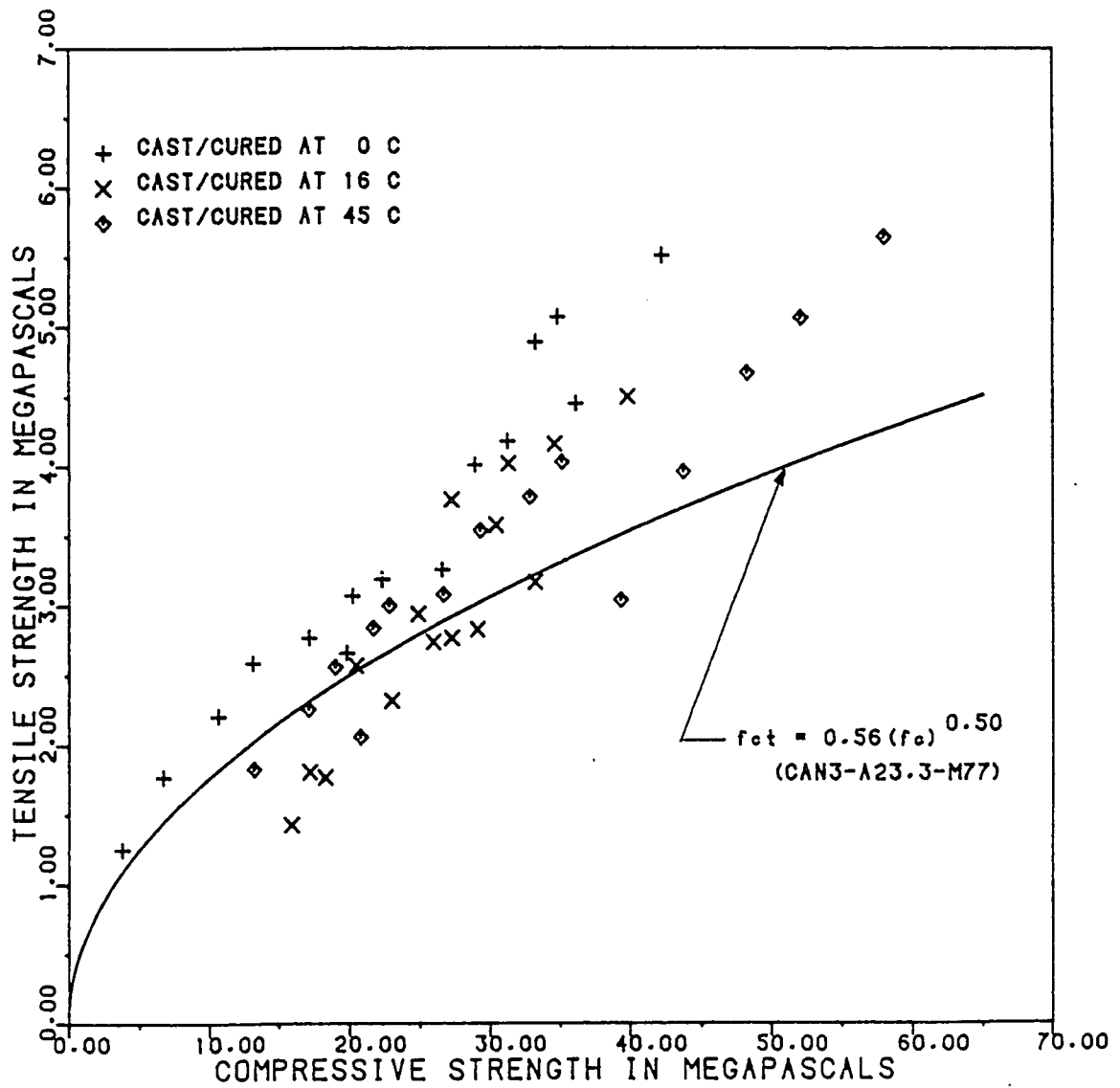


FIGURE 5.12 : RELATIONSHIP BETWEEN TENSILE & COMPRESSIVE STRENGTH

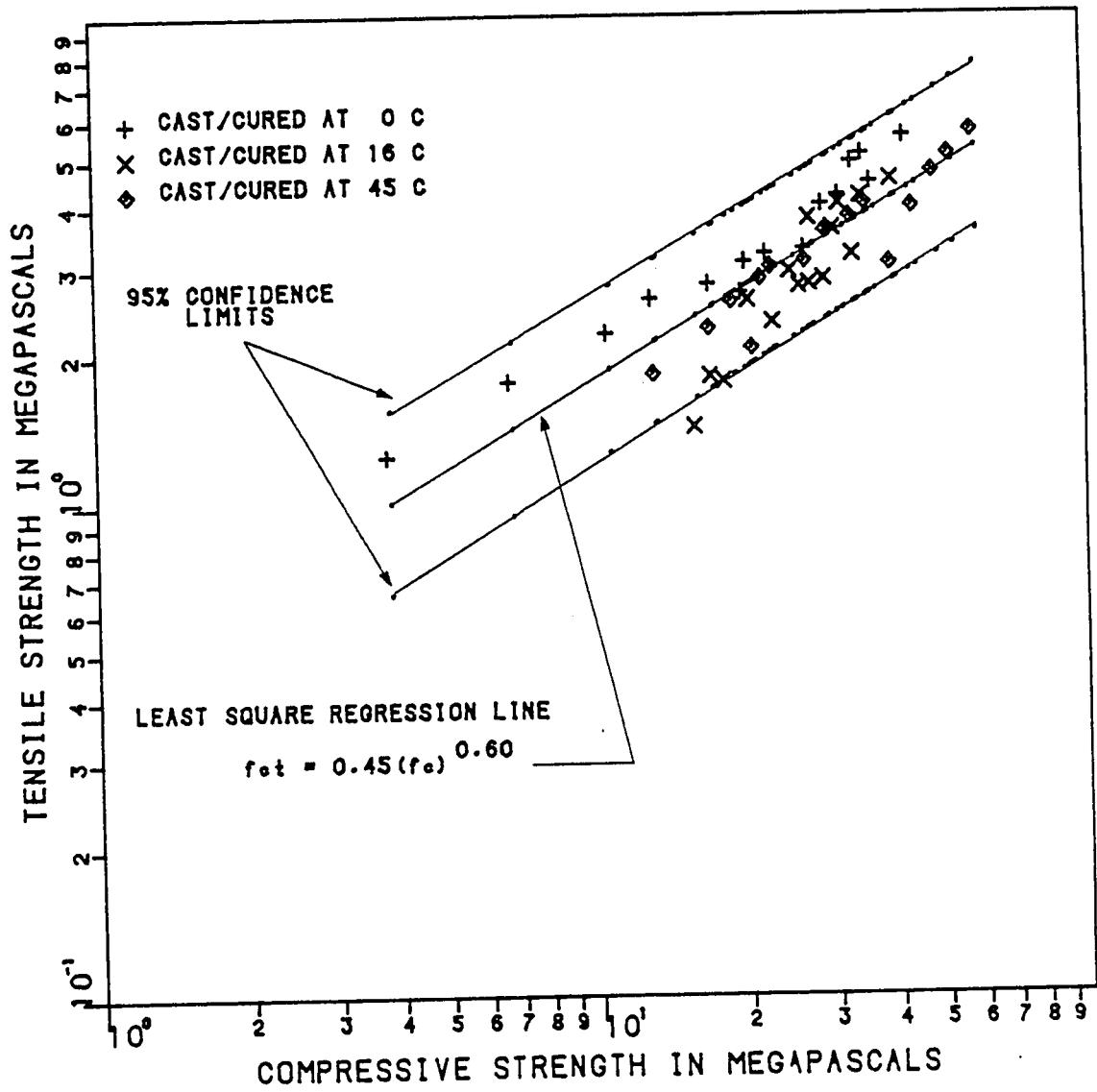


FIGURE 5.13 : RELATIONSHIP BETWEEN TENSILE & COMPRESSIVE STRENGTH

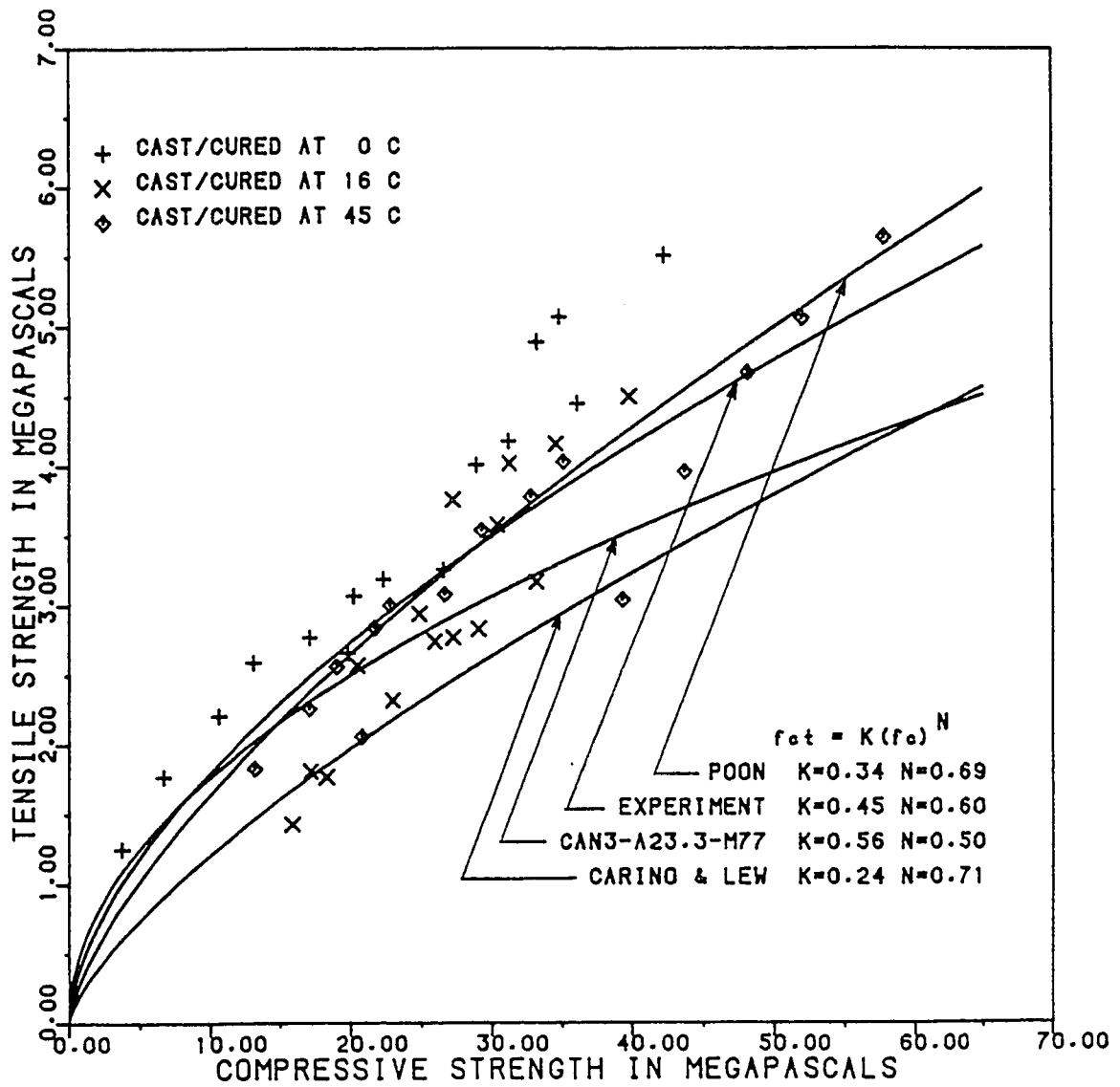


FIGURE 5.14 • RELATIONSHIP BETWEEN TENSILE & COMPRESSIVE STRENGTH

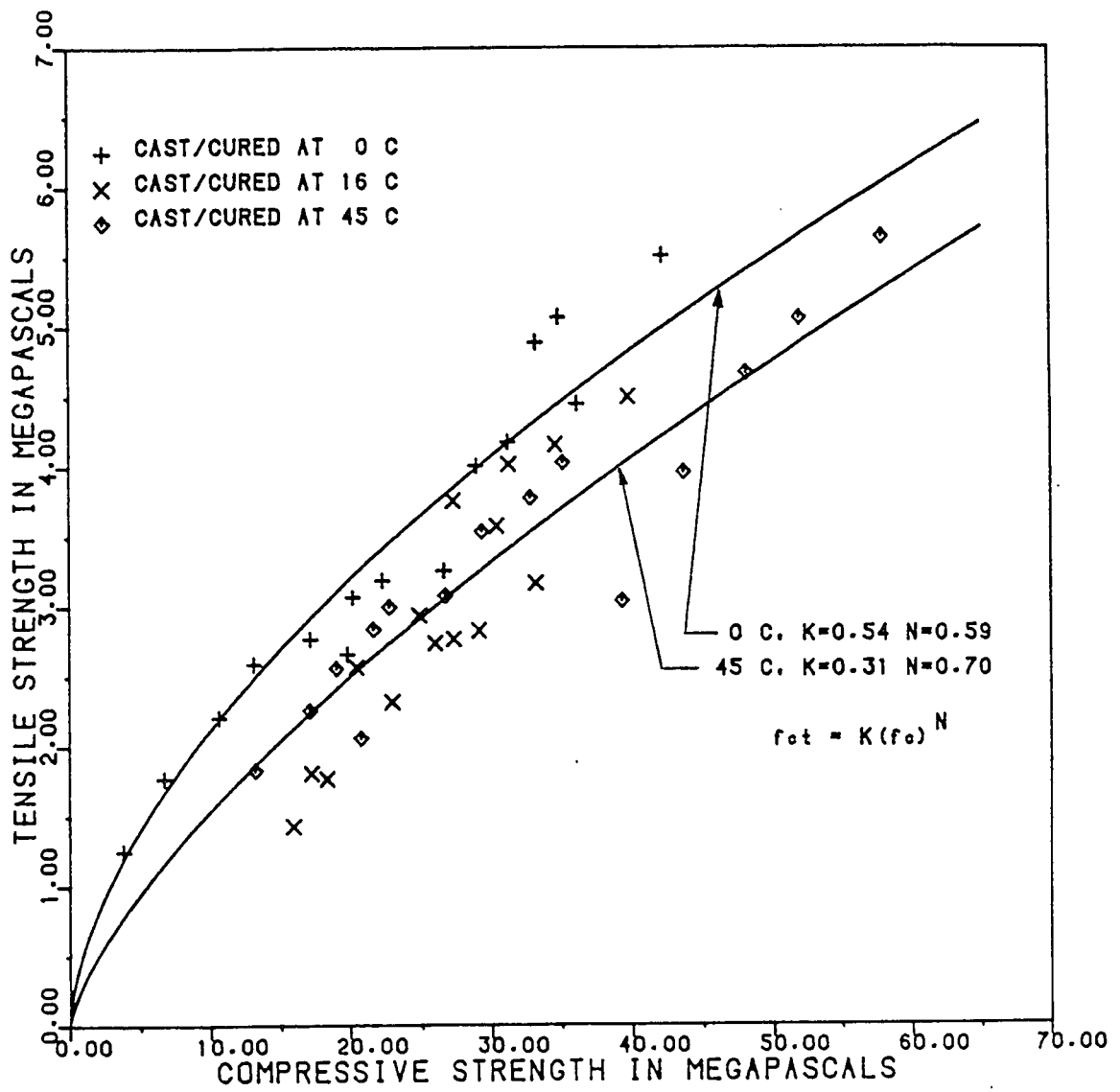


FIGURE 5.15 • RELATIONSHIP BETWEEN TENSILE & COMPRESSIVE STRENGTH

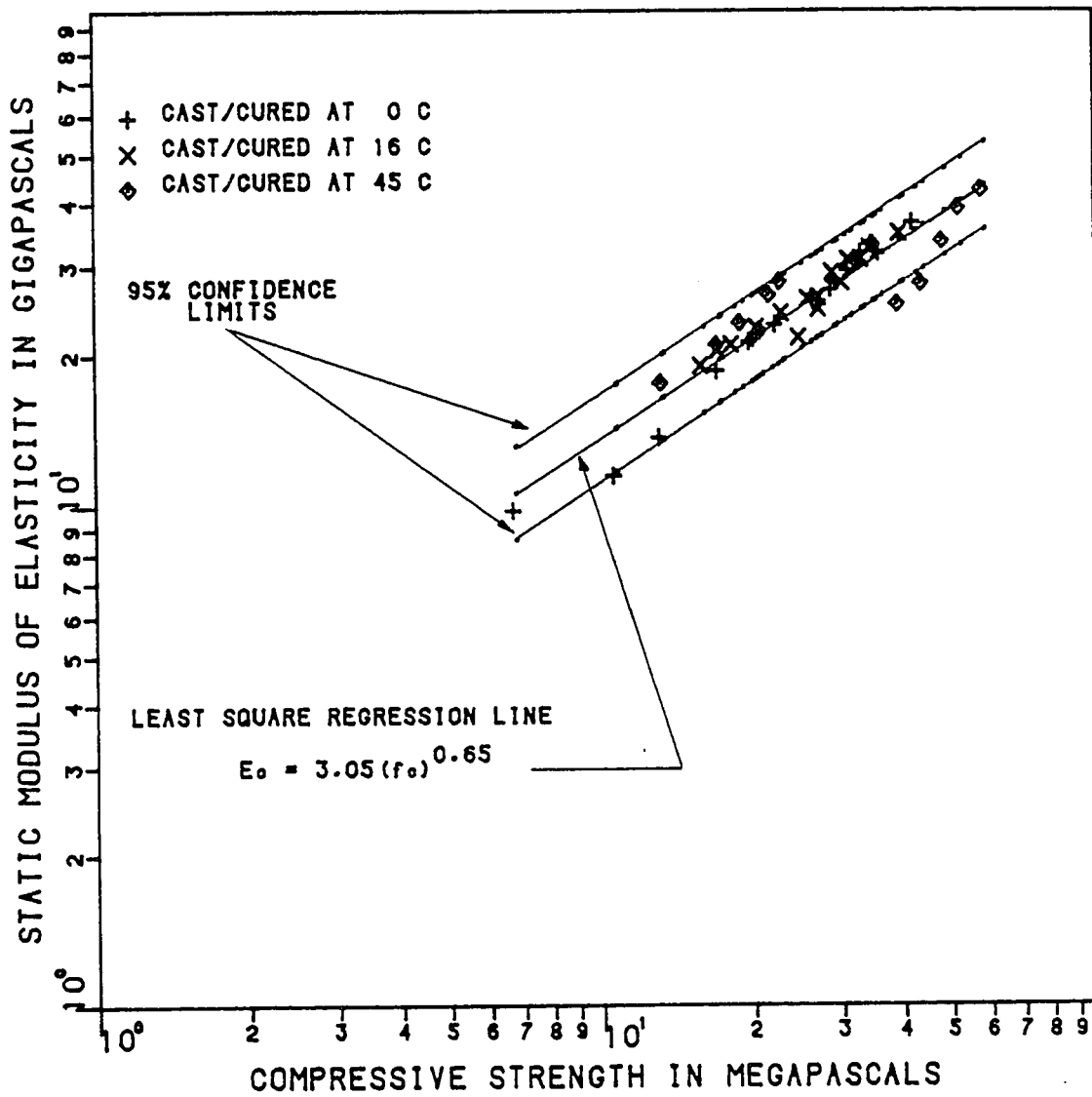


FIGURE 5.16 • RELATIONSHIP BETWEEN E_o & f_o

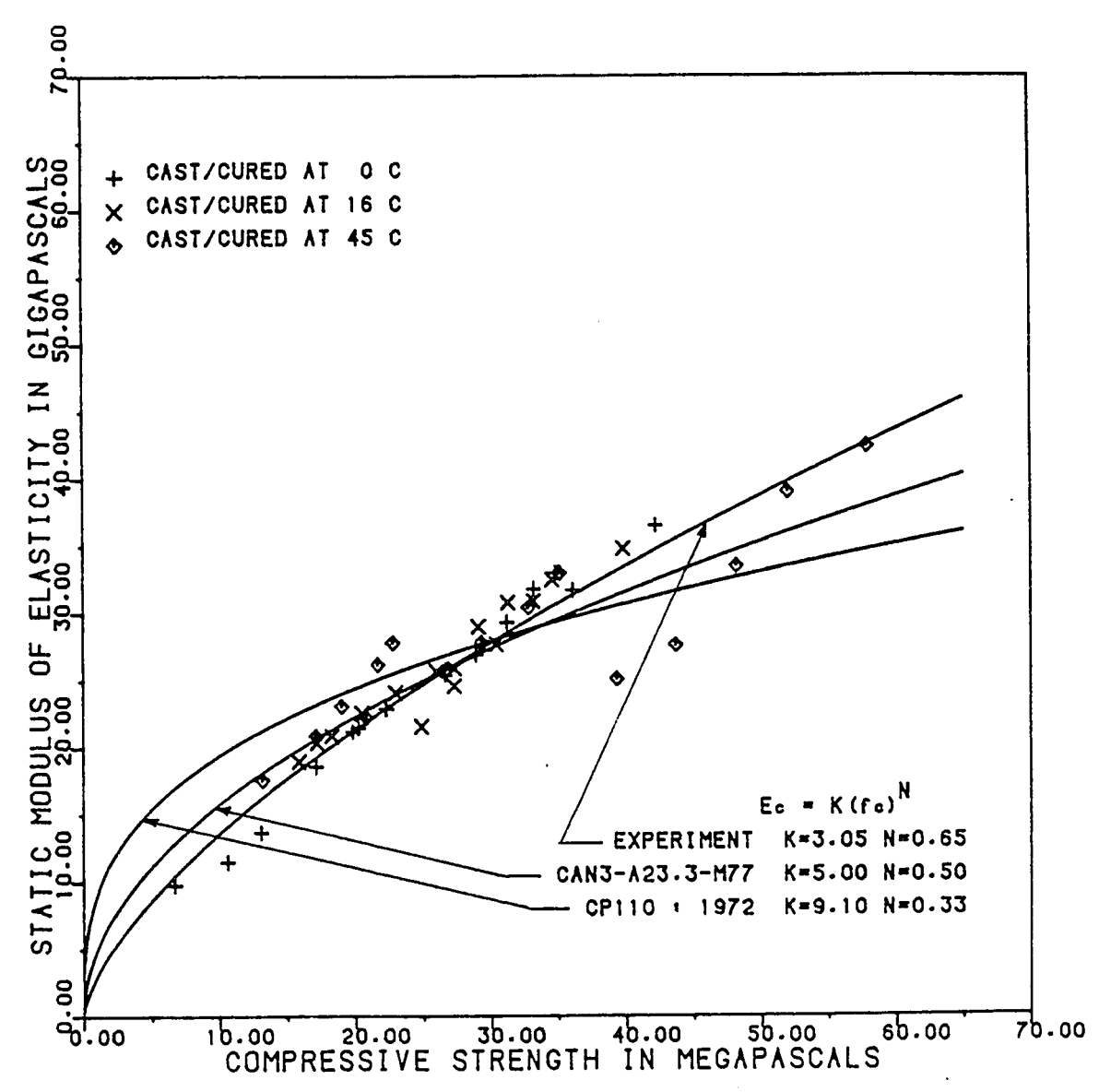
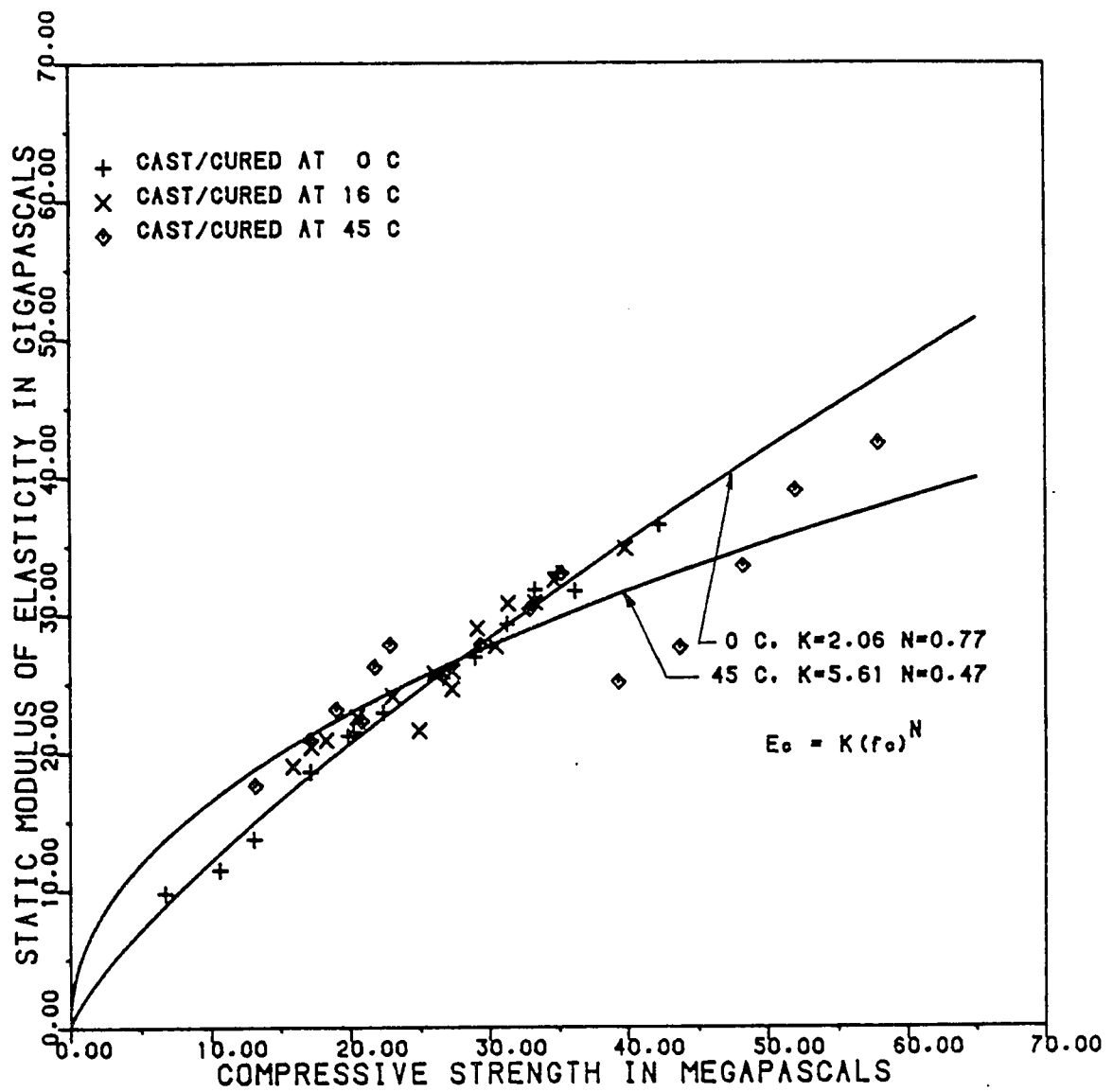


FIGURE 5.17 : RELATIONSHIP BETWEEN E_c & f_c

FIGURE 5.18 : RELATIONSHIP BETWEEN E_o & f_o

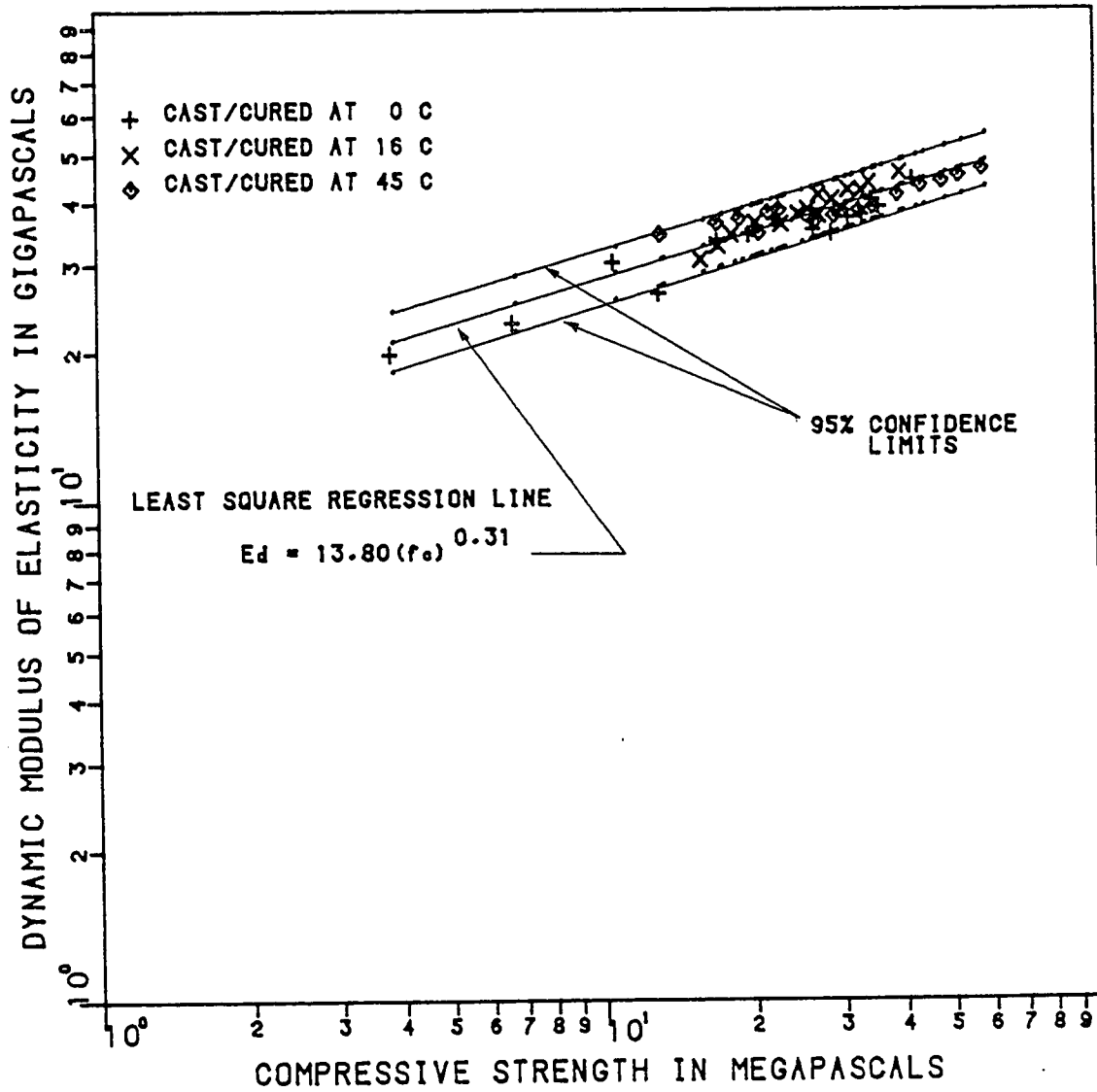
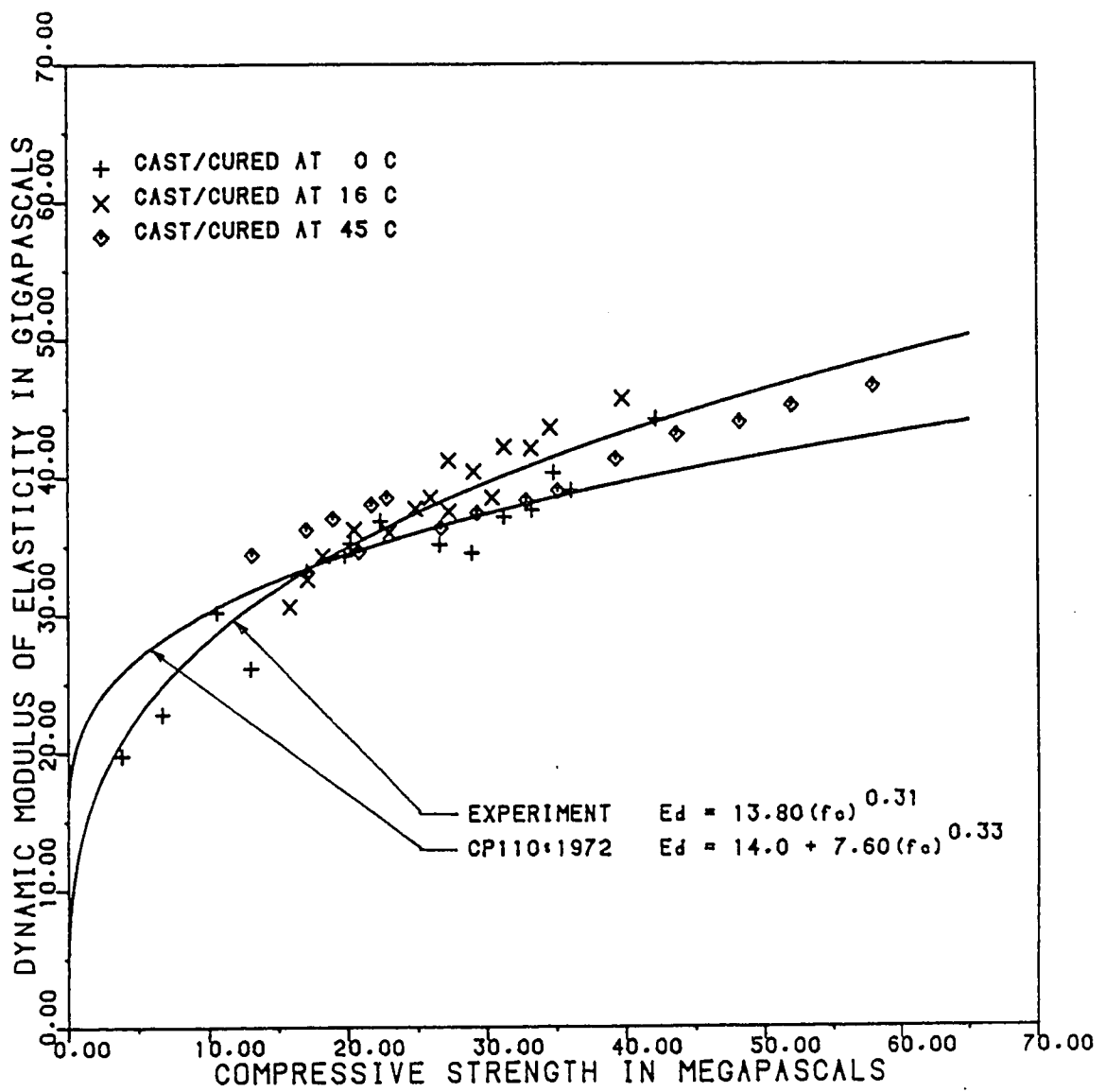


FIGURE 5.19 : RELATIONSHIP BETWEEN E_d & f_c

FIGURE 5.20 : RELATIONSHIP BETWEEN E_d & f_c

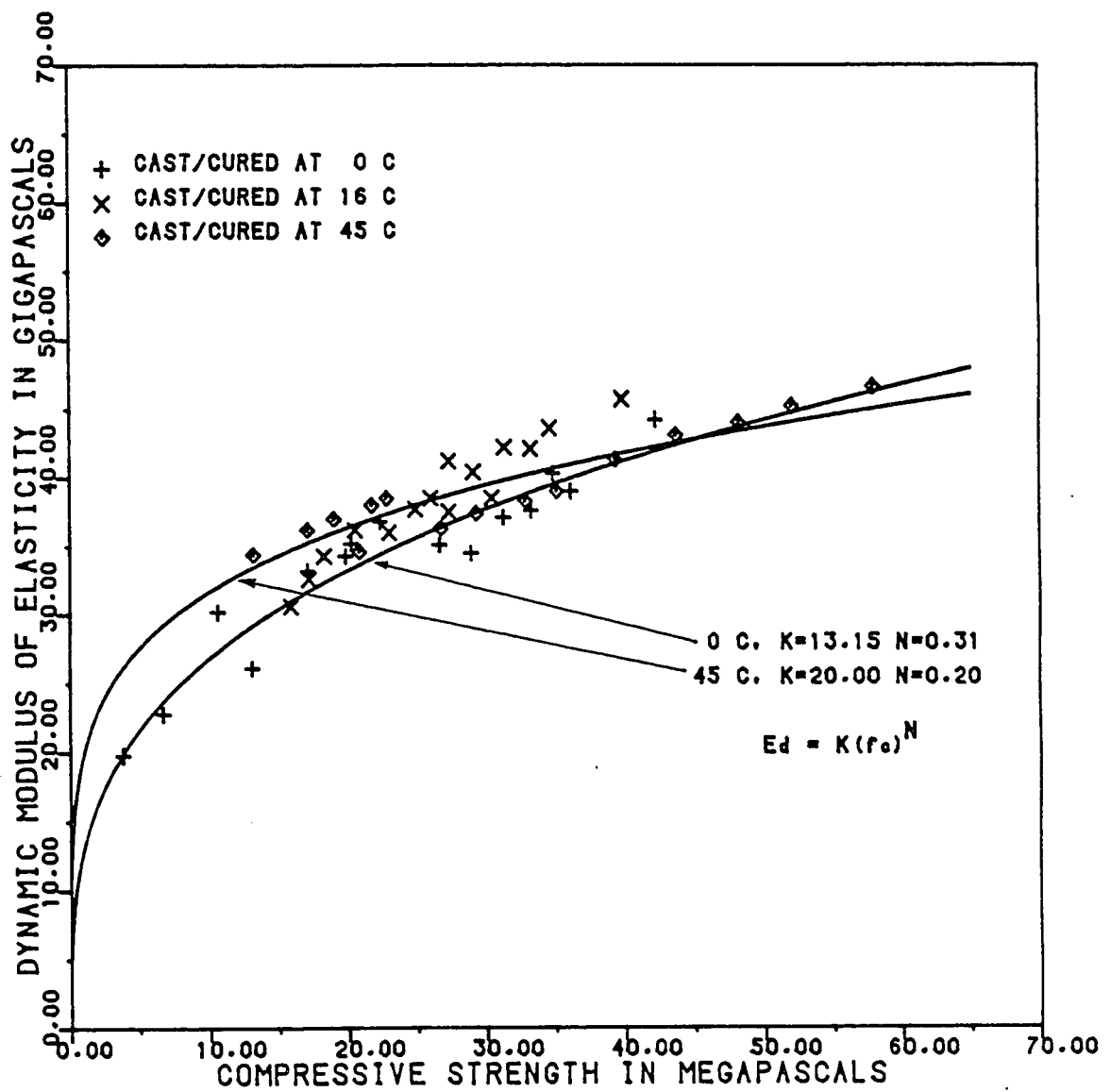


FIGURE 5.21 • RELATIONSHIP BETWEEN E_d & f_c

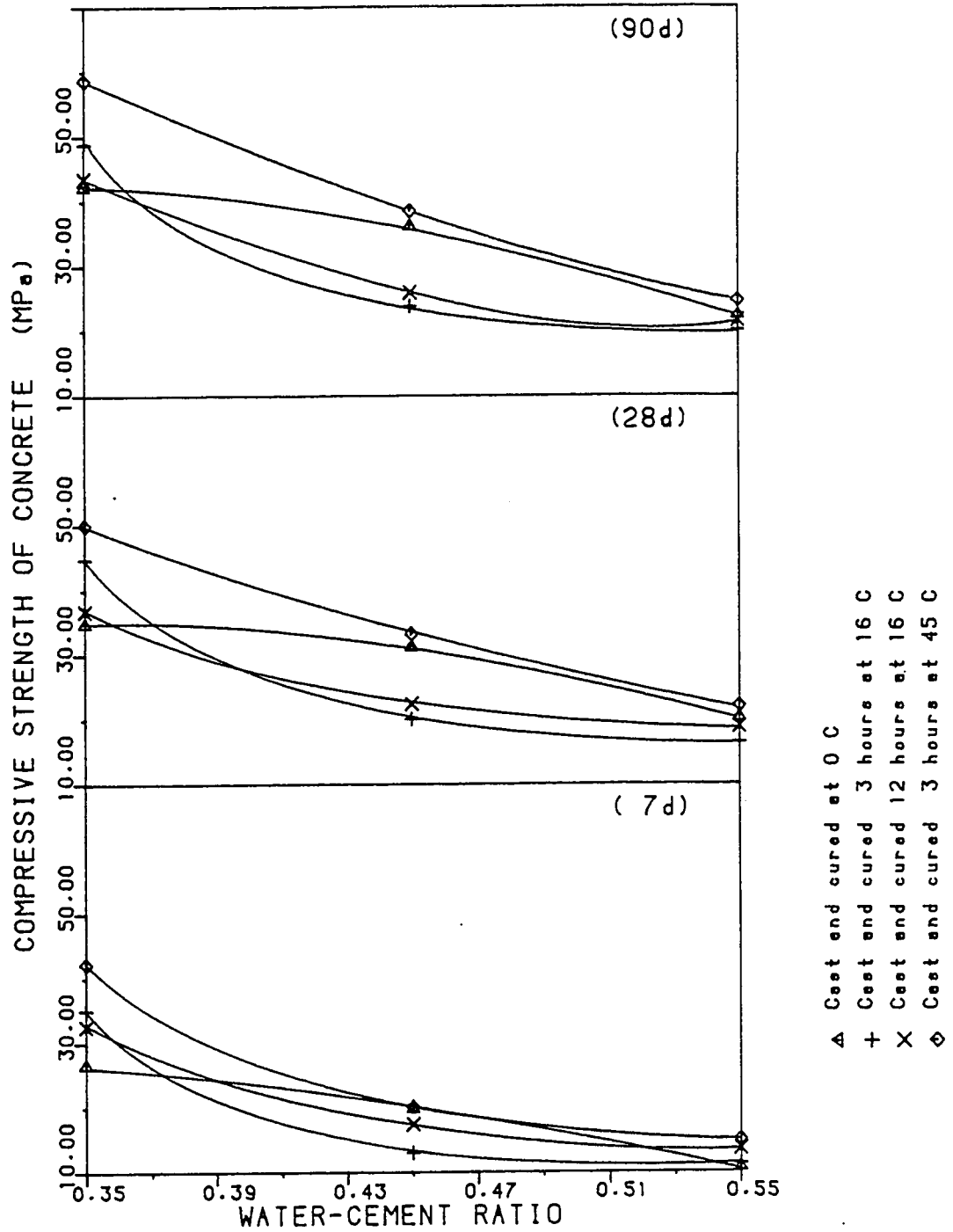


FIGURE 5.22 : STRENGTH OF CONCRETE CURED AT 0 C

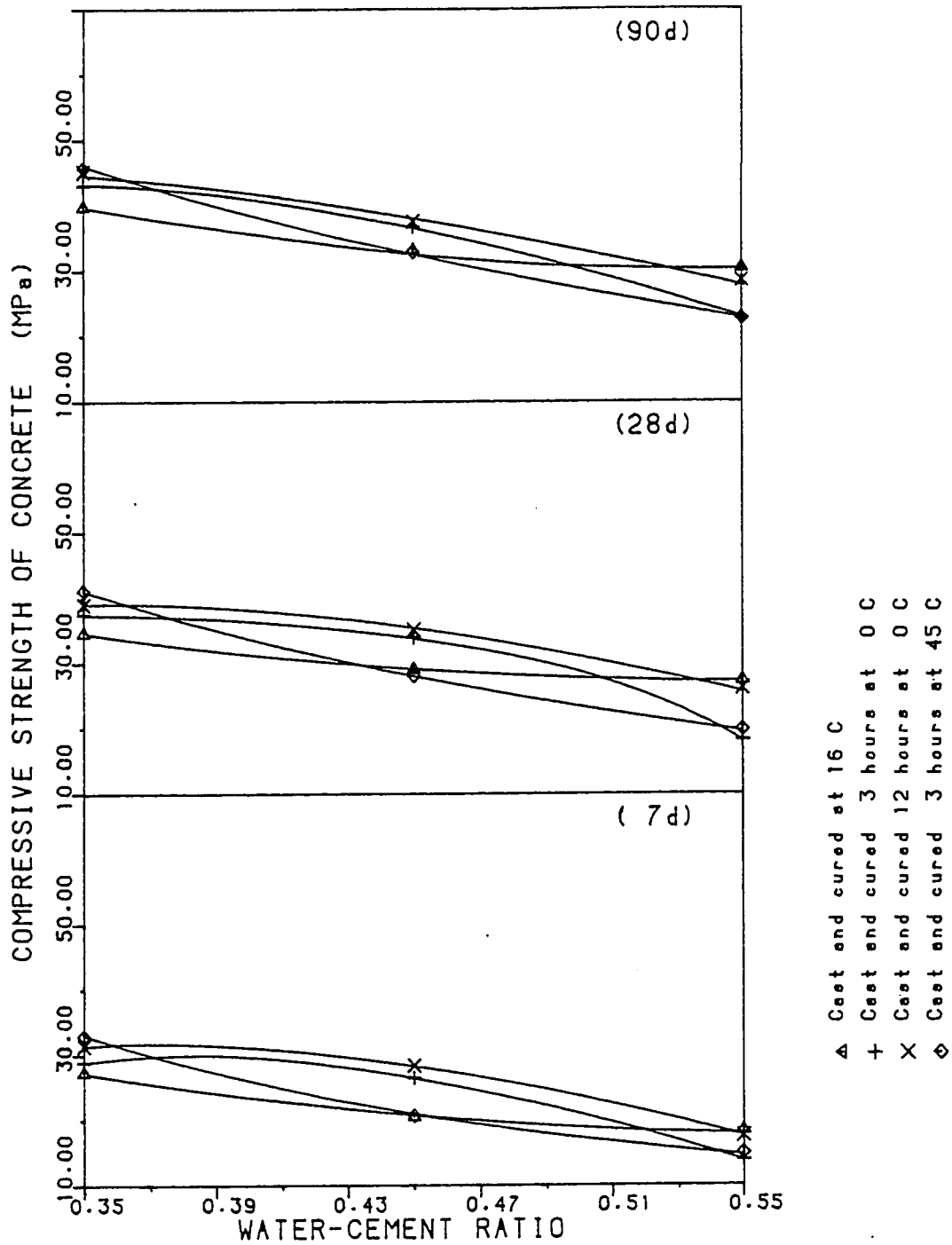


FIGURE 5.23 : STRENGTH OF CONCRETE CURED AT 16 C

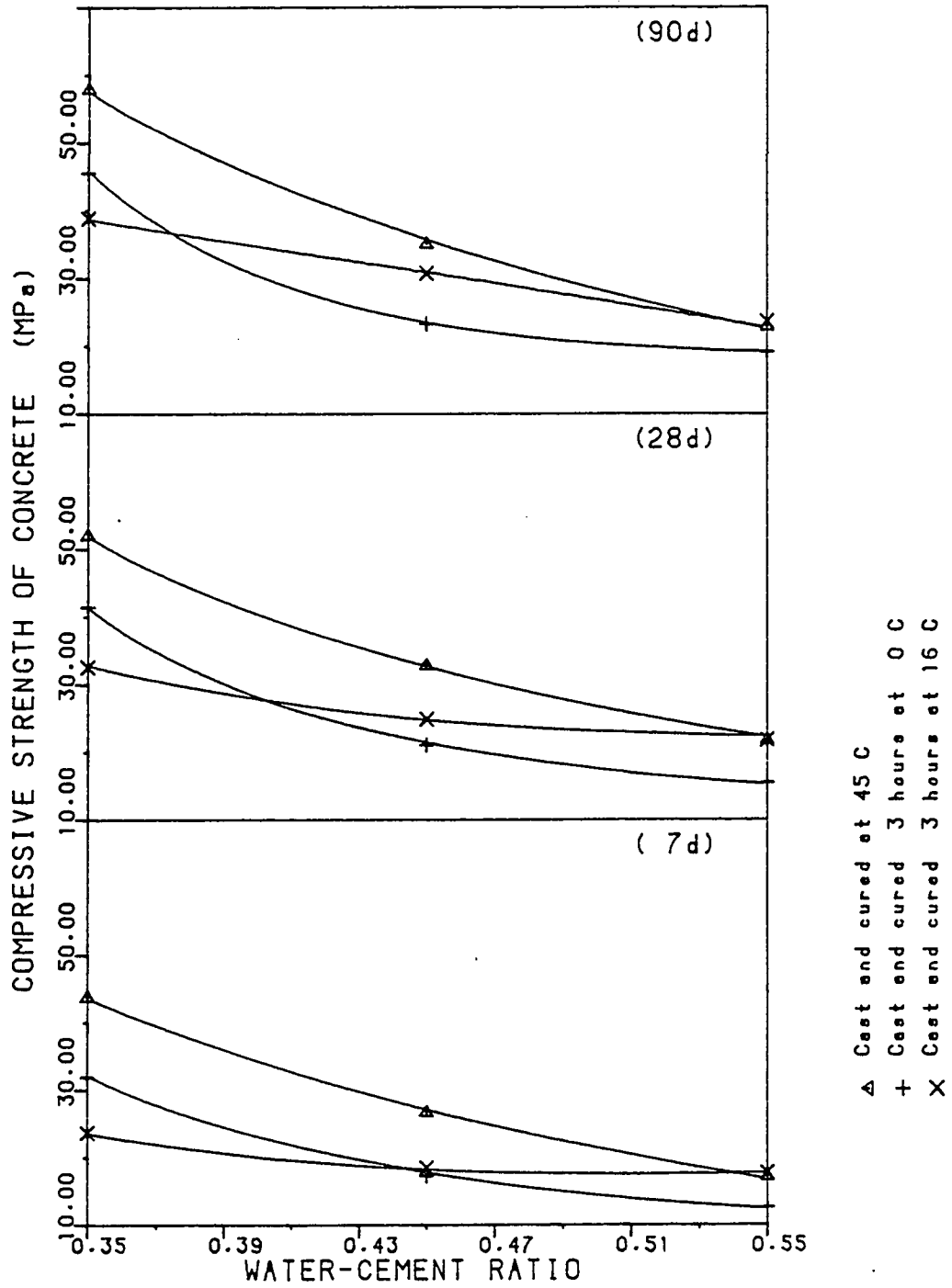


FIGURE 5.24 : STRENGTH OF CONCRETE CURED AT 45 C

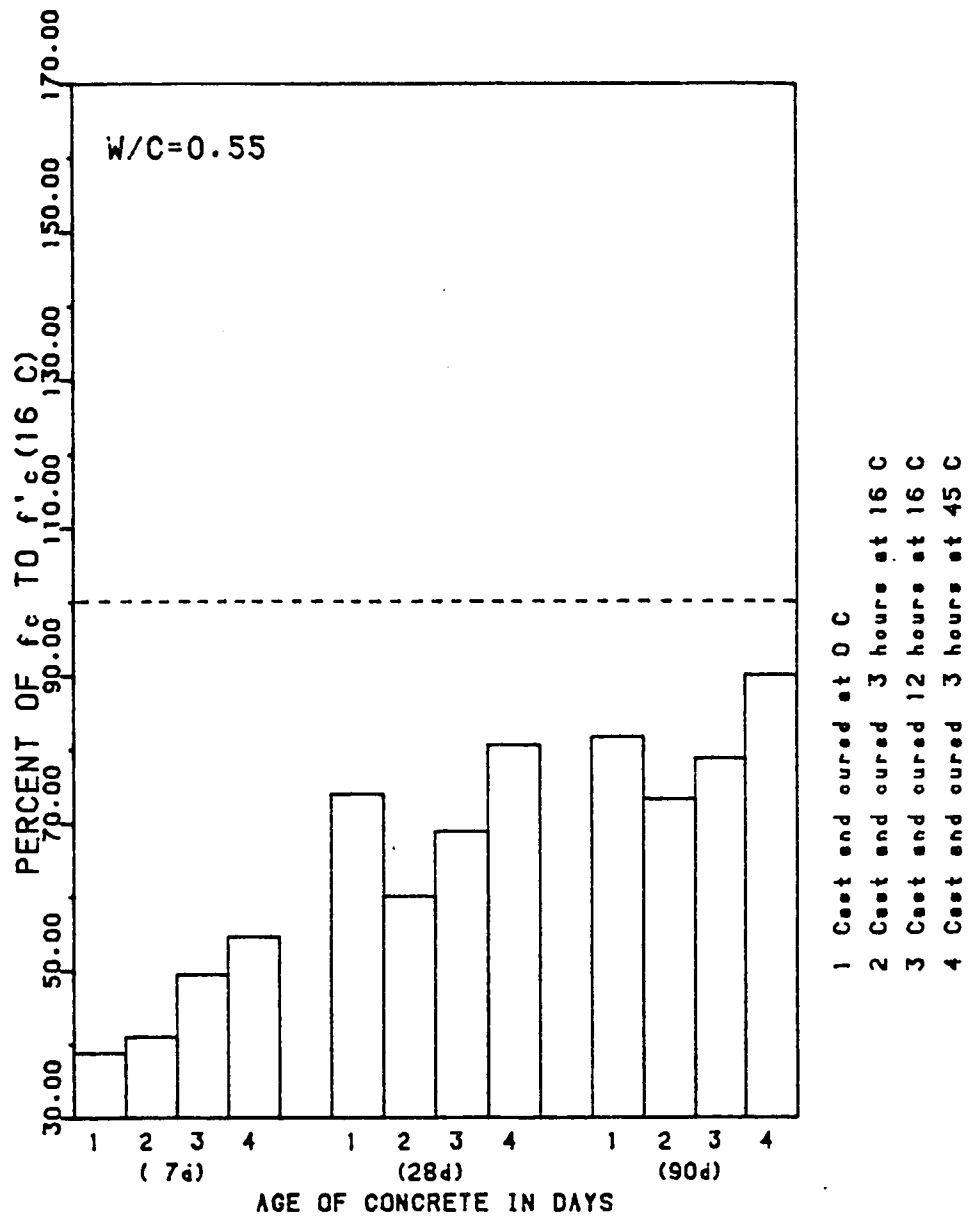


FIGURE 5.25 • STRENGTH DEVELOPMENT OF CONCRETE CURED AT 0 C

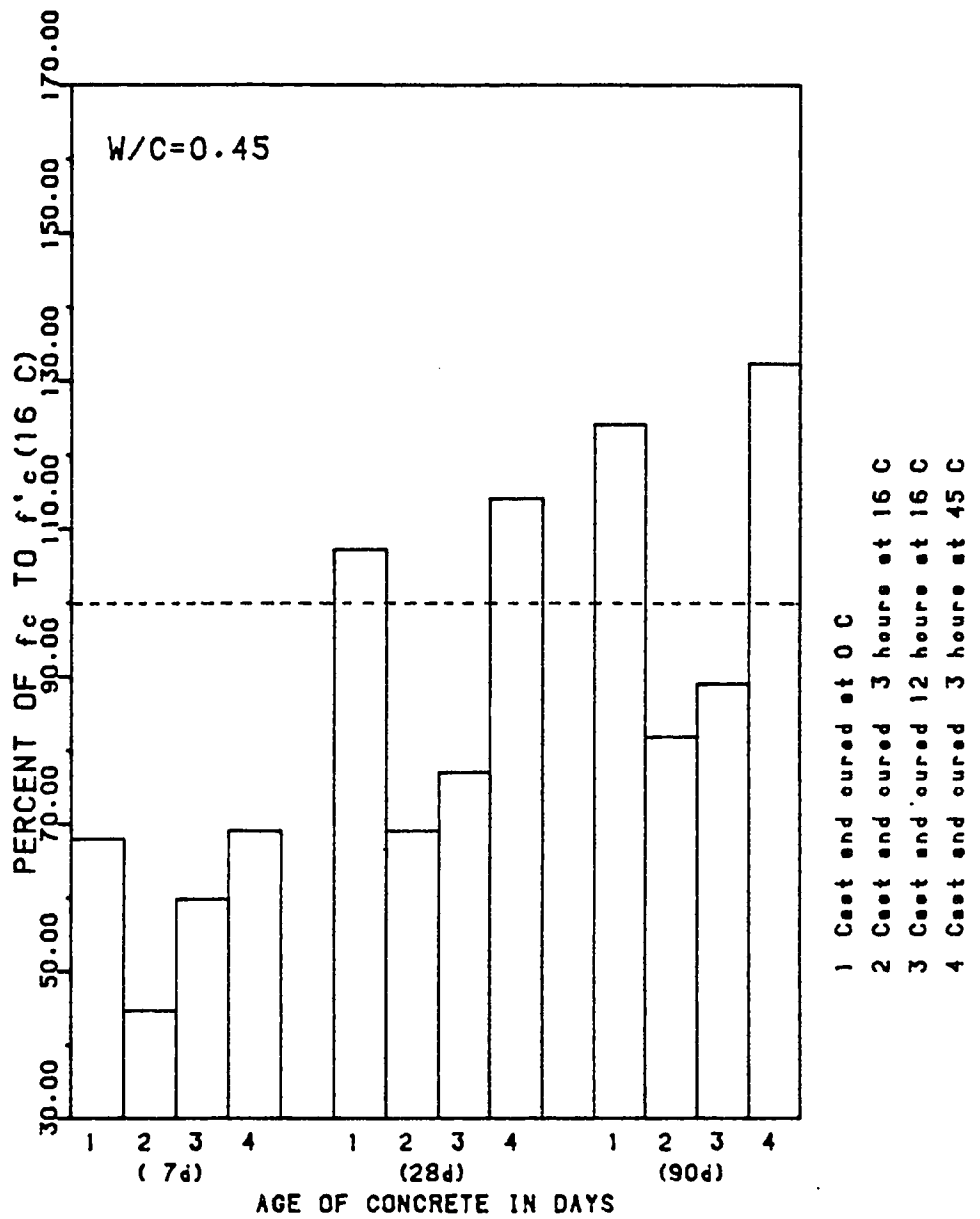


FIGURE 5-26 : STRENGTH DEVELOPMENT OF CONCRETE CURED AT 0 C

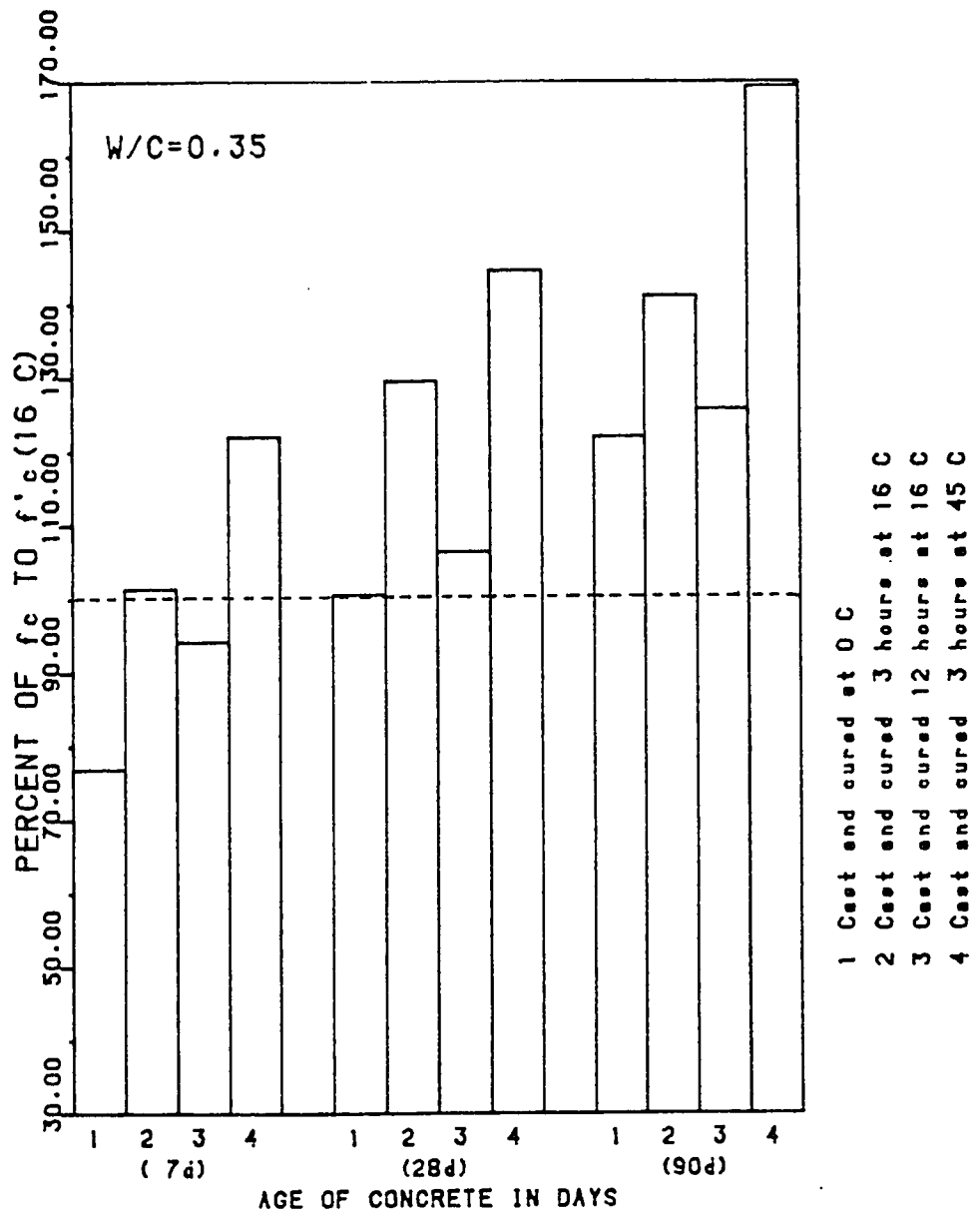


FIGURE 5-27 • STRENGTH DEVELOPMENT OF CONCRETE CURED AT 0 C

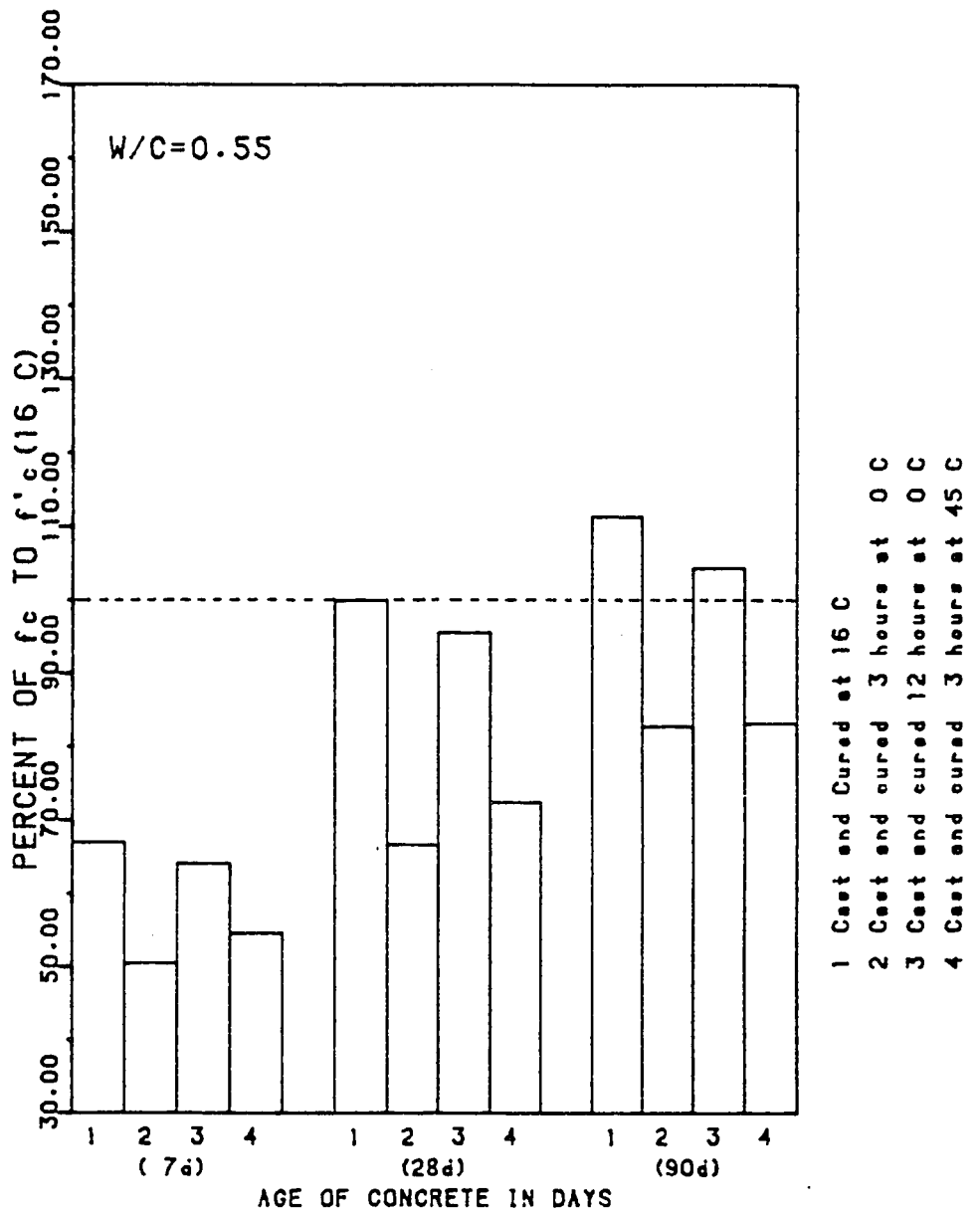


FIGURE 5-28 • STRENGTH DEVELOPMENT OF CONCRETE CURED AT 16 C

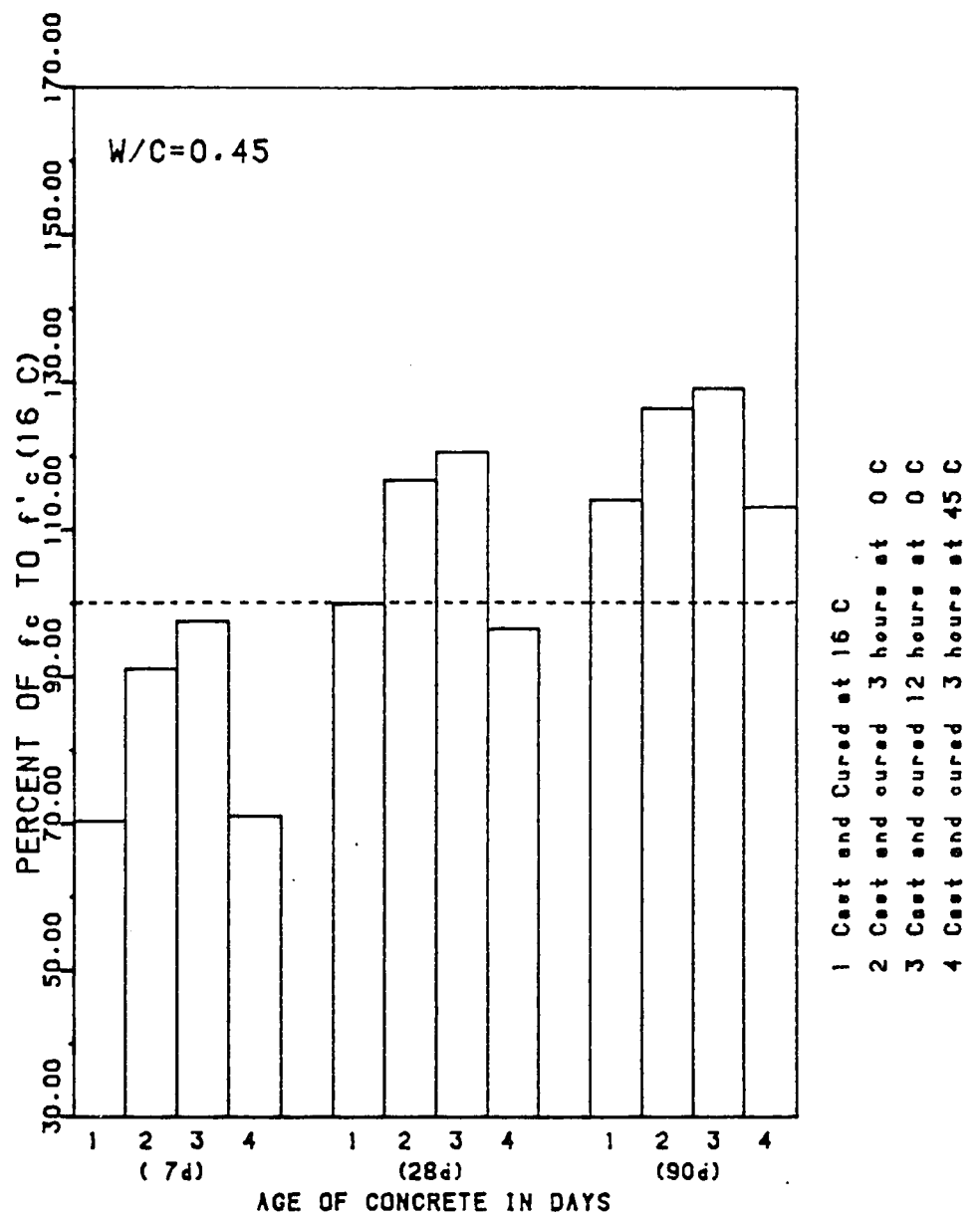


FIGURE 5-29 • STRENGTH DEVELOPMENT OF CONCRETE CURED AT 16 C

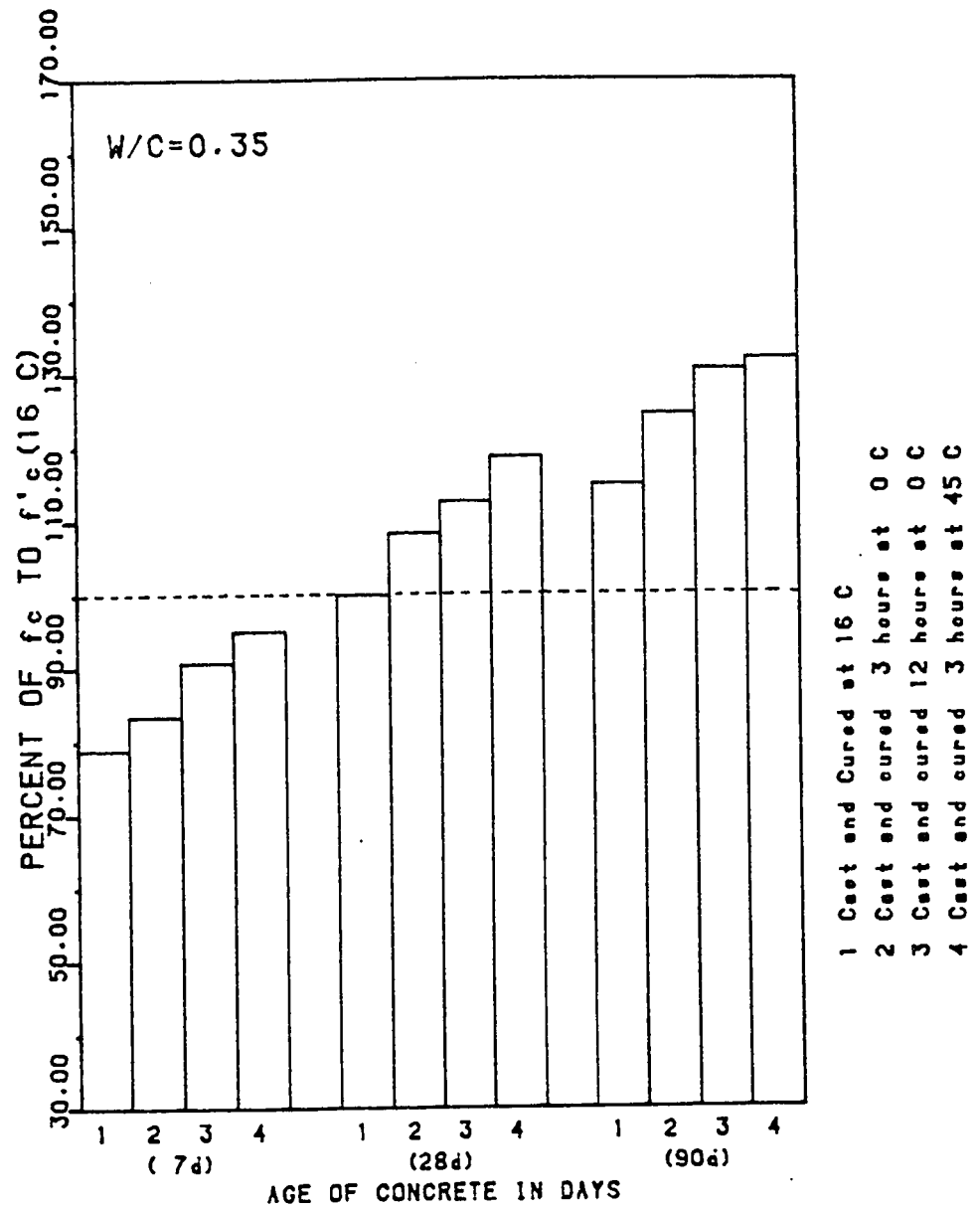


FIGURE 5.30 • STRENGTH DEVELOPMENT OF CONCRETE CURED AT 16 C

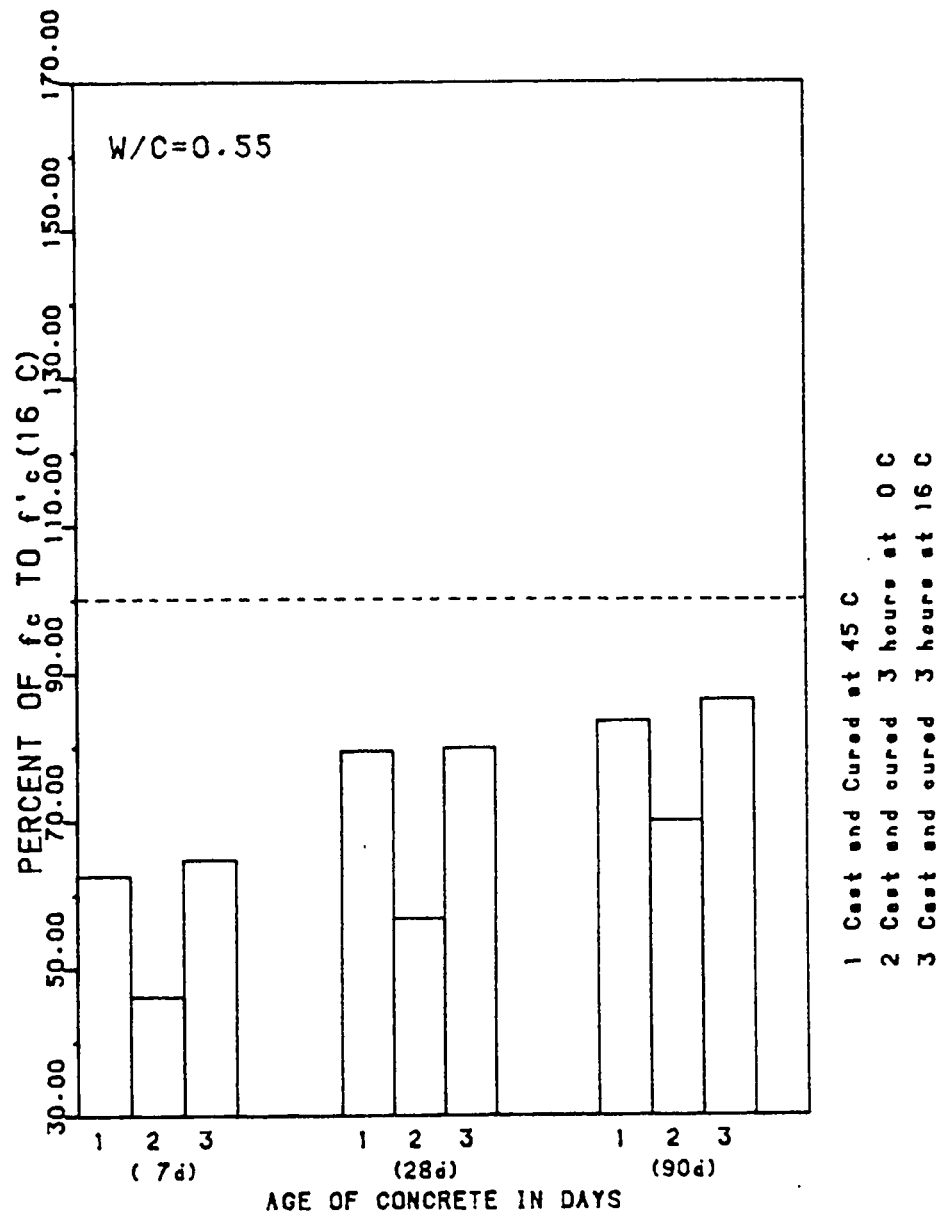


FIGURE 5.31 • STRENGTH DEVELOPMENT OF CONCRETE CURED AT 45 C

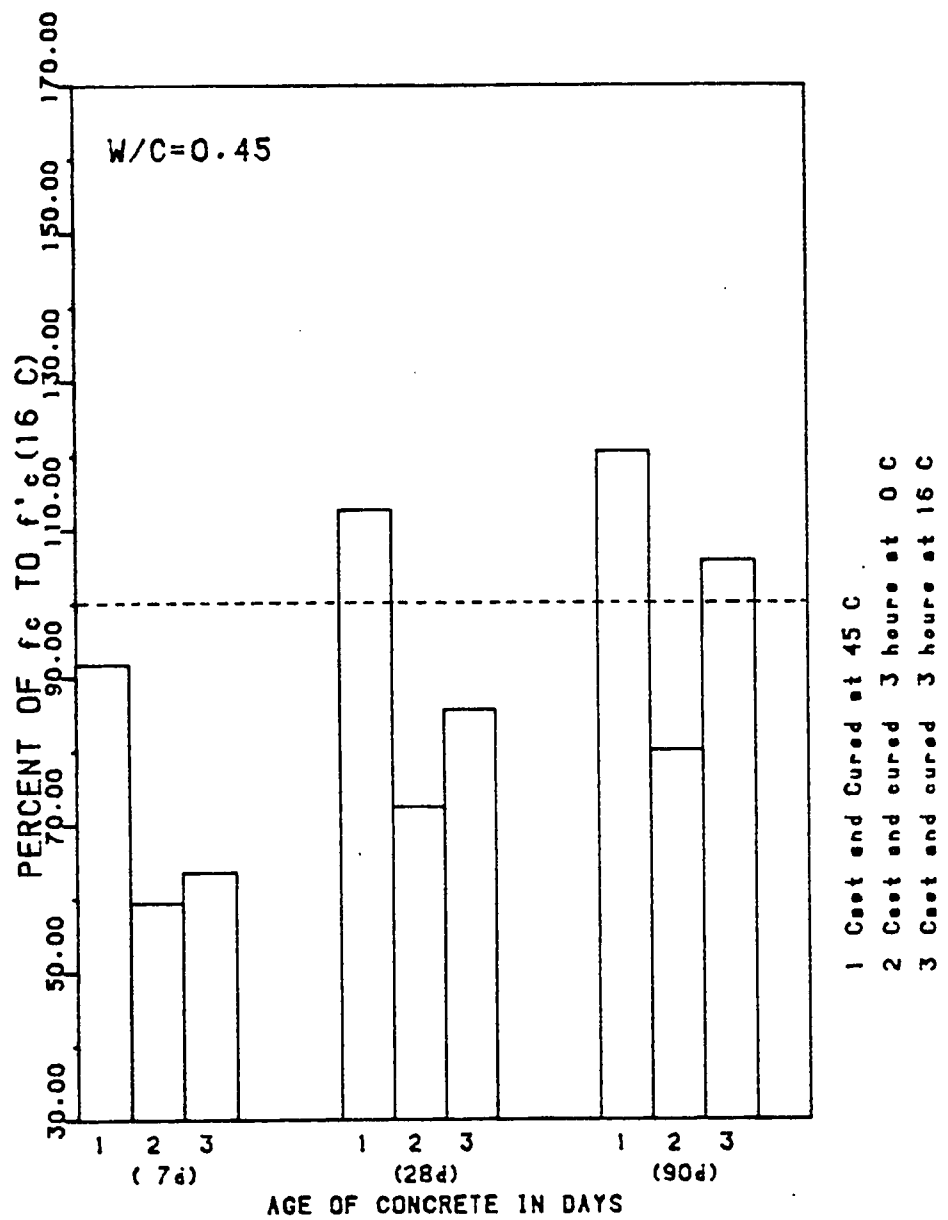


FIGURE 5.32 - STRENGTH DEVELOPMENT OF CONCRETE CURED AT 45 C

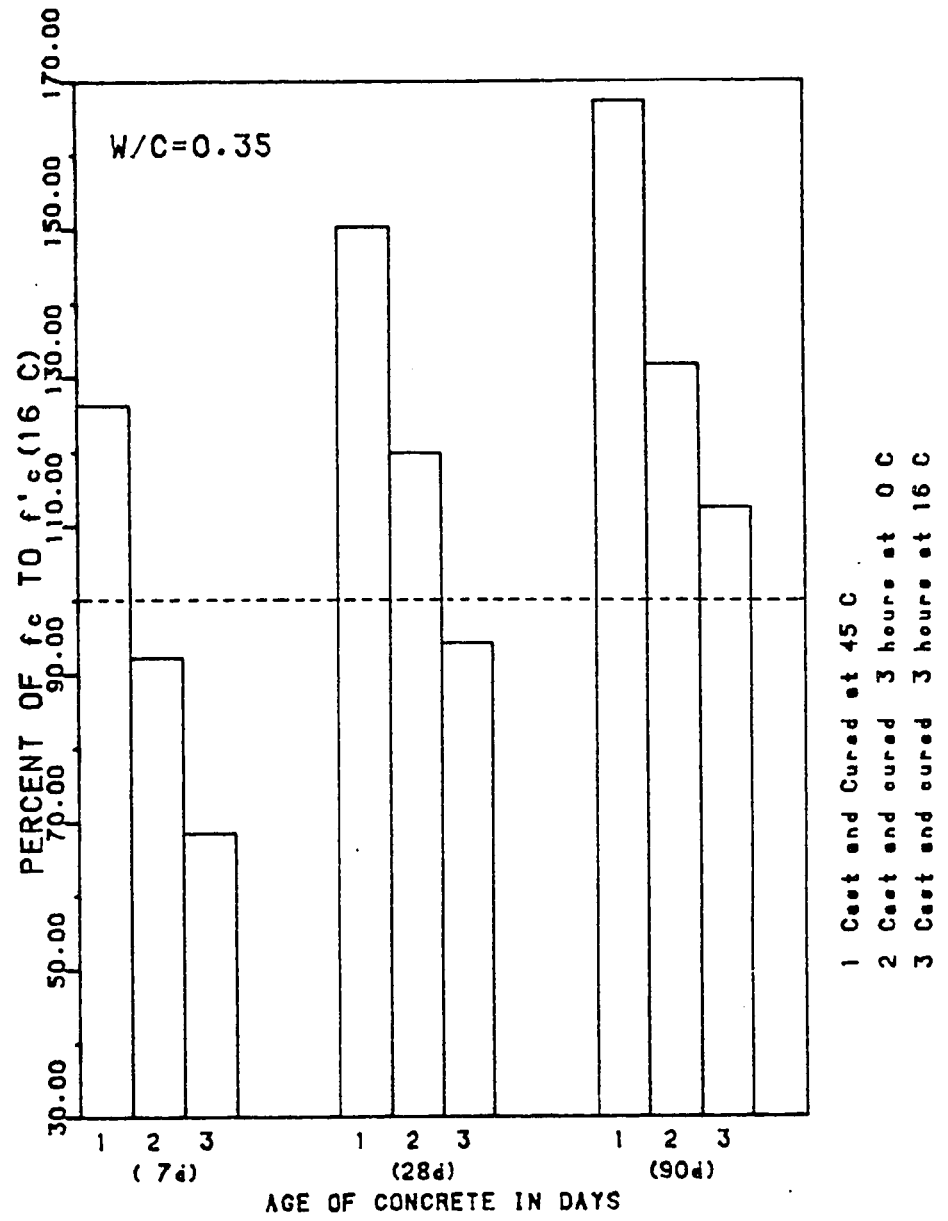


FIGURE 5.33 • STRENGTH DEVELOPMENT OF CONCRETE CURED AT 45 C

TABLE 5.1
MECHANICAL PROPERTIES OF CONCRETE CAST/CURED AT 0°C

	Compressive Strength	Tensile Strength	Static M.O.E.	Dynamic M.O.E.
	(MPa)	(MPa)	(GPa)	(GPa)
W/C = 0.55				
3 Days	3.8	1.25	n.a.	19.8
7 Days	10.6	2.21	11.5	30.2
14 Days	17.1	2.77	18.6	33.2
28 Days	20.2	3.07	21.5	35.2
90 Days	22.3	3.19	22.9	36.8
180	22.7	2.87	23.0	37.0
360	26.5	3.04	25.2	37.8
W/C = 0.45				
3 Days	6.7	1.77	9.8	22.8
7 Days	19.8	2.66	21.2	34.3
14 Days	25.9	4.01	26.9	34.5
28 Days	31.2	4.18	29.3	37.1
90 Days	36.1	4.45	31.7	39.0
180	35.8	3.90	32.0	40.6
360	37.9	4.25	33.2	42.6
W/C = 0.35				
3 Days	13.1	2.59	13.7	26.1
7 Days	26.6	3.26	25.4	35.1
14 Days	33.2	4.89	31.8	37.6
28 Days	34.8	5.07	33.0	40.3
90 Days	42.2	5.51	36.5	44.2
180	43.5	4.59	36.6	45.2
360	46.1	4.44	37.2	46.3

TABLE 5.2

MECHANICAL PROPERTIES OF CONCRETE CAST/CURED AT 16°C

	Compressive Strength	Tensile Strength	Static M.O.E.	Dynamic M.O.E.
	(MPa)	(MPa)	(GPa)	(GPa)
W/C = 0.55				
3 Days	15.9	1.43	19.0	30.6
7 Days	18.3	1.77	20.9	34.3
14 Days	23.0	2.32	24.1	36.0
28 Days	27.3	2.77	25.9	37.5
90 Days	30.4	3.56	27.7	38.5
180	32.7	3.61	32.2	39.9
360	32.0	3.58	30.4	40.7
W/C = 0.45				
3 Days	17.2	1.81	20.4	32.6
7 Days	20.5	2.57	22.6	36.2
14 Days	26.0	2.74	25.7	38.5
28 Days	29.1	2.83	29.0	40.4
90 Days	33.2	3.17	30.9	42.1
180	33.5	3.83	31.0	42.7
360	32.9	4.01	32.1	43.4
W/C = 0.35				
3 Days	24.9	2.94	21.6	37.7
7 Days	27.3	3.76	24.6	41.2
14 Days	31.3	4.02	30.8	42.2
28 Days	34.6	4.16	32.5	43.6
90 Days	39.3	4.50	34.8	45.7
180	43.4	4.32	35.4	46.0
360	46.3	4.62	37.5	46.3

TABLE 5.3
MECHANICAL PROPERTIES OF CONCRETE CAST/CURED AT 45°C

	Compressive Strength	Tensile Strength	Static M.O.E.	Dynamic M.O.E.
	(MPa)	(MPa)	(GPa)	(GPa)
W/C = 0.55				
3 Days	13.2	1.83	17.6	34.4
7 Days	17.1	2.26	20.9	36.2
14 Days	19.0	2.56	23.1	37.0
28 Days	21.7	2.84	26.2	38.0
90 Days	22.3	3.00	27.8	38.5
180	24.9	3.61	28.0	39.3
360	27.9	3.50	28.7	39.5
W/C = 0.45				
3 Days	20.3	2.06	22.3	34.6
7 Days	26.7	3.08	25.3	36.3
14 Days	29.3	3.54	27.3	37.4
28 Days	32.6	3.78	30.4	38.3
90 Days	35.1	4.03	33.0	39.0
180	36.3	3.95	32.3	40.0
360	38.5	4.17	33.2	40.4
W/C = 0.35				
3 Days	39.3	3.04	25.1	41.3
7 Days	43.7	3.96	27.6	43.1
14 Days	48.2	4.67	33.5	44.0
28 Days	52.0	5.06	39.0	45.2
90 Days	57.9	5.64	42.4	46.6
180	62.7	4.77	37.5	46.6
360	63.7	5.53	41.0	47.1

TABLE 5.4
LEAST SQUARE LINEAR REGRESSION AND CORRELATION

Items	Number of Observation	Correlation Coefficient	$Y = A+BX$	$y = K(x)^N$
y = fct x = fc	45	0.36	A = -0.351 B = 0.603	K = 0.45 N = 0.60
y = Ec x = fc	44	0.95	A = 0.484 B = 0.650	K = 3.05 N = 0.65
y = Ed x = fc	45	0.94	A = 1.140 B = 0.306	K = 13.30 N = 0.31

$Y = \text{Log } (y)$
 $A = \text{Log } (K)$
 $B = N$
 $X = \text{Log } (x)$

TABLE 5.5

STRENGTH OF CONCRETE CURED AT 0°C

Casting Temperature Hours of Delay	0°C	16°C 3	16°C 12	45°C 3
Compressive Strength (MPa)				
W/C = 0.55				
7 Days	10.5	11.2	13.5	14.9
28 Days	20.2	16.4	18.8	22.0
90 Days	22.3	20.0	21.5	24.6
360	26.5	31.2	26.2	28.4
W/C = 0.45				
7 Days	19.3	13.0	17.4	20.1
28 Days	31.2	20.1	22.4	33.2
90 Days	36.1	23.8	25.9	38.5
360	37.9	36.7	28.8	40.7
W/C = 0.35				
7 Days	26.6	35.1	32.6	42.2
28 Days	34.3	44.8	36.6	50.0
90 Days	42.2	45.8	43.5	58.6
360	46.1	51.2	43.3	61.6

TABLE 5.6
STRENGTH OF CONCRETE CURED AT 16°C

Casting Temperature Hours of Delay	16°C	0°C 3	0°C 12	45°C 3
Compressive Strength (MPa)				
W/C = 0.55				
7 Days	18.3	13.8	17.5	14.9
28 Days	27.3	18.2	26.1	19.8
90 Days	30.4	22.6	28.5	22.7
360	32.0	27.4	37.3	31.5
W/C = 0.45				
7 Days	20.5	26.5	28.4	20.7
28 Days	29.1	34.0	35.1	28.1
90 Days	33.2	36.8	37.6	32.9
360	37.9	38.2	48.5	51.3
W/C = 0.35				
7 Days	27.3	28.9	31.4	32.9
28 Days	34.6	37.5	39.0	41.1
90 Days	39.8	43.1	45.2	45.7
360	46.3	52.8	60.8	66.5

TABLE 5.7

STRENGTH OF CONCRETE CURED AT 45°C

Casting Temperature Hours of Delay	45°C -----	0°C 3 -----	16°C 3 -----
Compressive Strength (MPa)			
W/C = 0.55			
7 Days	17.1	12.6	17.7
28 Days	21.7	15.5	21.8
90 Days	22.3	19.1	23.6
360	27.9	20.5	32.4
W/C = 0.45			
7 Days	26.7	17.3	18.5
28 Days	32.3	21.1	24.9
90 Days	35.1	23.3	30.8
360	38.5	31.4	46.3
W/C = 0.35			
7 Days	43.7	31.9	23.7
28 Days	52.0	41.5	32.6
90 Days	57.9	45.6	38.9
360	63.7	53.0	51.9

TABLE 5.8

STRENGTH DEVELOPMENT OF CONCRETE CURED AT 0°C

Casting Temperature Hours of Delay	0°C	16°C 3	16°C 12	45°C 3
Percent f_c to $f'_c(16^\circ\text{C})$				
W/C = 0.55				
7 Days	38.3	41.0	43.5	54.6
28 Days	74.0	60.1	68.9	80.6
90 Days	81.7	73.3	78.8	90.1
360	88.7	114.3	96.0	104.0
W/C = 0.45				
7 Days	63.0	44.7	59.6	69.1
28 Days	107.2	69.1	77.0	114.1
90 Days	124.1	81.8	89.0	132.3
360	130.2	126.1	99.0	139.9
W/C = 0.35				
7 Days	76.9	101.4	94.2	122.0
28 Days	100.6	129.5	106.4	144.5
90 Days	122.0	141.0	125.7	169.4
360	133.2	150.9	125.1	178.0

TABLE 5.9

STRENGTH DEVELOPMENT OF CONCRETE CURED AT 16°C

Casting Temperature Hours of Delay	16°C	0°C 3	0°C 12	45°C 3
Percent f_c to $f'_c(16^\circ\text{C})$				
W/C = 0.55				
7 Days	67.0	50.5	64.1	54.6
28 Days	100.0	66.7	95.6	72.5
90 Days	111.4	82.8	104.4	83.2
360	117.2	160.4	136.6	115.4
W/C = 0.45				
7 Days	70.4	91.1	97.6	71.1
28 Days	100.0	116.8	120.6	96.6
90 Days	114.1	126.5	129.2	113.1
360	130.2	131.3	166.7	176.3
W/C = 0.35				
7 Days	78.9	83.5	90.8	95.1
28 Days	100.0	108.4	112.7	118.8
90 Days	115.0	124.6	130.6	132.1
360	133.8	152.6	175.7	192.2

TABLE 5.10

STRENGTH DEVELOPMENT OF CONCRETE CURED AT 45°C

Casting Temperature Hours of Delay	45°C	0°C 3	16°C 3
Percent f_c to $f'_c(16°C)$			
$w/c = 0.55$			
7 Days	62.6	46.2	64.8
28 Days	79.5	56.8	79.9
90 Days	83.5	70.0	86.4
360	102.2	75.1	118.7
$w/c = 0.45$			
7 Days	91.3	59.5	63.6
28 Days	112.7	72.5	85.6
90 Days	120.6	80.1	105.8
360	132.3	107.9	157.2
$w/c = 0.35$			
7 Days	126.3	92.2	68.5
28 Days	150.3	119.9	94.2
90 Days	167.3	131.8	112.4
360	186.1	153.2	150.0

TABLE 5.11

28-DAY COMPRESSIVE STRENGTH RATIO

Casting Temperature (°C)	4	0	46	45
Curing Temperature (°C)	4	0	46	45
Strength Ratio 1	0.82		1.07	
Strength Ratio 2		0.91		0.96

Casting Temperature (°C)	4	0	46	45
Hours at Casting Temp.	2	3	2	3
Curing Temperature (°C)	21	16	21	16
Strength Ratio 1	1.01		0.87	
Strength Ratio 2		0.92		0.85

Notes :

Strength Ratio 1 -- Price (Ref. 2), $f'_c/f'_c(13^\circ\text{C})$
 Strength Ratio 2 -- Experiment, $f'_c/f'_c(16^\circ\text{C})$

TABLE 5.12
PHYSICAL CHARACTERISTICS OF CEMENT

Cement	Percent by Weight of Cement				fc (MPa)		
	C ₃ S	C ₂ S	C ₃ A	C ₄ AF	50 mm Mortar 7 d	14 d	28 d
a. Type I	42.5	28.8	11.3	3.0	13.6	21.7	31.2
b. Type III	58.2	13.1	10.3	3.0	27.8	39.9	47.2
c. Average	50.4	21.0	10.3	3.0	20.7	30.8	39.2
d. Type 10	51.7	24.2	9.3	5.9	19.0	29.8	40.2

Notes :

C₃S -- Tricalcium Silicate
 C₂S -- Dicalcium Silicate
 C₃A -- Tricalcium Aluminate
 C₄AF -- Tetracalcium Aluminoferrite

- a. ASTM type I Cement (Klieger, Ref. 3)
 b. ASTM type III Cement (Klieger, Ref. 3)
 d. CSA type 10 Cement -- Information supplied
 by Canada Cement Lafarge Ltd.

TABLE 5.13
28-DAY COMPRESSIVE STRENGTH RATIO

Casting Temperature (°C)	4	0
Curing Temperature (°C)	4	0
Strength Ratio 1	0.83	
Strength Ratio 2	1.14	
Average	0.99	
Strength Ratio 3		1.07

Notes :

- Strength Ratio 1 -- Klieger (Ref. 3), $f'_c/f'_c(13^\circ\text{C})$
ASTM Type I Cement
- Strength Ratio 2 -- Klieger (Ref. 3), $f'_c/f'_c(13^\circ\text{C})$
ASTM Type III Cement
- Strength Ratio 3 -- Experiment, $f'_c/f'_c(16^\circ\text{C})$
CSA Type 10 Cement

Chapter VI

CONCLUSIONS

Apparently, there is no unique solution to determine which casting or curing temperature or combination of one to another produced the highest concrete strength. However, one thing is clear that concrete with low water-cement ratio not only yielded satisfactory compressive strength, regardless of the casting and curing temperature, but also improved the mechanical properties of concrete as well. It is difficult to come up with a general conclusion because concrete is sensitive to many different parameters. But the author truly believes that this study has served its purposes and has demonstrated, from the experimental results, several important issues on the temperature effects on the mechanical properties of concrete. One additional issue that must bring into the discussion is the water-cement ratio which was found to play an important role in this study. The following are the conclusions summarized from the experimental results:

1. Compressive strength increased with increasing time and decreasing water-cement ratio.
2. The lower the water-cement ratio, the faster the concrete gained its strength.

3. Casting and curing at 0°C or 45°C did not damage the strength of concrete but conversely increased the strength (both 7-day and 90-day) as long as the water-cement ratio was kept to its minimum (ie. 0.35).
4. The compressive strength was very much sensitive to water-cement ratio at 45°C where a slight decrease in water-cement ratio could result in a substantial increase in strength.
5. Tensile strength, static and dynamic modulus of elasticity were all related to some power function of its compressive strength.
6. Tensile strength was related to the power of 0.60 of the cylinder strength, static modulus of elasticity was related to the power of 0.65 of the cylinder strength; and finally, dynamic modulus was related to the power of 0.31 of the cylinder strength.
7. Tensile strength, static and dynamic modulus of elasticity increased with increasing compressive strength but at a rate depending on the casting and curing temperature.
8. Regardless of the casting temperature, curing at 0°C or 45°C has no adverse effects to the concrete strength providing water-cement ratio was as low as 0.35.

9. Extreme casting or curing temperature would damage the strength of concrete with water-cement ratio of 0.55.
10. Concrete cast and cured several hours at 0°C or 45°C and subsequently cured at 16°C received no damage but benefits to its strength providing water-cement ratio was as low as 0.45.

Chapter VII

RECOMMENDATIONS

From this study, it was found that low water-cement ratio not only increased the mechanical strength of concrete but also caused the strength to increase substantially from casting and curing at adverse temperature. Since low water-cement ratio means more cement and accordingly more calcium silicates in the concrete, it is logical to believe a concrete made of type 30 Portland cement could have a better strength under adverse temperature conditions. Therefore, future research is recommended to study the effect of temperature on the mechanical properties of concrete made of type 30 Portland cement. The characteristics of shrinkage and creep of concrete are also recommended to be included into the investigation.

Lastly, a field investigation is also recommended to correlate the field results to the results obtained from laboratory-made concrete.

Appendix A
REGRESSION ANALYSIS

When the functional relation between two variables (x, y) are of interest, regression analysis is commonly employed to investigate the probabilistic relationship between the variables in terms of the mean and variance of one variable as a function of the other variable. The following equations which were useful to this study were reproduced from Reference 20.

A.1 METHOD OF LEAST SQUARE

If the functional relationship between variables x and y is linear, a linear regression equation $(Y=A+BX)$ which describes a straight line passing through majority of the data points (x_i, y_i) can be determined by minimizing the squared error terms as stated in equation (A-1).

$$E^2 = \sum (Y_i - y_i)^2 = \sum (A + BX_i - y_i)^2 \quad (A-1)$$

If \bar{x} is the sample mean of x and \bar{y} is the sample mean of y , the regression parameters B and A can be determined by equations (A-4) and (A-5), respectively.

$$\bar{x} = \frac{\sum x_i}{n} \quad (A-2)$$

$$\bar{y} = \frac{\sum y_i}{n} \quad (A-3)$$

$$B = \frac{\sum x_i y_i - n \bar{x} \bar{y}}{\sum x_i^2 - n \bar{x}^2} \quad (A-4)$$

$$A = \bar{y} - B \bar{x} \quad (A-5)$$

In addition, the 95% confidence intervals on individual predicted value of Y having the t-distribution and n-2 degrees of freedom are also constructed to justify the proposed model. The upper and lower 95% confidence limits are stated in equations (A-6) and (A-7), respectively.

$$U(x_i) = A + Bx_i + t_{0.975, n-2} \sqrt{\frac{E^2}{n-2}} \sqrt{1 + \frac{1}{n} + \frac{(x_i - \bar{x})^2}{\sum (x_i - \bar{x})^2}} \quad (A-6)$$

$$L(x_i) = A + Bx_i - t_{0.975, n-2} \sqrt{\frac{E^2}{n-2}} \sqrt{1 + \frac{1}{n} + \frac{(x_i - \bar{x})^2}{\sum (x_i - \bar{x})^2}} \quad (A-7)$$

A.2 CORRELATION COEFFICIENT

Correlation Coefficient (R) is a measure of linear relationship between two variables x and y. Mathematically, the correlation coefficient can be determined by

$$R = \frac{1}{n-1} \frac{\sum x_i y_i - n \bar{x} \bar{y}}{S_x S_y} \quad (A-8)$$

where S_x and S_y are the sample standard deviations as stated in equations (A-9) and (A-10), respectively.

$$S_x = \sqrt{\frac{1}{n-1} \sum (x_i - \bar{x})^2}$$

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(A-9)

$$S_y = \sqrt{\frac{1}{n-1} \sum (y_i - \bar{y})^2}$$

(A-10)

If R is close to unity, a strong linear relationship between x and y exists. In contrast, it indicates a lack of linear relationship if R is close to zero.

A.3 FORTRAN PROGRAM

```
DIMENSION X(45),Y(45)
200 FORMAT(2F8.3)
201 FORMAT(F15.3)
XSUM=0.0
YSUM=0.0
XXSUM=0.0
YYSUM=0.0
XYSUM=0.0
XYBAR=0.0
YYBAR=0.0
NOP = 45
DO 987 I = 1,NOP
C READ IN DATA
  READ(5,200) X(I),Y(I)
C CONVERT DATA INTO LOG SCALE
  Y(I)=ALOG10(Y(I))
  Y(I)=ALOG10(Y(I))
C SUMMATION OF X, Y-SQUARE, Y, Y-SQUARE, X-TIMES-Y
  XSUM=XSUM+X(I)
```

```
XXSUM=XXSUM+X(I)*X(I)
```

```
YSUM=YSUM+Y(I)
```

```
YYSUM=YYSUM+Y(I)*Y(I)
```

```
XYSUM=XYSUM+X(I)*Y(I)
```

```
987 CONTINUE
```

```
C SAMPLE MEANS, EQNS (A-2) & (A-3)
```

```
XBAR=XSUM/NOP
```

```
YBAR=YSUM/NOP
```

```
WRITE(6,201) XBAR
```

```
WRITE(6,201) YBAR
```

```
C SAMPLE STANDARD DEVIATIONS, EQNS (A-9) & (A-10)
```

```
DO 988 I = 1,NOP
```

```
XXBAR=XXBAR+(X(I)-XBAR)*(X(I)-XBAR)
```

```
YYBAR=YYBAR+(Y(I)-YBAR)*(Y(I)-YBAR)
```

```
988 CONTINUE
```

```
XSTD=SQRT(XXBAR/(NOP-1.0))
```

```
YSTD=SQRT(YYBAR/(NOP-1.0))
```

```
WRITE(6,201) XSTD
```

```
WRITE(6,201) YSTD
```

```
C CORRELATION COEFFICIENT, EQN (A-8)
```

```
R = (XYSUM-NOP*XBAR*YBAR)/((NOP-1.0)*XSTD*YSTD)
```

```
WRITE(6,201) R
```

```
C REGRESSION PARAMETERS, EQNS (A-4) & (A-5)
```

```
B = (YYSUM-NOP*YBAR*YBAR)/(XYSUM-NOP*XBAR*YBAR)
```

```
A = YBAR-B*XBAR
```

```
WRITE(6,201) A
```

```
WRITE(6,201) B
```

```
C SQUARED ERROR TERMS, EQN (A-1)
  E2SUM=0.0
  DO 498 I =1,NOP
    ERROR = A+B*X(I)-Y(I)
    E2SUM = E2SUM+ERROR*ERROR
  498 CONTINUE
C 95% CONFIDENCE LIMITS, EQNS (A-6) & (A-7)
  STOP1 = SQRT(E2SUM/(NOP-2.0))
  DO 436 I = 1,NOP
    XCON = (X(I)-YBAR)*(X(I)-XBAR)/XXBAR+1.0/NOP+1.0
    YES = A+B*X(I)
    YUP = YES+2.018*STOP1*SQRT(XCON)
    YLO = YES-2.018*STOP1*SQRT(XCON)
C CONVERT DATA BACK FROM LOG SCALE
  XXX = 10.0**X(I)
  YYY = 10.0**Y(I)
  YUP = 10.0**YUP
  YLO = 10.0**YLO
  YES = 10.0**YES
  WRITE(6,150) XXX,YYY,YUP,YLO,YES
150 FORMAT(' ',5F8.3)
436 CONTINUE
STOP
END
```

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NOMENCLATURE

t	Time Period after Casting, Days
f _c	Compressive Strength of Concrete at Time t, MPa
f' _c	28-day Compressive Strength of Concrete, MPa
f _{ct}	Tensile Strength of Concrete, MPa
E _c	Static Modulus of Elasticity, GPa
E _d	Dynamic Modulus of Elasticity, GPa
M.O.E.	Modulus of Elasticity, GPa
n	Number of Observations
A, B, K, N	Regression Parameters
X, Y	Estimated Regression Variables
x, y	Observed Data
U, L	Upper and Lower 95% Confidence Limits
R	Correlation Coefficient
E ²	Squared Error Terms
Σ	Summation from i=1 to i=n
<i>t</i> _{0.975, n-2}	95 - Percentile of the Student t-Distribution with n-2 Degree of Freedom