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MATURITY CONCEPT AND THE ESTIMATION OF CONCRETE STRENGTH - A REVIEW*

by

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Mines Branch IC 277

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SYNOPSIS

The determination of strength of concrete without physically testing a specimen has been the subject of research for the past several decades. It has been suggested by several researchers that strength of concrete can be expressed in terms of the maturity, commonly defined as the product of time and temperature above -10°C (14°F). Others have used the maturity concept to estimate strength of concrete at various ages.

This paper critically reviews the literature published on the subject since 1904 and presents results of limited investigations carried out at the Mines Branch to estimate the compressive strength of concrete at low maturities, usually associated with accelerated strength tests. The paper is concluded with a summary of the literature reviewed and a list of pertinent references.

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Direction des Mines IC 277

CONCEPT DE MATURITE ET L'ESTIMATION DE LA RESISTANCE
DU BETON - UNE REVISION

par

V. M. Malhotra*

SOMMAIRE

La détermination de la résistance du béton, sans mettre un échantillon à une épreuve physique, a été le sujet de recherches depuis un bon nombre de décades. Plusieurs chercheurs scientifiques ont suggéré que la résistance du béton pouvait être exprimée en termes de maturité, ordinairement définie comme le produit du temps et de la température au-dessus de -10°C (14°F). D'autres ont utilisé le concept de maturité pour estimer la résistance du béton à des âges différents.

Cette étude révise critiquement la littérature publiée sur ce sujet depuis 1904 et présente les résultats des recherches limitées, effectuées à la Direction des Mines pour estimer la résistance du béton à la compression à de basses maturités, procédé habituellement associé avec les épreuves accélérées de résistance. L'étude se termine avec un résumé de la littérature révisée et une liste de reférences pertinentes.

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INTRODUCTION

It is well known that the compressive strength of well-cured concrete increases with time. The increase in strength, however, is governed by many factors other than curing time, the most important being the temperature of curing. The combined effect of time and temperature has been the subject of study by several investigators [1-4] since 1904, but no hypothesis was formulated in the early years. Then, in the 1950's the concept of maturity was advanced by McIntosh [5], Nurse [6], Saul [7], Bergstrom[8] and others [9, 10], and strength-maturity relationships were published; maturity was defined as the product of time and temperature with a datum temperature of -10°C (14°F). In 1956, Plowman [11] attempted to place the datum temperature on a more rational basis and published a "law" relating the strength at any maturity to that at a given maturity. The validity of the proposed "law" was strongly questioned by Klieger, Powers, McIntosh and others [12, 13], who noted its serious limitations. Also, Ordman and Bondre [14] and Narayanan [15, 16], carried out studies to check the validity of Plowman's formula at temperatures greater than 37.5°C (100°F). The need for more data at low maturities was pointed out by Marshall [12]. At about the same time, at the RILEM[17]** Symposium on Winter Concreting, several papers were presented discussing the maturity concept and its limitations. In recent years, Alexander and Taplin [18] and Ramakrishnan and Chielokitchley [19] have carried out experimental investigations to check the validity of the maturity concept, and Swenson [20] has attempted to estimate the strength gain of concrete using the Nurse-Saul strength-time relationship.

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* In the text, the units have been expressed in the metric system and the British equivalents are given in the parentheses. As a large number of figures have been reproduced from the published literature, it has not been possible to show both units on the Figures.

** Réunion Internationale des Laboratories d'Essais et de Recherches sur les matériaux et les constructions, Paris, France.

This Information Circular critically reviews the literature published on the subject and presents results of limited investigations carried out at the Mines Branch to see if the maturity concept can be applied to strength values obtained using different accelerated curing methods. Data are also presented on relationships between strength and maturity for both accelerated- and standard-cured test cylinders.

REVIEW OF THE EARLIER WORK

Past Developments, 1904-1940

During the period 1904-1940, McDaniel (1), and Wiley (2) and Timms and Whithey (3) published results of their investigations on the effect of temperature on strength of concrete. Though these publications made no direct reference to the maturity concept, the research workers were, in fact, thinking about the combined effect of time and temperature.

McDaniel(1) was one of the earliest research workers to publish data on the influences of temperature on the strength of concrete. The purpose of his investigation was to determine:

(i) the strength which the concrete would attain at different ages at a constant temperature.
(ii) the age at which a particular strength could be gained at different temperatures.
(iii) the strengths which may be expected at different ages at different temperatures.

His investigation included a large series of concrete mixes using normal portland cement. Coarse and fine aggregates, respectively, were crushed limestone and natural sand. Water/cement and aggregate/cement ratios of the concrete mixes were 0.7 and 7.0 with a cement content of 240 kg/cu m (405 lb/cu yd). Immediately after casting, the 20 x 40-cm (8 x 16-in.) cylinders were brought into curing chambers which were kept at temperatures of 33, 22, 1.5 and -3°C (91.4, 71.6, 34.7 and 26.6°F). The test specimens were cured under wet burlap and after two days were removed from the moulds for testing at 3, 7, 10, 14 and 28 days.

From his investigations McDaniel concluded (Figure 1) that concrete maintained a temperature of 15.5 to 21.1°C (60 to 70°F) will at the age of one week have practically double the strength of the same material kept at a temperature of 0 to 4.4°C (32 to 40°F).

In 1928, Wiley [2] reported the results of his studies dealing with the effect of temperature on the hardening rate of concrete. His samples consisted of 90 cylinders 15 x 30 cm (6 x 12 inches) in size containing river-washed gravel and natural sand as coarse and fine aggregates. Nominal water/cement ratio by weight was 0.8, with mix proportions of 1:2:3 by dry-rodded volume. The cylinders were left in their moulds for 24 hours and then cured at temperatures as shown in Figure 2. Testing was carried out at 1, 3, 5, 7, 14, and 28 days. From his investigations, Wiley concluded:

(i) With temperatures between 1.6 and 37.7°C (35 and 100°F) the hardening of concrete proceeds in the same manner but at different rates.

(ii) At a temperature of 37.7°C (100°F) the same strength is obtained in approximately one-half the time as at 21.1°C (70°F).

(iii) At a temperature of 1.6°C (35°F) something more than twice the time is required to gain the same strength as at 21.1°C (70°F).

(iv) At all ages between 3 and 28 days, with the mix and materials here used, the difference in strength is practically 3.6 kg/cm^2 per°C (30 lb per sq in. per°F).

In 1934, Timms and Withey [3] carried out investigations to obtain much needed information on strength of concrete when exposed to different temperatures with particular reference to conditions which prevail during winter concreting. Their investigations included a large series of concrete mixes involving several hundred 7.5 x 15-cm (3 x 6-in.) test cylinders. The initial curing conditions were varied from exposure at 21.1°C (70°F) for 1/4 day to exposure at 21.1°C (70°F) for 3 days; subsequent curing was carried out at -8.9°C (16°F) to 21.1°C (70°F). The

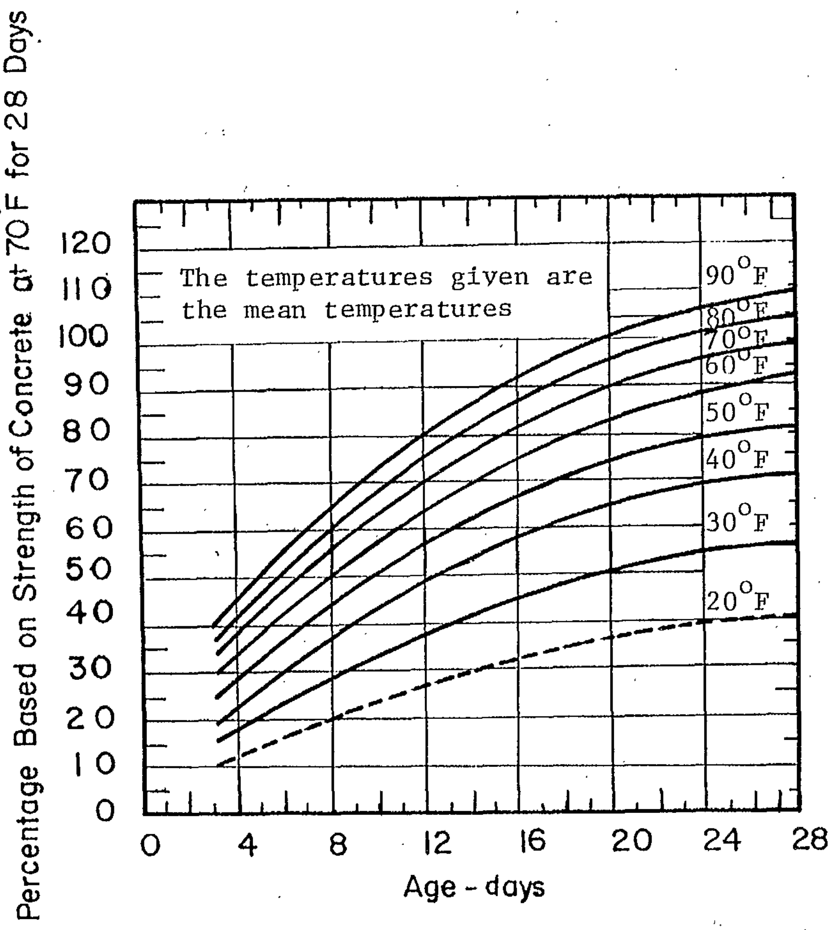

Fig. 1 - Percentages of Strength for Different Temperatures[1].

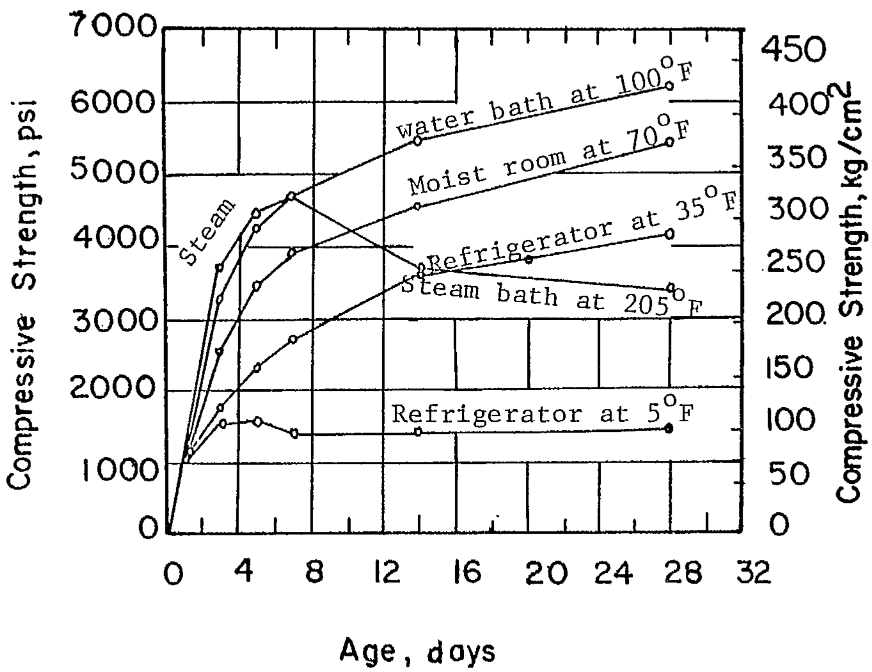

Fig. 2 - Effect of Temperature on Hardening of Concrete(2).

specimens were tested at 28 days.

Some of their significant conclusions were as follows:

> "...when the temperature of exposure is from 0.5 to 10°C (33 to 50°F) the initial curing period at 21.1°C (70°F) should be at least 3 days for normal portland cement and at least 1 day for high-early-strength cement. When the temperature of exposure is below freezing these minimum initial curing periods should be increased depending on the strength required for safety. For concretes exposed to temperatures below freezing, the strength at any time after the period of initial curing depends primarily on the strength developed during the initial curing period."

The data of Timms and Withey were extensively analyzed by Bergstrom to check the validity of the Nurse-Saul strength-time function; this study is described later.

Developments During 1940-1960

During this period a number of significant papers were published on the subject in England and Europe. The term "maturity" was introduced and the relationships between maturity and strength were published. The "Symposium on Winter Concreting" sponsored by RILEM in 1956 devoted a full session to these concepts. The significant contributors during this period were McIntosh (5), Nurse (6), Saul (7), Bergstrom (8), Rastrup (9), Hallstrom (10), Plowman(11), Klieger (12, 13), Nykänen (17), and Bernhardt(17).

Basic Age Concept by McIntosh

In 1949, McIntosh reported his investigations on electrical curing of concrete investigating a series of twenty-five mixes. Eight cubes, 7.6 x 7.6 x 6.4 cm (3 x 3 x 2-1/2 in.) were made from each mix, four of which were subject to electrical curing and four used as control specimens. The standard concrete mix had a water/cement ratio by weight of 0.63 and aggregate/cement ratio by weight of 6:1. Rapid-hardening portland cement was used and the aggregates were 19-mm (3/4-in.) maximum size whinstone and two river sands mixed in suitable proportions to give a good grading. Some changes were made in the mix design for non-standard mixes.

Electrical curing of the specimens started immediately after casting and continued for about 24 hours. The treated cubes were allowed to cool to room temperature before testing, usually within 2 to 3 hours.

In order to take into account the combined effects of time and temperature, McIntosh introduced a term called "basic age", defining it as the product of time and temperature above -1.1°C (30°F); he selected this datum because at that temperature hydration of cement virtually ceases.

McIntosh's comparison of strength of electrically cured and normally cured specimens with reference to basic age is reproduced in Figure 3, and anticipated compressive strength - basic age curves for various maximum temperatures are reproduced in Figure 4. From the investigation, McIntosh concluded:

(i) The strength of heated specimens at a given basic age is not independent of the maximum temperature. Therefore, the assumption that rate of hardening is directly proportional to the difference of the specimen temperature and no-hardening temperature cannot be true; it appears that reaction occurs more rapidly at higher temperatures than the simple relationship would suggest.

(ii) Heated concrete attains a large proportion of its strength at an early age, the period during which its temperature is near the maximum.

Introduction of Time-Temperature Function by Nurse

In 1949, Nurse [6] reported the results of his work on the steam-curing of concrete products. A series of laboratory mixes were made using different types of aggregates. The specimens used were 20 x 5 x 5-cm (8 x 2 x 2-in.) prisms which were subjected to flexural strength testing with compression tests carried out on the halves. Coarse aggregate was of 19-mm (3/4-in.) maximum size, and a water/cement ratio was chosen to give a normal workable concrete. The specimens were steam-cured at atmospheric pressures at 40, 60, 80 and 100°C (104, 140, 176 and 212°F). To allow for the differences in strength due to different aggregate and mixes, Nurse expressed strength as a percentage of 3 days' curing at normal

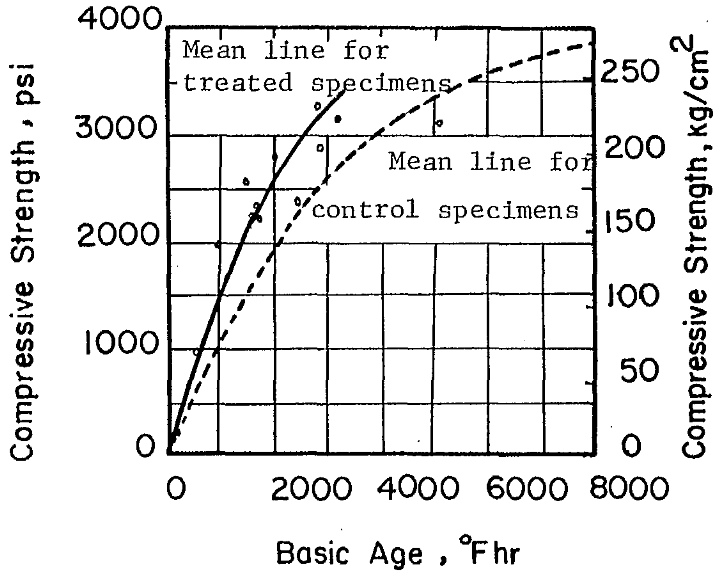

Fig. 3 - Compressive Strength of Standard-Mix Heated Specimens (5)

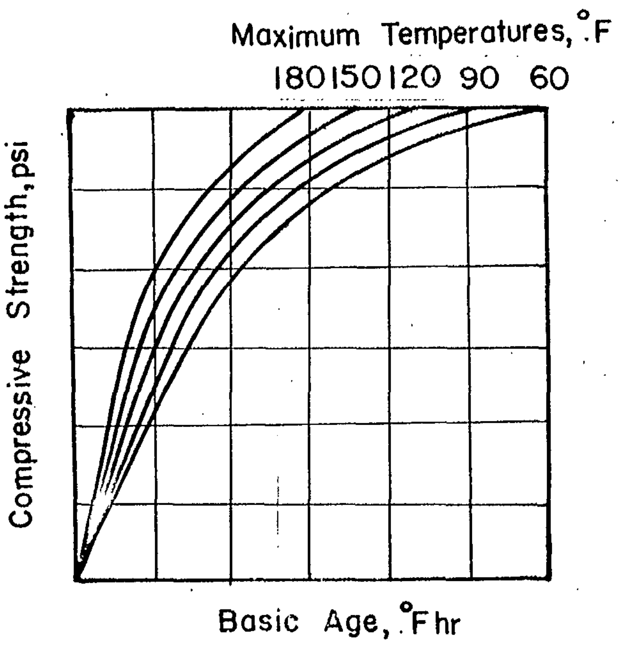

Fig. 4 - Compressive Strength vs Basic Age
Curves for Various Maximum Temperatures (5).

temperature and plotted it against the product time-temperature, 0°C (32°F) being taken as the datum temperature (Figure 5). The data in Figure 5A refer to concretes made with gravel and dense clinker where no aggregate-cement reaction is supposed to take place, while data in Figure 5B refer to concretes made with clinker A, expanded clay and foamed slag where aggregate-cement reaction has taken place. The test results fall above the minimum curve (Figure 5B), indicating the limitations of the use of time x temperature in predicting strength values.

Saul and the Principle of Maturity

During his investigations on steam-curing of concrete at atmospheric pressure, in 1951, Saul [7] defined the term "maturity" as follows:

> "The maturity of concrete may thus be defined as its age multiplied by the average temperature above freezing* which it has maintained."

From the above definition of maturity he went on to state the "law" of gain of strength with maturity as follows:

> "Concrete of the same mix at the same maturity (reckoned in temperature-time) has approximately the same strength whatever combination of temperature and time go to make up that maturity."

He also stated the above "law" of gain of strength held good only for the range of temperature and time considered, i.e., 40 to 100°C (104-212°F)

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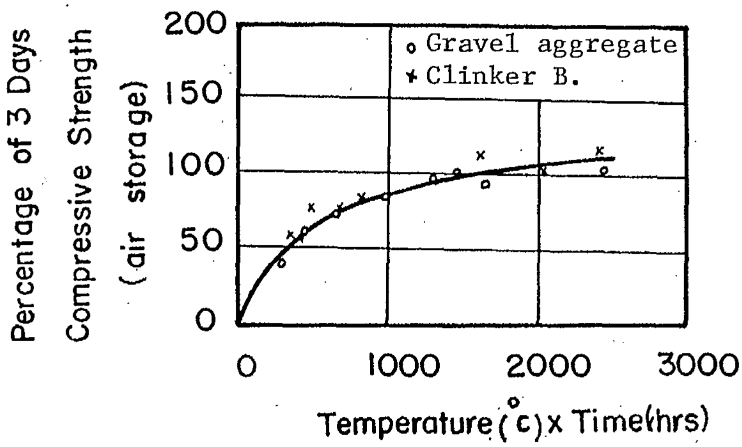
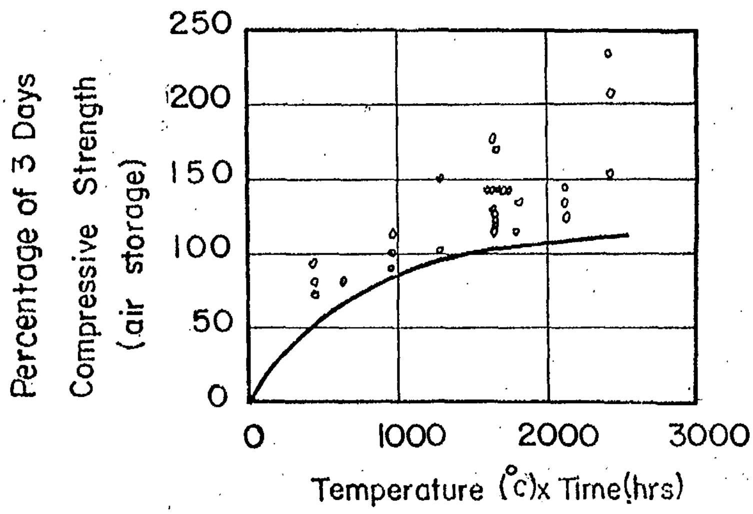
*Concrete will set at freezing point, and after setting will continue to gain strength slowly even at -10°C (12.2°F). For general purposes, therefore, including long periods of high and, more particularly, low temperatures, the maturity should be calculated from some lower temperatures, say -10.5°C. This will give an approximate comparison under all conditions, but some corrective factor should be applied, temperature having a greater effect at first and time later. For the purposes of steam curing, involving the comparison of normal curing with short periods at higher temperatures followed by normal curing, calculation of maturity from freezing point tends to correct for the above and gives comparative results approximating to those found by experiment for ages of 24 hours and more. During the first few hours of treatment, however, steam-cured concrete gains strength in relation to maturity more rapidly than does normally cured concrete. For long periods at low temperatures, maturity should be calculated from -10.5°C.



A



B

Fig. 5 - Strength Development vs Time x Temperature(6).

A: Non-reactive aggregates, B: Reactive aggregates.

and up to 28 days. Another limitation was that concrete must not reach 45°C (113°F) until 1-1/2 to 2 hr, nor 100°C (212°F) until 5 to 6 hr after the time of mixing. His investigations showed that when the concrete had been raised in temperature more rapidly than this it failed to obey the above law, gaining strength more rapidly during its first few hours of treatment but thereafter being adversely affected in strength.

A comparison of the strengths of normally cured concrete and steam cured concrete, both plotted against maturity, are shown in Figure 6. The strengths of concrete having a slow initial temperature rise (refer to black dots on the Figure) follow the strengths of normally cured concrete at early maturities but tend to be slightly weaker at later maturities. The strengths of concrete raised to 100°C (212°F) within 2 hours from the time of mixing (refer to triangles in the Figure) fail to obey the maturity law, while the strengths of concrete subjected to intermediate temperature gradients (refer to circle in the Figure) tend to fall somewhere between the two.

<u>Bergstom's Contribution</u>

In 1953, Bergstrom analyzed the published data of McDaniel [1], Wiley[2], Timms and Withey[3], and Price [4] to check the validity of the Nurse-Saul maturity law and the principle of superposition as suggested by Hallstrom [10]. He expressed the Nurse-Saul law in the following form:

$$\text{Maturity, °C x days} = \sum a_t\,(t + 10)$$

where, a_t = duration of curing in days,

t = temperature in °C; the introduction of 10°C takes into account the circumstances that the strength also continues to increase at temperature below zero.

Bergstrom's analyses of Timms and Withey[3] and Price's[4] data, reproduced in Figures 7 and 8, indicate that an excellent correlation exists between the strength and the maturity functions.

Bergstrom also reported some investigations carried out at the Swedish Cement and Concrete Research Institute. Test beams, 10 x 15 x 80 cm

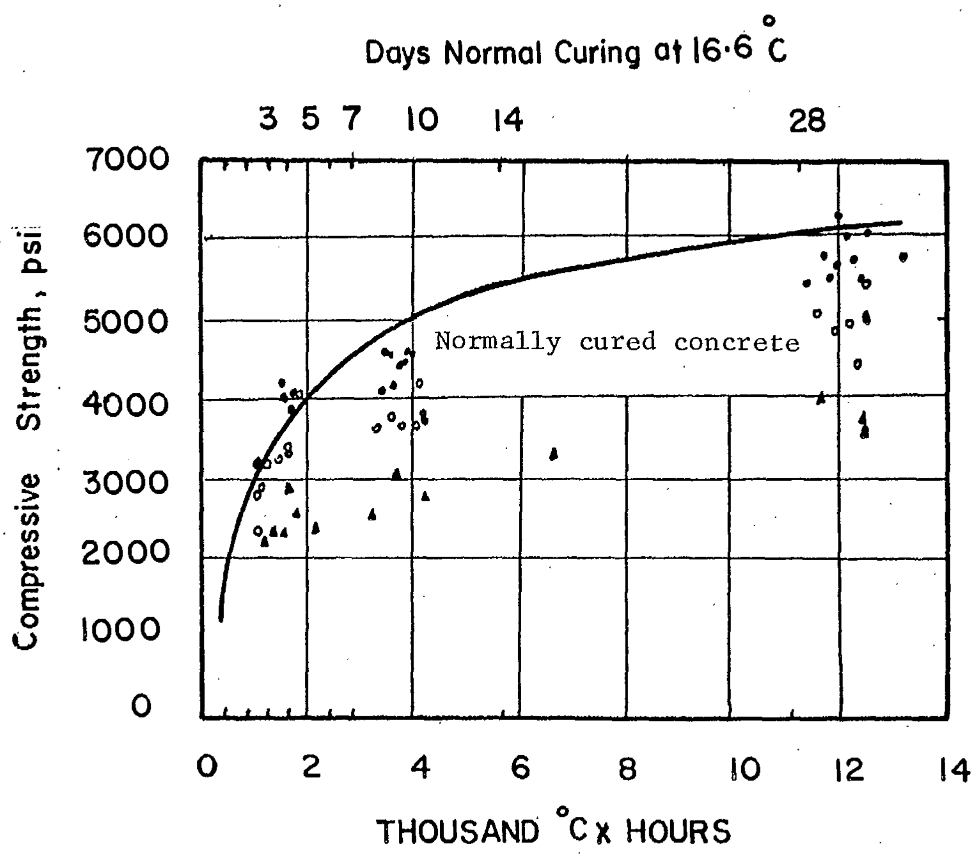


Fig. 6 - Gain of Strength of Steam-Cured Concrete with Time[6].

Water/cement ratio = 0.50
Aggregate/cement ratio = 5.5:1
Type of cement = rapid hardening

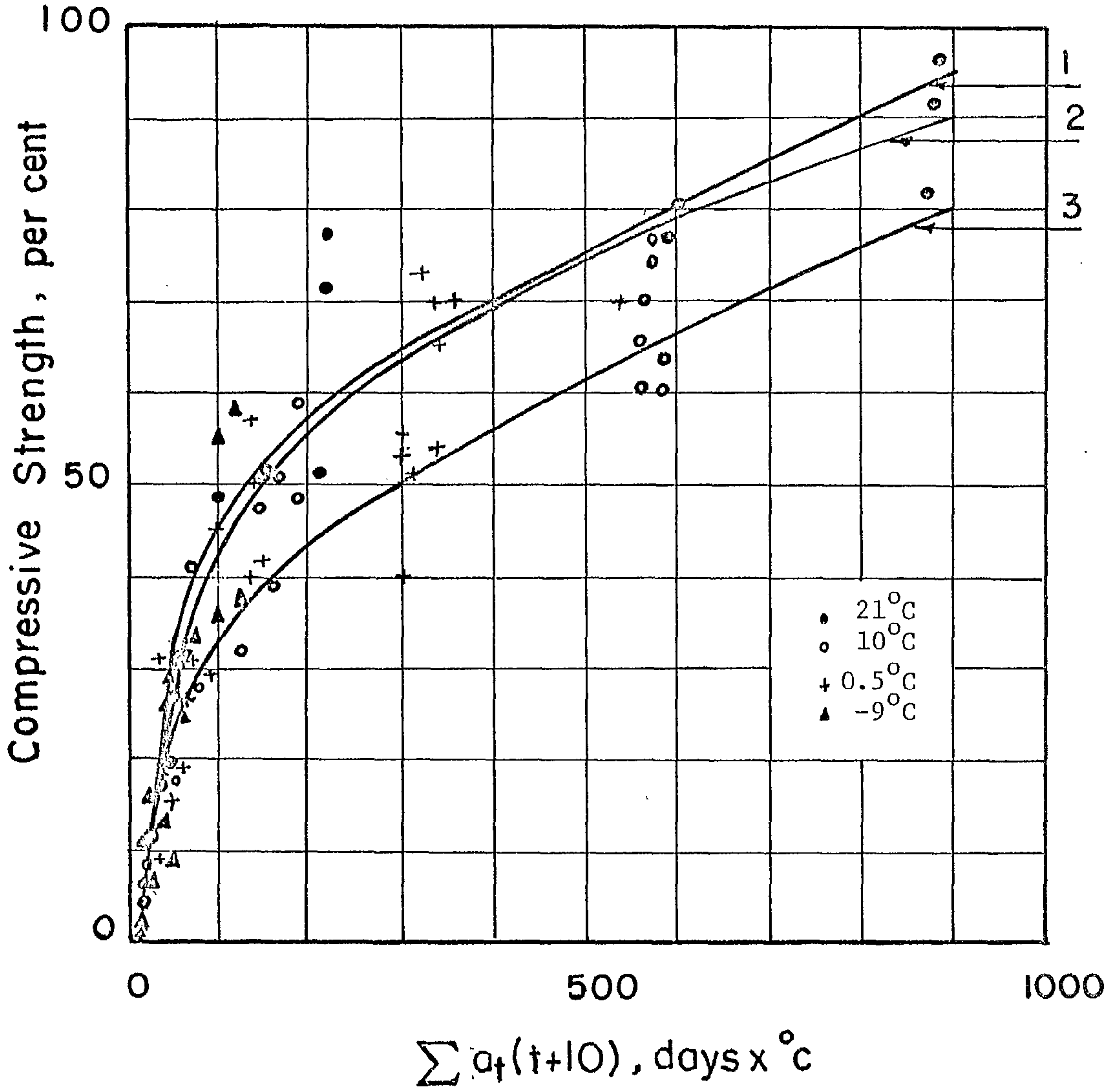


Fig. 7 - Percentage Compressive Strength as a Function of Age x Temperature for Timms and Withey's Tests (8).

		Curve 1	Curve 2	Curve 3
Cement content	=	380 225	540 320	725 lb/cu yd 430 kg/cu m
Water/cement ratio	=	0.80	0.53	0.40
Initial curing in moist air, days	=	1/4	1	3
Specimen size	=	7.5 x 15-cm (3 x 6-in.) cylinders		
Testing age	=	1, 3, 7, and 28 days		

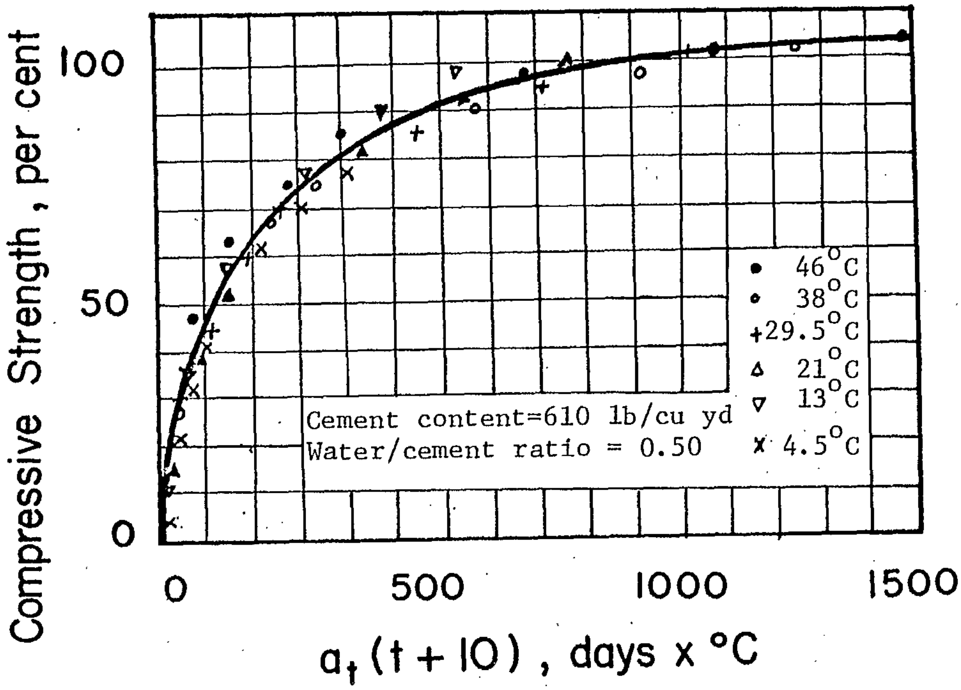


Fig. 8 - Percentage Compressive Strength as a Function of Age x Temperature for Price's Tests (8).

Cement content	= 360 kg/cu m (610 lb cu yd)
Water/cement ratio	= 0.50
Specimen size	= 15 x 30-cm (6 x 12-in.) cylinder
Initial curing	= nil
Testing age	= 1, 3, 5, 7, 14, 21, and 28 days

(4 x 6 x 30 in.) in size, were cast and cured at various temperatures in order to check the method of superposition. The modulus of rupture was plotted as a function of $\sum a_t\,(t + 10)$ and the high degree of correlation indicated that the parameter $\sum a_t\,(t + 10)$ was satisfactory.

Bergstrom drew attention to the fact that his analyses of the published data were confined to the effects of the curing time and the curing temperature, but humidity conditions were not considered. He also warned against indiscriminate application of maturity curves to massive concrete structures because the rates of heat loss during the curing process would be different from those of standard specimens.

Rastrup's Time-Temperature Function

In 1954, Rastrup[9] published a time-temperature function of the form

$$a_1 = 2^{\frac{t_2 - t_1}{10}} \times a_2$$

where a_1 = the curing time at the temperature t_1

a_2 = the curing time at the temperature t_2

and he further attempted to relate this function to strength.

Rastrup's function is based on the well-known physico-chemical rule which states that the speed of a reaction is doubled when the temperature is increased by 10°C (50°F).

If the temperature varies, then a sum is formed over the time interval in accordance with this function:

$$a = \sum_{0}^{t} 2^{\frac{t_2 - t_1}{10}} . \Delta t$$

Rastrup's comparison of the Nurse-Saul time-temperature function and his relationship for a unit value of time with t_1 = 15°C (59°F) is shown in Figure 9. The two curves indicate that the agreement between the formulae is good only for concrete temperatures below 20-25°C (68-77°F).

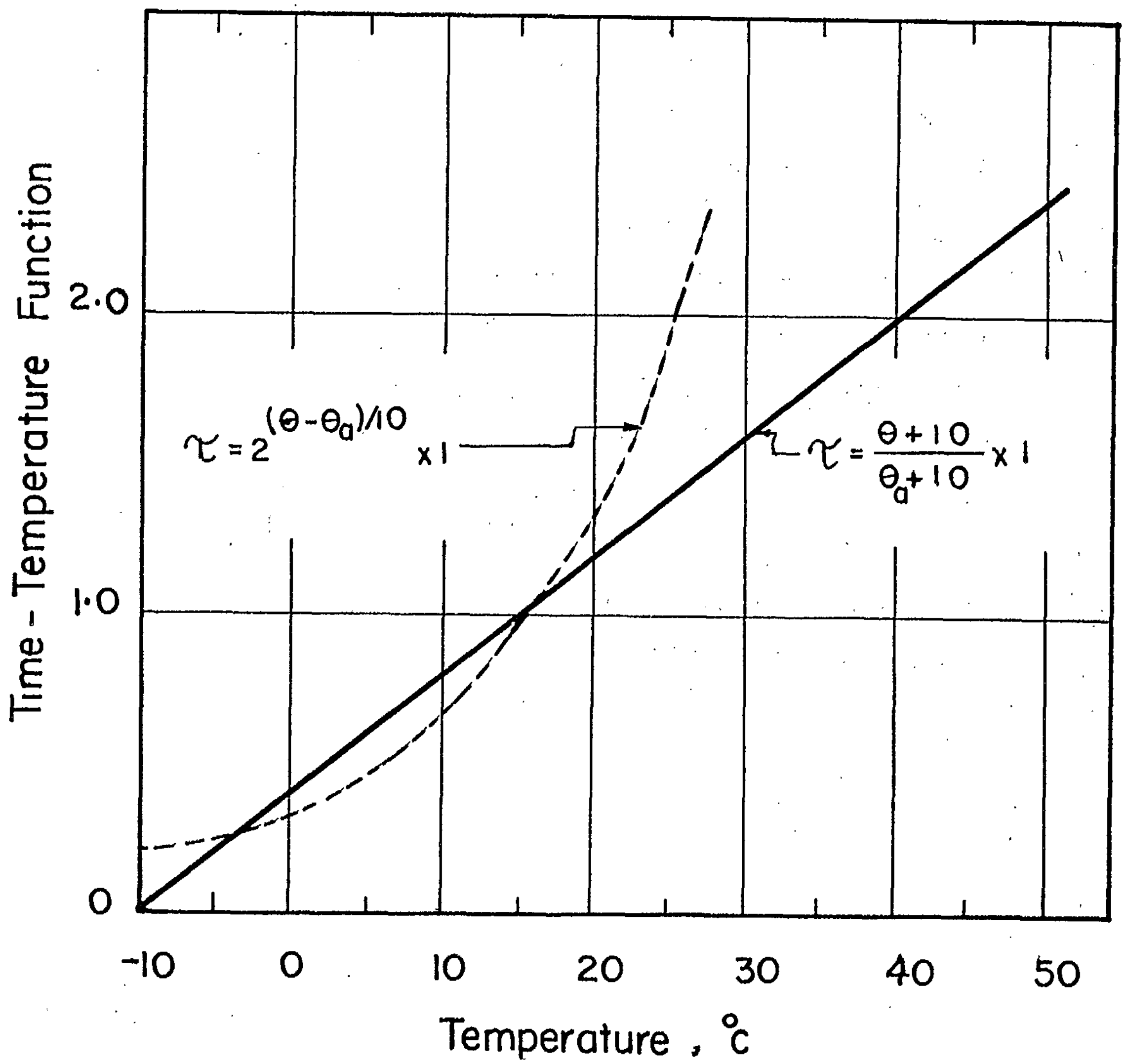


Fig. 9 - Comparison between Saul's Time-Temperature Function and that of Rastrup [9].

According to Nurse-Saul function Maturity, $M = \sum (\theta + 10)\,\Delta t$

Also, at a constant θ_a for time of hardening τ, expressed in the same units as t $\quad M = (\theta_a + 10)\,\tau$

then
$$\tau = \frac{\sum (\theta + 10)\,\Delta t}{\left(\theta_a + 10\right)}$$

The relationship shown in Figure 9 is plotted for a unit value of time and $\theta_a = 15°C$

For $\theta = 15°C$ and $\Delta t = 1$, $\tau = \frac{(\theta + 10)t}{15 + 10} = \frac{15 + 10}{15 + 10} \times 1 = 1$

Also $\tau = 2^{\frac{(\theta-\theta_a)}{10}} \times t = 2^{\frac{(15-15)}{10}} \times 1 = 1$

Rastrup applied both Nurse-Saul and his own time-temperature functions to published values dealing with heat of hydration and obtained results which indicated that his function was more closely in agreement with the test results than were Saul's, in this case.

Based on the relation between the non-evaporable water content and heat of hydration, as established by Verbeck [21], and the relation between non-evaporable water and strength as suggested by Powers [22], Rastrup visualized the applicability of the same time-temperature function to the development of strength as to the heat of hydration.

<u>Plowman's "Law of Maturity"</u>

In 1956, Plowman [11] examined relationships between concrete strength and its maturity, and attempted to establish a rational basis for datum temperature for use in maturity calculations. He defined the datum temperature for maturity as the temperature at which the strength of concrete remains constant.

In his investigations, he made several batches of concrete. After normal curing for 24 hours, cube test specimens were cured at temperatures of -11.5°C (11.3°F), -11°C (12.2°F), -8.0°C (17.6°F), 15.5°C (60°F) and 18.3°C (65°F), testing being carried out at ages up to 28 days. The relationships between compressive strength and age for these cubes are shown in Figure 10. As a result, he concluded the datum temperature to be -12.2°C (10°F).

Based on the above and the analyses of the other published data, he published the following relationship:

> "The percentage of the strength obtained at a maturity of
>
> $$35{,}600\,°F \times hr^{*} = A + B \log \frac{(\text{Maturity in } °F \times hr)}{10^3}, \text{ where A and B}$$
>
> are constants related linearly to the strength at any age".

He further stated that the above relationship was independent of:

(a) the quality of the cement
(b) the water/cement ratio
(c) the aggregate/cement ratio
(d) the curing temperature below 100°F
(e) the shape of the test specimens

*Maturity for 28 days curing at 64°F = 28 x 24(64-11) $\simeq$ 35,600°F-days.

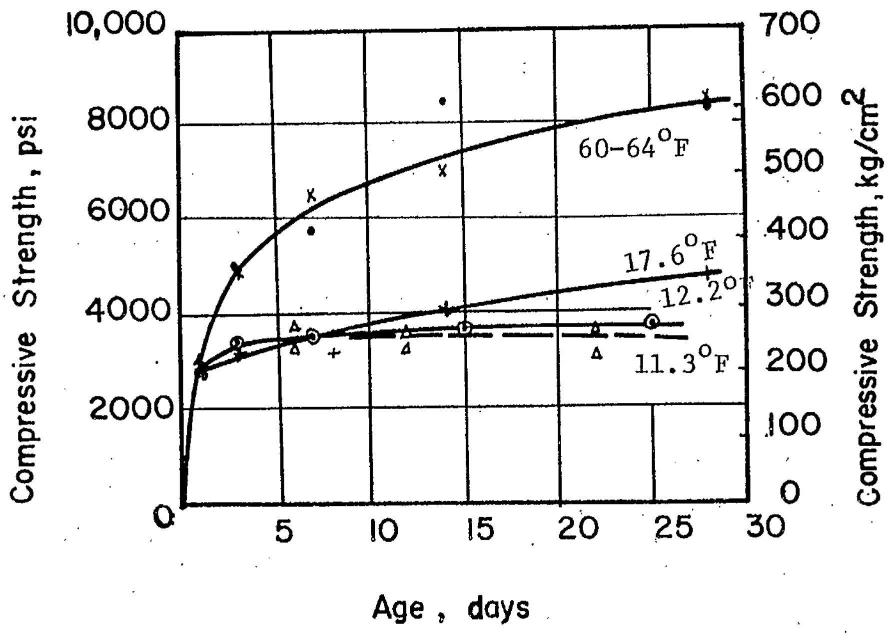


Fig. 10 - Relationships Between Age and Strength for Different Curing Temperatures (11).

A lively discussion followed the publication of Plowman's paper. Ockleston and Mills[12] agreed that the formula proposed by Plowman can give reliable estimates of the increase in the strength of concrete over very considerable periods of time, but advised caution in applying the strength--maturity relation proposed by Plowman to the estimation of the strength of concrete in a semi-arid climate where the period of moist curing is, as a rule, relatively short. It should be mentioned that their application of Plowman's formula was limited to concretes cured at 17.7°C (64°F).

Klieger[12] strongly questioned the validity of the strength-maturity relations for a wide variety of concretes. He pointed out that the relationship by Plowman would be applicable only if the following requirements were met:

(a) the relationbetween the logarithm of maturity and strength is linear;

(b) the initial temperature of the concrete is in the range of 15.5 to 26.6°C (60 to 80°F);

(c) that no loss of moisture by drying occurs during the curing period.

He presented much experimental data to back up his arguments; Figures 11 and 12 show some of the data indicating the effect of drying as it affects the strength-maturity relationship. He concluded his discussion by stating that the use of Plowman's relation of strength to maturity may have practical use provided the limitations were kept clearly in mind. Obviously, Klieger was sceptical of the usefulness of the proposed relationship.

Powers [12] in his discussion generally supported the points raised by Klieger. His theoretical calculations indicated that the datum temperature should be -4°C (24.8°F) but, as the theoretical basis of the calculations may not be exact, he was prepared to accept -12°C (10.4°F) as the datum temperature.

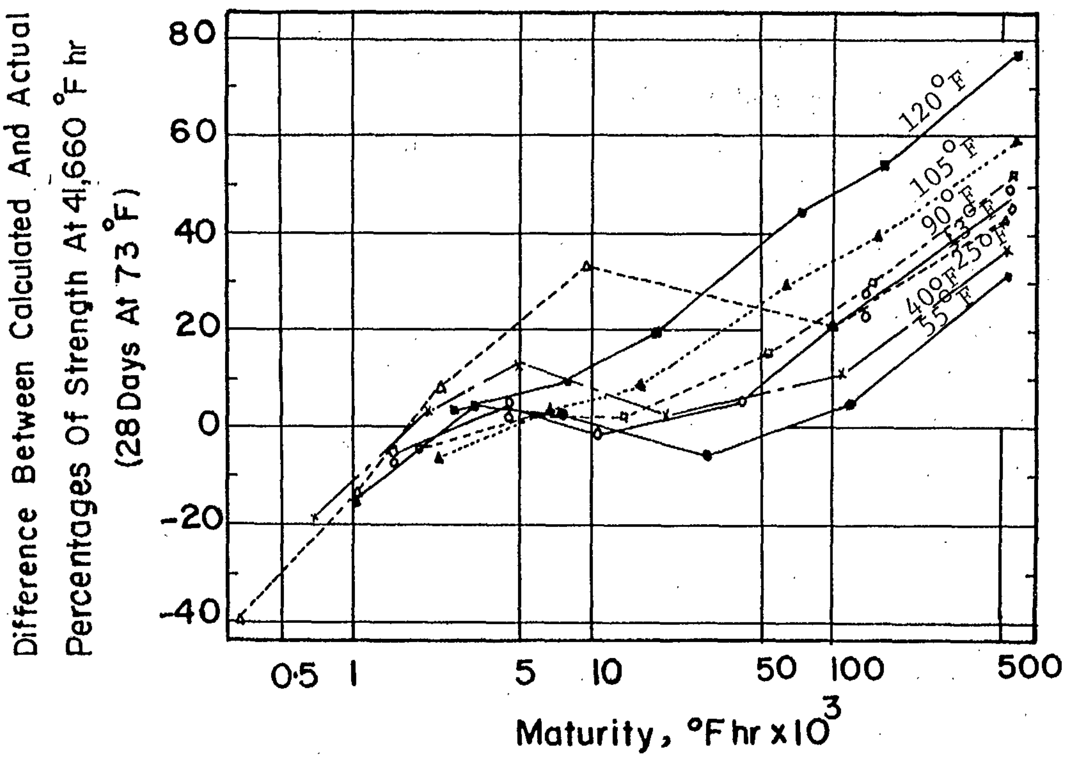


Fig. 11 - Comparison of Calculated and Actual Strengths [12].

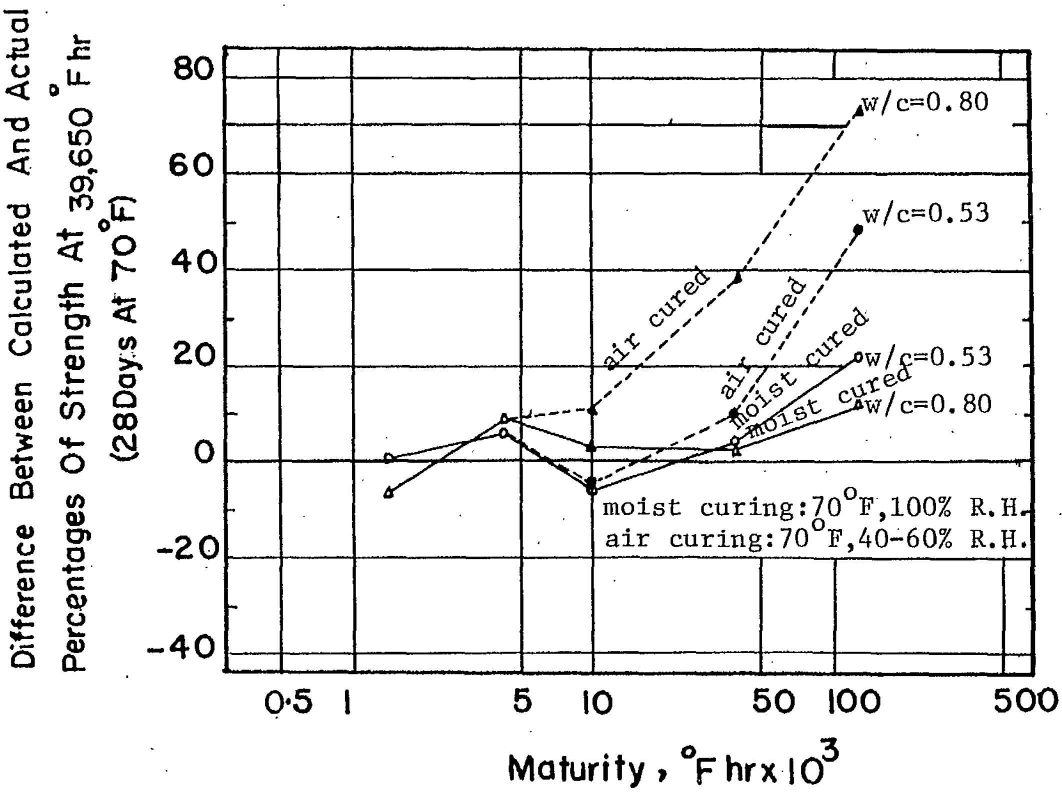


Fig. 12 - Effect of Drying as Indicated by Timms and Withey's Data [12].

Marshall[12] presented some data indicating that Plowman's maturity relationship overestimates the 28-day strength if calculated from the accelerated strength tests and underestimates the 12-month strength when 28-day and 12-month strengths are compared. He stressed that accelerated strength tests were of great importance and indicated the importance of obtaining information about strengths at maturities of, say 1650°C x hours (3000°F x hours).

McIntosh[12] submitted data which indicated that the relation between strength and logarithm of age could be taken as linear over only a very limited range of age (Figure 13); this supported Klieger's submission. He also stated the following two points:

(i) "...that difficulties occur in estimating the strength of concrete at low maturities and that they may be due to calculating the maturity from the time of mixing or casting rather than from some later time at which the concrete begins to gain real strength as distinct from the apparent strength due to the stiffening of the paste during the setting period.

(ii) ...that it may not be possible to assess the strength of concrete from its maturity if the temperature varies appreciably during the period before testing, because concrete cured at a low temperature for up to a quarter of its age at test and then at normal temperature for the rest of the time can have a higher compressive strength than similar concrete cured at normal temperature for the same length of time."

He concluded that the relationship proposed by Plowman should be restricted to concrete cured at a fairly uniform temperature, within the range of maturity represented by about 3 to 28 days at normal temperatures.

Klieger's Contribution

In 1958, Klieger[13] published further data showing that the concrete strength did not correlate well with the simple maturity index known as "degree x days". Figure 14 shows his relationships between the product of degree days of curing and the compressive strength of concrete cured at -3.9, 12.8, 22.8, and 48.9°C (25, 55, 73, and 120°F), the temperature referring to the initial temperature of concrete. The fact that the concrete

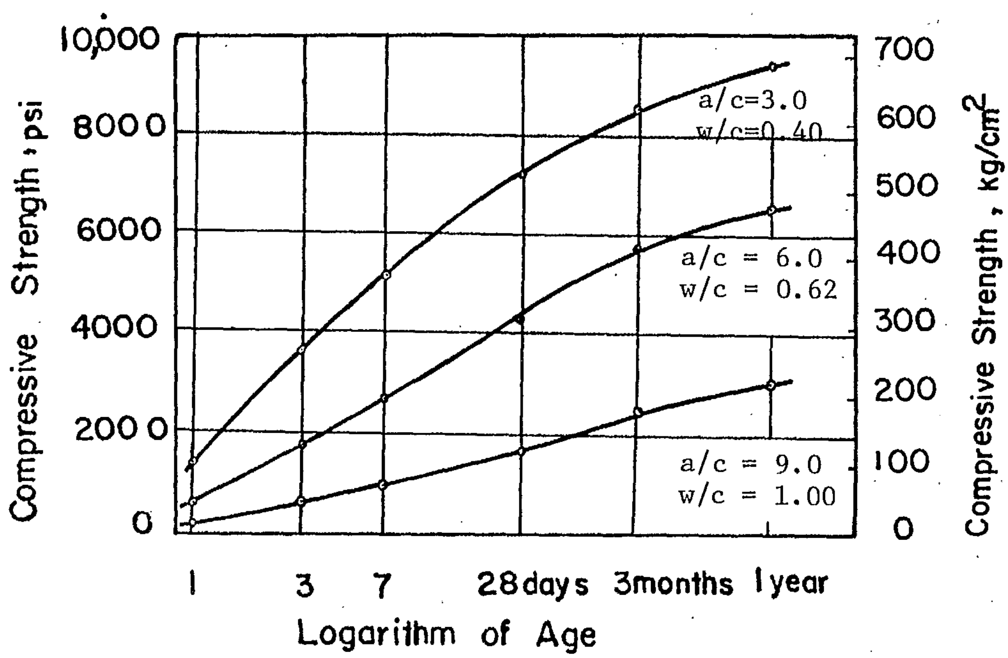


Fig. 13 - Relationship Between Strength and Logarithm of Age[12].

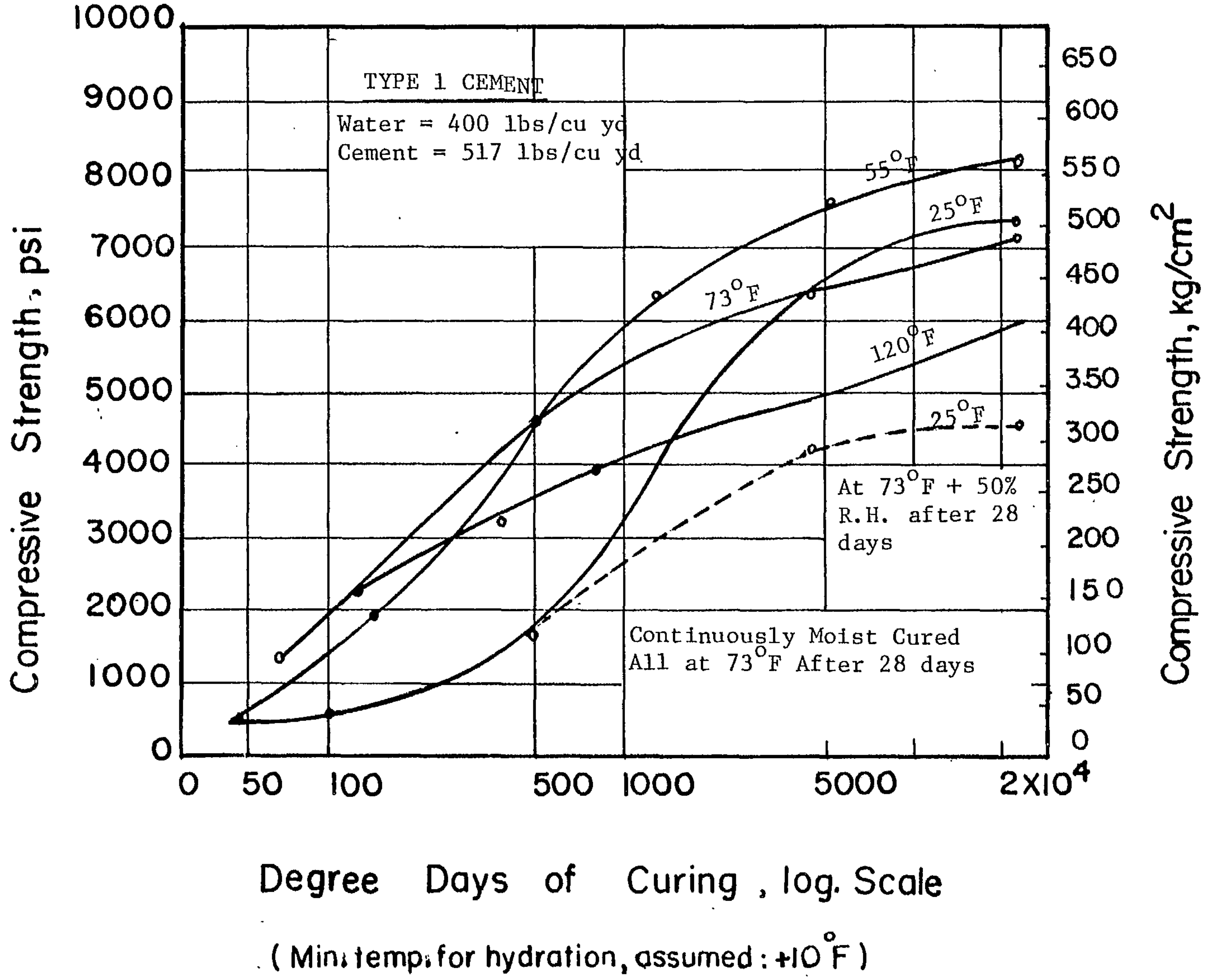


Fig. 14 - Relationship between Degree x Days of Curing and Compressive Strength of Concrete (13).

cured at 12.8°C (55°F) produced higher strength at the later ages than the concretes cured at 22.8°C (73°F), and even higher strengths than concrete cured at 48.9°C (120°F) led Klieger to conclude that there was little chance of significant correlation on a basis as simple as the product of degrees and days.

He also referred to the presence or absence of moisture during curing and its effect on the above type of correlation. His investigations revealed that for concretes cured at -3.9°C (25°F) for the first 28 days, the strength development during subsequent curing at 22.8°C (72°F) depended largely upon the presence of water during this period. This was more marked for -3.9°C (25°F) concretes than for conretes made and cured at 4.4°C (40°F) and higher.

A part of Klieger's data is reproduced in Table 1.

Ordman and Bondre's Contribution

In 1958, Ordman and Bondre[14] reported data on accelerated strength testing. They also published curves illustrating maturity-strength relationships for concrete cured continuously at 85°C (185°F) for curing cycles of 6, 19, and 23 hours with 1/2 hour allowed before and after heating for moulding and testing specimens. Their relationships were similar to Plowman's for normally cured concrete, i.e., the relationship between percentage of 28-day strength and $\log \frac{\text{maturity}}{10^3}$ gave straight lines (Figure 15). They noted that the constants A and B were nearly equal to one another for all 28-day strengths in the range from 267 to 457 kg/cm^2 (3800 to 6500 psi).

Narayanan's Investigations

In 1959-60, Narayanan[15, 16] reported an investigation of the effect of early curing on strength decelopment of concrete at 60, 70, 73.3, 77.2, 85.0° and 93.3°C (140, 158, 164, 171, 185, and 200°F) for various periods, using hot water as the heating media. The strength parameter was to be related to maturity of concrete above -11.5°C (11°F).

He made a series of concrete mixes in the laboratory using normal portland cement, irregular river gravel and natural sand. The mixes chosen

TABLE 1

Compressive Strengths of Concrete, 22.8°C (73°F) and Below

Cement content of all mixes, 308 kg/cu m (517 lb per cu yd),
Net W/C constant for each cement type.
Specimen Size: 15-cm (6-in.) modified cubes.

Cement ASTM Type	Fabrication and curing, temperature, °F first 28 days °F	°C	Compressive strength, psi 1 day	3 days	7 days	28 days	3 months** 100% relative humidity	3 months** 50% relative humidity	1 year** 100% relative humidity	1 year** 50% relative humidity
No $CaCl_2$										
I	73	22.8	1410	3120	4190	6050	6360	7070	7190	7100
	55	12.8	580	1930	3750	6250	7550	7990	8100	7720
	40	4.4	80	730	2140	5180	7120	7010	7730	6600
	25*	-3.9	40	460	620	1580	6290	4300	7360	4560
III	73	22.8	2640	3930	4780	5750	6320	7290	6910	7070
	55	12.8	1440	3180	4010	5470	6490	6680	6880	6740
	40	4.4	360	2000	4160	6260	7740	8090	8570	8260
	25*	-3.9	140	1360	2540	4020	6430	6500	6940	6720
II	73	22.8	860	1860	2760	5050	6480	7070	7440	6760
	55	12.8	400	1140	1990	4720	7190	7720	8150	7170
	40	4.4	60	560	1320	3290	7150	6360	7900	6430
	25*	-3.9	40	220	640	680	6360	2780	7800	3020
2 Per Cent $CaCl_2$, by Weight of Cement										
I	73	22.8	2530	3970	4960	6170	6980	7590	8340	7520
	55	12.8	1390	3210	4610	6300	7450	7840	8040	8220
	40	4.4	430	1940	3470	5350	7420	7920	8550	7540
	25*	-3.9	200	950	1930	4080	6500	6550	7910	6200
III	73	22.8	4440	5900	6820	7310	7820	8050	8680	8370
	55	12.8	3030	5120	5780	6740	8100	8230	8500	8280
	40	4.4	1640	3880	5320	6660	7970	7780	8040	7630
	25*	-3.9	1320	3240	4400	6460	7880	7400	8210	8020
II	73	22.8	1870	3300	4180	5690	7210	7640	8160	7280
	55	12.8	1030	2640	3870	5620	7470	7840	8280	7460
	40	4.4	290	1440	2740	4960	7220	7400	8460	6800
	25*	-3.9	220	920	1870	3180	6920	6400	9020	5840

*Fabricated at 4.4°C (40°F) and placed immediately in room at -3.9°C (25°F)
**Cured at 22.8°C (73°F) and either 100 per cent or 50 per cent relative humidity after first 28 days.

Note: To convert strength values in psi in strength values in kg/cm^2, multiply by 0.0703

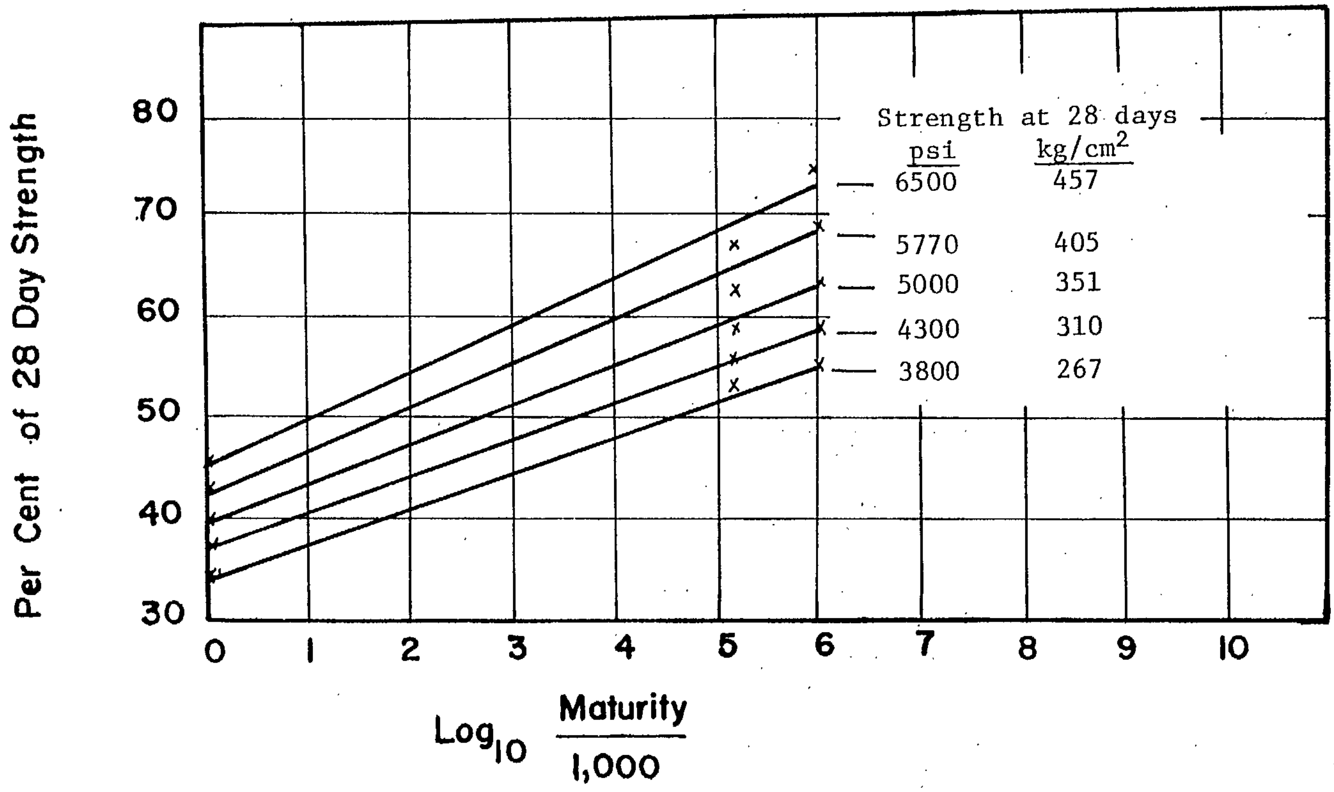


Fig. 15 - Relationship $\log_{10}\left(\frac{\text{maturity}}{1000}\right)$ vs per cent of 28-day Strength (14).

covered a wide range of aggregate/cement ratios varying from 3.0 to 7.5 and water/cement ratios varying from 0.35 to 0.70. The test specimens employed were 10-cm (4-in.) cubes.

Narayanan's analysis of the data showed that log maturity vs strength relationship as suggested by Plowman was applicable to all curing temperatures below 70°C (158°F). However, above 70°C (158°F), a different relationship existed for each temperature.

Narayanan also reported results of his studies in which a number of test specimens had been cured at 16.1°C (61°F) for periods of 13, 18, 24, and 37 hours and 2, 3, 5, 7, 14, and 28 days. The compressive strength versus logarithm of age were linear for ages from 2 to 28 days, i.e., between maturities of 2400 and 35,600°F x hours. He also concluded from his studies that the values of constants A and B in Plowman's formula needed constant updating due to continual improvement in the fineness of cement.

Akroyd(16) in his rather critical discussion of Narayanan's paper emphasized that more work was needed to obtain revised values for constants A and B for high-temperature curing. Also, according to him, the chemical composition of cement, in addition to its fineness, must be taken into account when discussing any revision in values of these constants.

RILEM Symposium on Winter Concreting

In 1956, RILEM sponsored a symposium on winter concreting and devoted almost a full session to the problems of hardening of concrete as influenced by temperature(17). Prominent contributors were McIntosh, Nykänen, Rastrup, Bernhardt and Wästlund.

McIntosh's contribution(17) followed the lines of his earlier contribution as a discussion to Plowman's paper. Once again, he stressed that for concrete cured continuously at low temperatures an estimate of strength based on maturity calculated from -10°C (14°F) leads to an over estimate at low maturities and an underestimate at high maturities. From his laboratory investigations he concluded that an accurate estimate of strength cannot rationally be based on any concept of maturity.

Nykanen's experimental studies[17] indicated that although the Nurse-Saul temperature function was suitable within the temperature range of 20 to 0°C (68 to 32°F); at temperatures below zero, the formula suited better in the form:

Maturity = $K(t+15)a_t$, where

a_t = duration of curing
t = temperature of curing, °C
K = constant

The value of constant "K" varies from 0.24 to 0.4 depending on the type of cement used. A datum temperature of -15°C (5°F) was selected because Nykänan found that gain in strength could be observed in the concrete up to -15°C (5°F).

His laboratory studies also indicated the dependency of the maturity (T x hr) of concrete on both the water/cement ratio and the quality of cement.

Bernhardt's contribution[17] dealt with some modification of the basic Nurse-Saul function similar to that suggested by Nykänen. His work also indicated that there was some gain in concrete strength even when cured at -20°C (-4°F), at least up to the age of 21 days. This is rather surprising, because Powers' calculations had shown that, theoretically, the datum temperature at which concrete ceases to gain strength is about -4°C (24.8°F).

The Swedish Cement and Concrete Research Institute made comparisons of strength development using the Nurse-Saul and Rastrup temperature x time functions for published data. The general conclusion reached was that, in most cases, the Nurse-Saul maturity function is in close agreement with the test results, whereas the scatter about Rastrup's mean is broad (Figures 16, 17).

From this information, Wästlund[17], the general reporter for the 1956 RILEM symposium, concluded as follows:

> "...study of the two functions under consideration seems to indicate that Rastrup's function may possibly describe the development of the heat of hydration better than Saul's function, whereas Saul's function gives a better description of the development of strength. This is an apparent contradiction, which may perhaps be due to the fact that the conversion of the heat of hydration into strength is not exact.

In the General Reporter's opinion, Saul's function is simpler in practical use than Rastrup's."

In his general report on session dealing with laboratory experiments on winter concreting, Inge Lyse(17) noted that the Nurse-Saul parameter seems to give a good indication of the strength development of the concrete, but cautioned its use for temperatures below 0°C (32°F). He presented no original data.

Discussion of Papers Presented at the RILEM Symposium

In the discussions(17) that followed the presentation of the papers, notable contributors were Hakanson, Danielson, Bergstrom, Akroyd, Brand, and Wästlund.

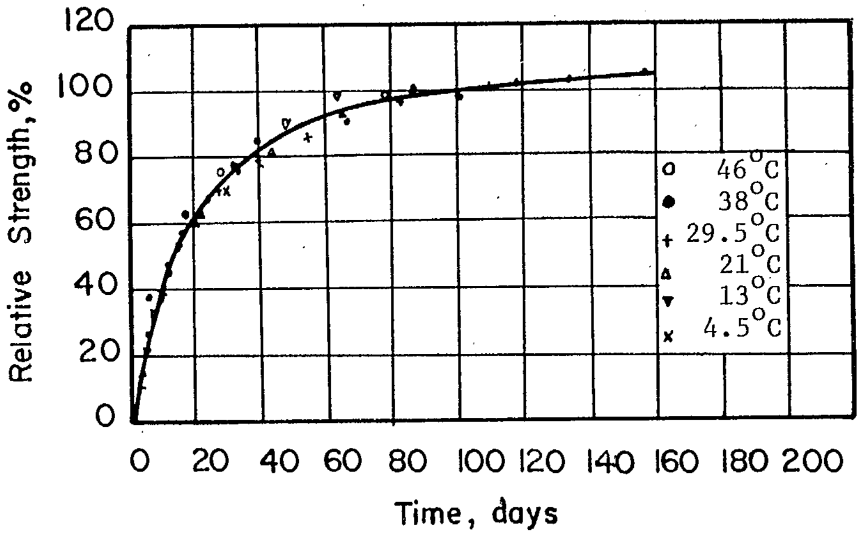
Hakanson doubted that the time x temperature functions could be applied universally. Danielson referred to the investigations at the Swedish Cement and Concrete Research Institute dealing with heat of hydration of cement. He considered that, while the maturity concepts were of practical value, the processes involved were complex and that contradictory findings need not necessarily be due to experimental errors. Bergstrom stressed that Saul's time x temperature function, with limitations proposed by Nykänan and McIntosh, was satisfactory for all practical purposes. Akroyd presented data on the accelerated curing of concrete and remarked that factors other than maturity must be taken into account when assessing the strength; in particular, the effects of the ratio of cement to aggregate were important.

Wästlund, in summarizing the discussion, concluded as follows:

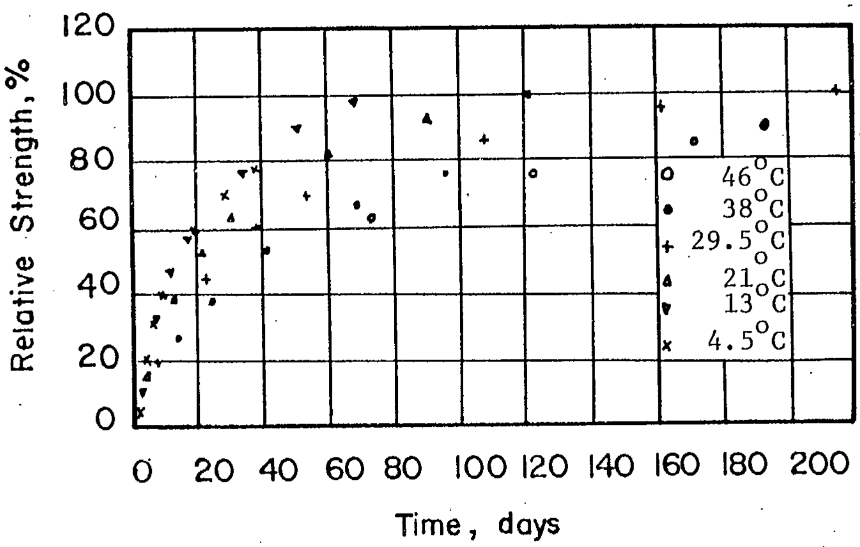
> "The result of the discussion is evidently that time-temperature functions must be used with care and that we should not regard them as physical laws. They have been criticized, showing that further research is needed."

DEVELOPMENTS DURING 1960-1970

In 1962, Alexander and Taplin(18) carried out experimental investigations to check the validity of the maturity rule. They studied the strength of concrete and the strength and hydration of its paste matrix under



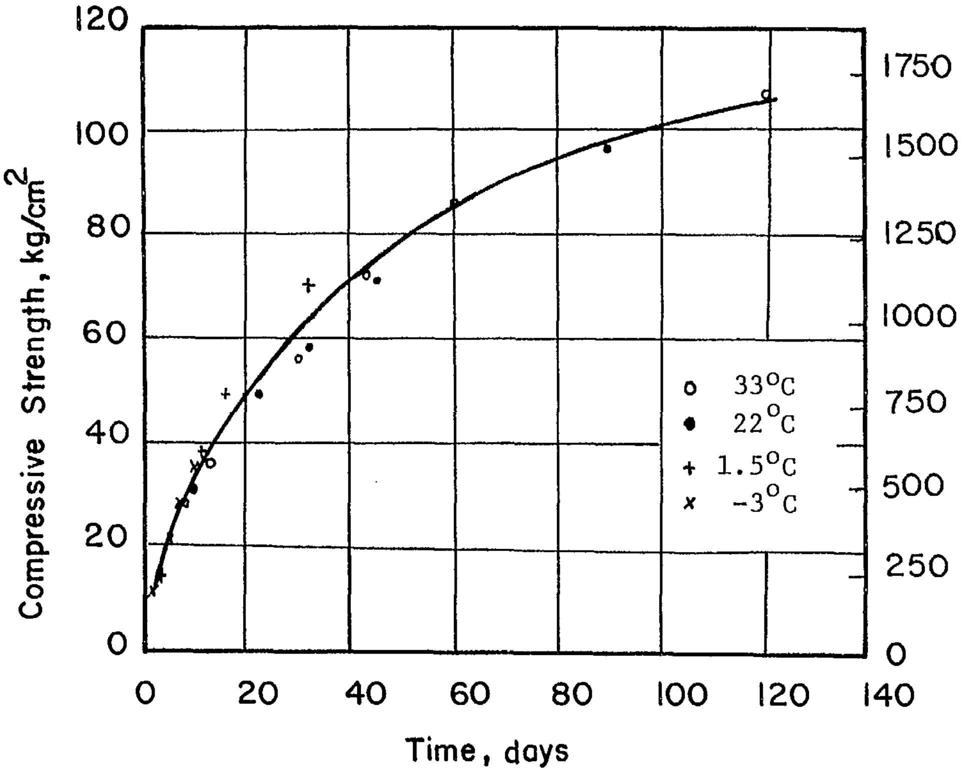
(a)



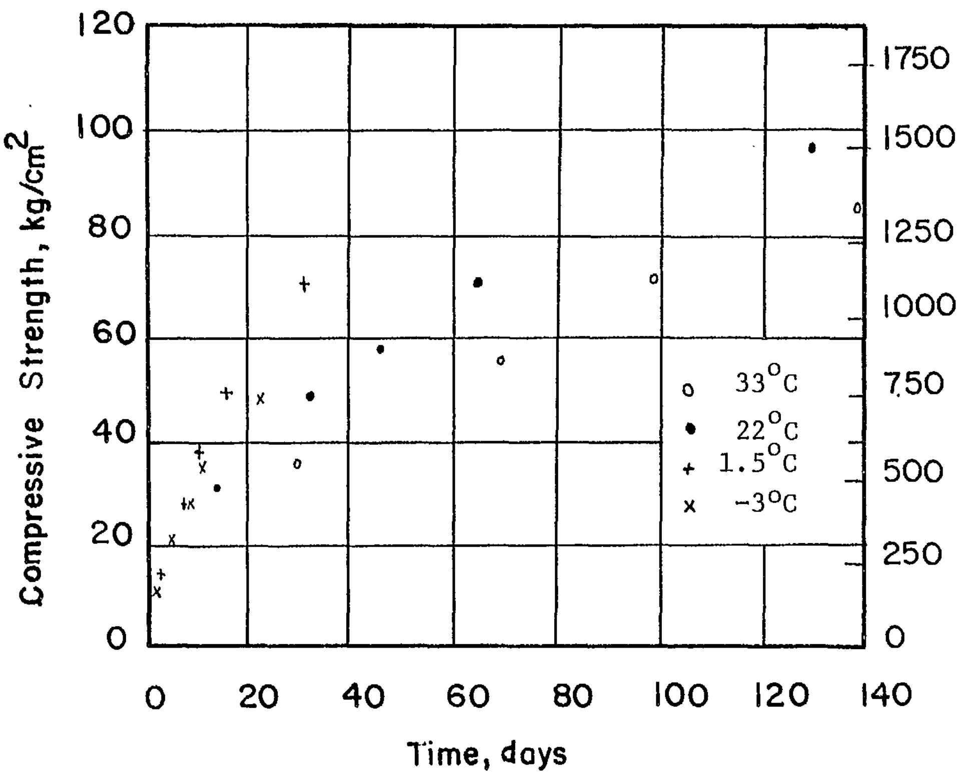
(b)

Fig. 16 - Compressive Strength in Price's Tests vs Saul's (a) and Rastrup's (b) Time-Temperature Function[17].

Note: In the above Figure, the maturity values have been reduced to the number of days at a temperature of 32° F (0°C).



(a)



(b)

Fig. 17 - Compressive Strength in McDaniel's Tests vs Nurse-Saul (a) Rastrup (b) Time-Temperature Function[17].

Note: In the above Figure, the maturity values have been reduced to the number of days at a temperature of 32°F (0°C).

one set of experimental conditions. The general conclusion drawn from their investigation was that both concrete and its paste constituent exhibit similar systematic deviations from the behaviour predicted by the maturity rule (Figures 18, 19). They summarized their conclusions as follows:

> "(i) At earliest maturities, the maturity rule greatly underestimates the influence of temperature on the strength of concrete and on the strength and degree of hydration of the cement paste matrix.
>
> (ii) However, by the time maturities equivalent to 28 days curing at 21°C (69.8°F) have been attained, the position has changed considerably, the greatest change being observed in the case of concrete compressive strength at low W/C ratios, where the maturity rule now overestimates the influence of temperature. Concrete strengths at higher W/C ratios, and paste strengths and hydrations at low W/C ratios show a similar though less-pronounced tendency to reverse the sign of their deviations from the rule at these later maturities.
>
> Evidence obtained with other brands of cement suggests that conclusion (i) is of general application. On the other hand, the reversal mentioned in (ii) may be only partial, or even absent, with some brands of cements."

In 1966, Ramakrishnan and Chielokitchley[19] presented the results of an experimental investigation on the influence of different curing temperatures and methods on the compressive strength of concrete. The water/cement and aggregate/cement ratios varied from 0.45 to 0.90 and 3.59 to 9.17. Crushed granite with a maximum size of 13 mm (1/2 in.) was used as coarse aggregate and fine aggregate was natural sand. Normal portland cement was used throughout the investigation.

Several curing methods and regimes were used, the most important being curing under water, curing under moist conditions, and curing under accelerated conditions. The temperature of curing varied from 27°C to 98°C (80.6 to 208.4°F) and the curing period varied from 1 day to 91 days. A total of 1400 ten-cm (four-inch) test cubes were tested. Based

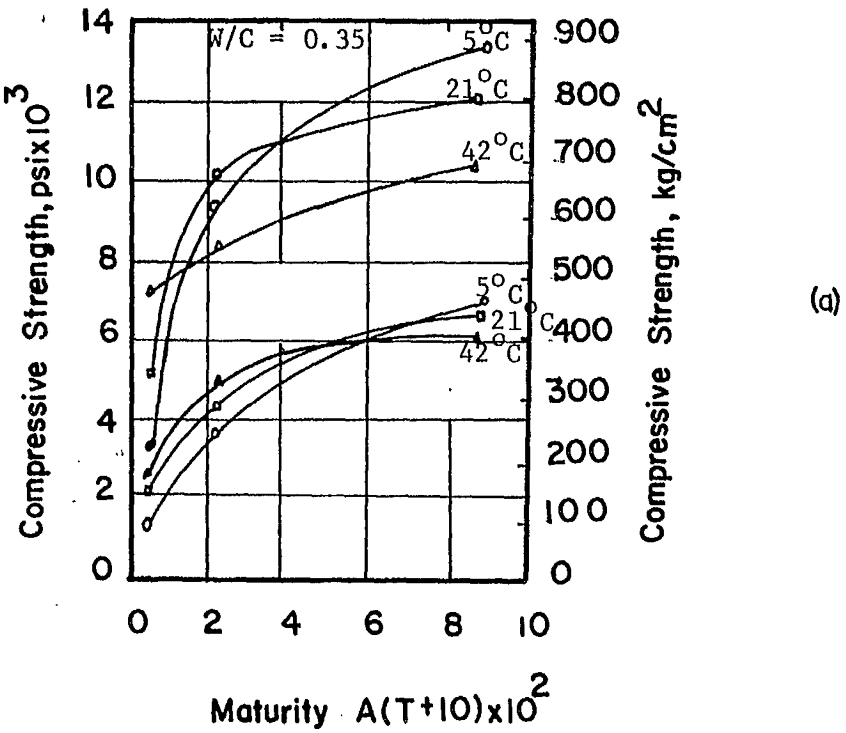


Fig. 18 - The Compressive Strength of Concrete vs Maturity [18].

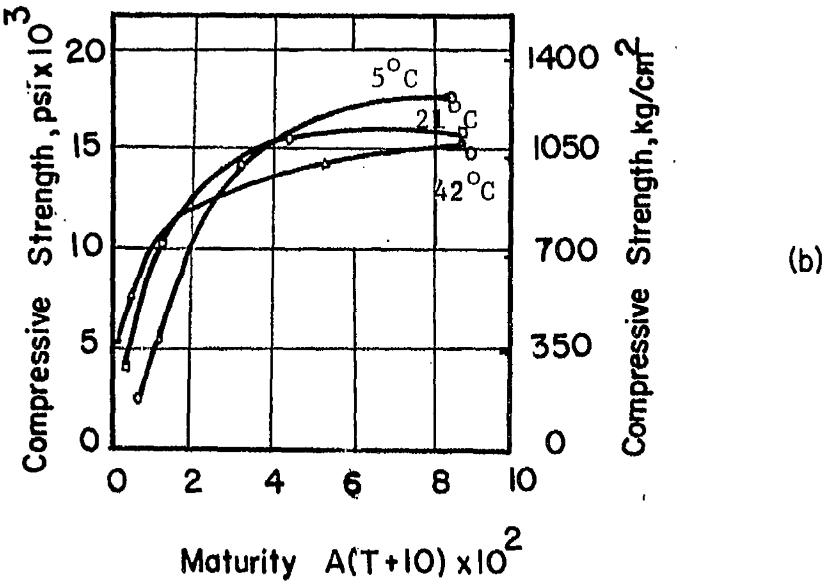


Fig. 19 - The Compressive Strength of Cement Paste vs Maturity [18].

on the results of these tests, they presented equations relating strength and log maturity together with a correction curve. They claim that with these equations and the correction curve it is possible to predict the strength of concrete subjected to water or humid curing for any given maturity between 871 and 17,758°C x hours (2600-32000°F x hours) at any particular temperature between 27 and 98°C (80.6 and 208.4°F). Their data also indicated that the relationship between log maturity and strength of a particular mix can only be represented by a straight line for maturities between 1 day and 19 days.

In 1967, Swenson[20] reported a case history where the maturity concept had been applied to investigate a field problem in Canada. During winter work, a floor slab had failed after the removal of some of the form work on lower floors, and it was important to estimate the strength of the concrete at the time of the failure in order to surmise that the concrete had developed the expected strength.

In spite of the large number of assumptions made and relatively few available data, Swenson reported that correlation between calculated strength values using the Nurse-Saul formula and corrected core strengths was good. Because of this generally good correlation at the time of test, Swenson considered that the calculated strengths at the time of failure were reliable.

In 1970, Malhotra[23] reported a series of investigations concerning maturity and accelerated strength testing carried out at the Canadian Mines Branch. The investigations showed that the only way to establish maturity-strength relationships with accelerated strength test results is by plotting strength versus the product of time and temperature. Conventional age:strength relationships cannot be used because different accelerated strength tests give different maturities. Figure 20 shows a plot of maturity* versus compressive strength for a series of concrete mixes

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Nurse-Saul time-temperature function with datum temperature taken as -12.2°C(10°F) made in the Canadian Mines Branch laboratory. Coarse and fine aggregates were crushed limestone and natural sand and cement was normal portland. All mixes were air-entrained. It is seen from Figure 20 that accelerated strength test values fall on the curve obtained from the strength test results of the 28-1/2 hour, 7 days and 28 days standard-cured cylinder specimens. Similar results were obtained when strength values from other accelerated strength tests were employed[23].

Other investigations carried out by Malhotra [23] revealed that:

(i) There appears to be some degree of correlation between the maturity obtained from various accelerated strength tests standardized by the ASTM in the U.S.A. and the corresponding compressive strength values obtained. This appears to be true for a wide range of water/cement ratios, though for each water/cement ratio there is a different correlation, (Figure 21).

(ii) When test specimens have been subjected to accelerated curing using the boiling water method and are subsequently moist-cured, the strength gain fails to follow the gain in maturity.

(iii) For the same maturity, concrete made with different brands of cement, gives different strength results. This is in accord with the other published data[17] and should serve as a warning against the indiscriminate use of the maturity principle.

---

* Accelerated Strength Test Curing Cycle:

Commencement of curing	= Immediately after mixing
Duration of curing at 70°F and 100% R.H.	= 23 hours; Maturity= 23(73-10)=1449°F x hr
Duration of curing in water at 210°F	= 3.5 hours;Maturity= 3.5(210-10)=700°F x hr
Commencement of testing = 2 hours after completion of curing	) Maturity= 2(140-10)= 260°F x hr
Total curing cycle	= 28.5 hr; Total Maturity = 2409° F x hr

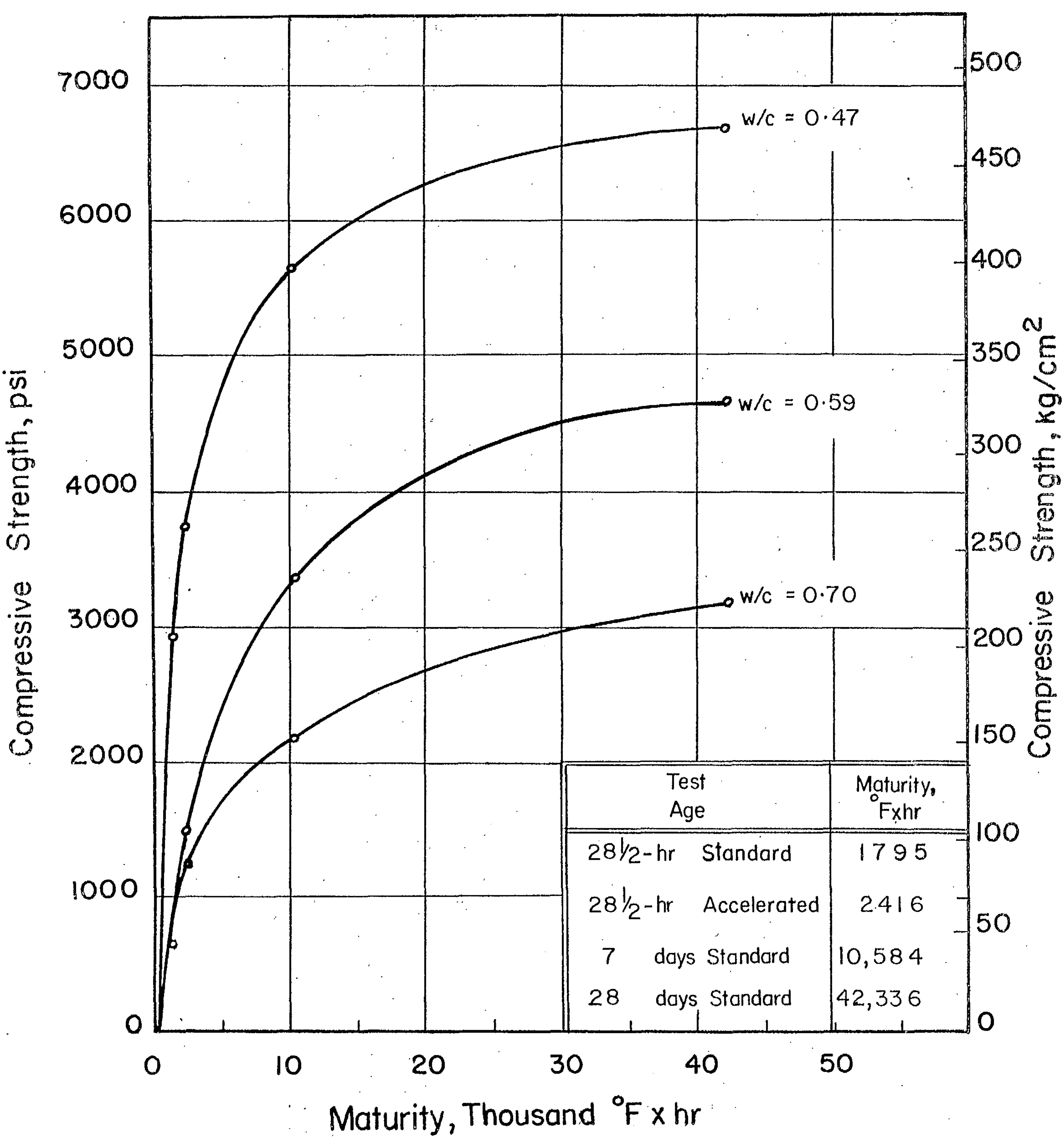

Fig. 20 - Relationship Between Maturity and Compressive Strength of Concrete [23].

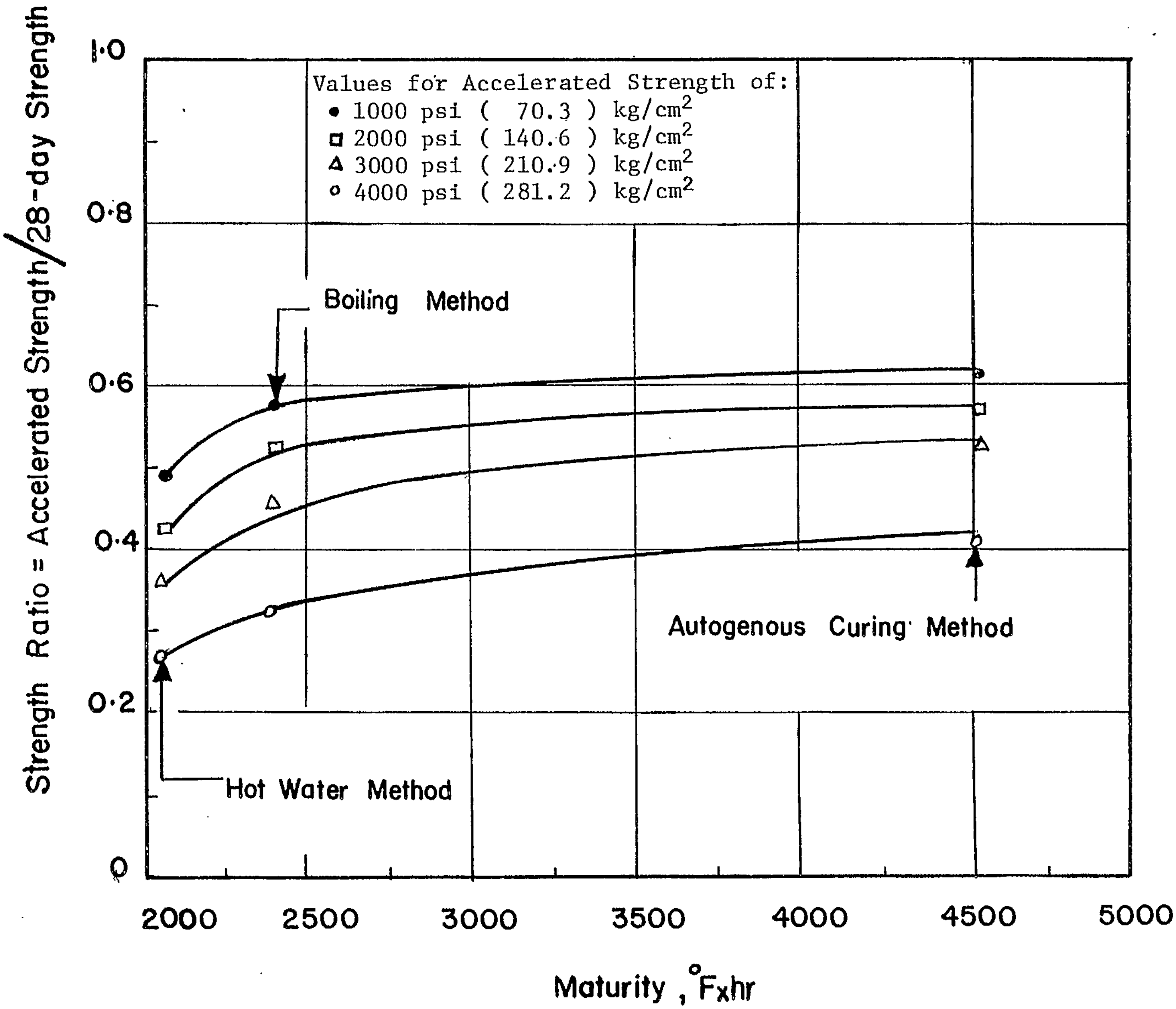

Fig. 21 - Relationship between the Strength Ratio[23] and the Maturity.

In 1970, Chin Fung Kee (24, 25) analysed some published data on concrete strengths and established the following linear relationship between strength and maturity:

$$D/_q = mD + C$$

where, q is the strength at age D, or maturity, and C and m are constants. It is claimed that this relationship is valid for concrete specimens, (i) cured initially at a temperature different from that used subsequently, (ii) made with various water/cement ratios, (iii) of ordinary portland cement and rapid hardening cement, and (iv) of normal as well as of lightweight aggregates.

SUMMARY OF THE LITERATURE UNDER REVIEW

1. Most of the earlier work on the effects of different curing temperatures on strength of concrete had originated in the United States during the period 1904-1940. Significant contributions were made by McDaniel[1], Wiley[2], and Timms and Withey[3] in an attempt to obtain strength data for winter concreting. However, no attempt was made by these researchers to establish relationships between strengths and the combined effect of time and temperature. During the period 1940-1960, a series of research papers originating from England and Europe gave birth to the concept of time x temperature function known as maturity. Notable contributors were McIntosh[5], Nurse[6], Saul[7], Bergstrom[8], Rastrup[9], Plowman[11], and Nykänen[17]. It is interesting to note that although problems associated with winter concreting stimulated the earlier work in the U.S.A., it was the attempt to obtain more data on electric- and steam-curing of concrete that led to the development work in the U.K.

2. The time x temperature function of the following form as suggested by Nurse-Saul[6, 7], and somewhat modified by Bergstrom[8], appears to best describe the strength development of concrete. Its limitations have been pointed out by McIntosh[12, 17], and modifications have been suggested by Nykänen[17] and Bernhardt[17].

Maturity in deg x days = a_t (t + 10)

where a_t = duration of curing in days

t = temperature of curing in °C

3. There are conflicting data as to the exact datum temperature at which concrete ceases to gain strength. Powers'[12] theoretical calculations indicate it to be -4°C (24.8°F); limited experimental investigation by Plowman[11] shows, it to be -12.2°C (10°F) and Bernhardt's[17] data show that concrete gains strength at temperatures as low as -20°C (-4°F), though very slowly.

The most accepted datum temperature appears to be between -12.2°C and -10°C (10 - 14°F). Further research work is needed on this aspect of maturity concept.

4. Rastrup's [9] time x temperature function of the form given below is well suited to describe the development of heat of hydration but it correlates less well with strength than does the time x temperature function of Nurse-Saul[6, 7].

$$a_1 = 2^{\frac{t_2 - t_1}{10}} \times a_2$$

where a_1 = the curing time at the temperature t_1

a_2 = the curing time at the temperature t_2

5. Plowman's "law" of maturity, i.e., the percentage of concrete strength obtained at a maturity of 35,600°F hr is equal to

$$A + B \operatorname{Log}_{10} \frac{\text{Maturity in °F hr}}{10^3}$$

where A and B are constants related linearly to the strength at any age, has serious limitations as pointed out by Klieger and others[12]. It appears that the above "law" is applicable only if:

(a) The relation between the logarithm of maturity and strength is linear and this is so only within the range of maturity represented by about 3 to 28 days at normal temperatures.

(b) The initial temperature of the concrete is between 15.5 and 26.6°C (60 and 80°F); this is a rather limited range.

(c) No loss of moisture by drying occurs during the curing period, a very difficult condition to achieve in the field.

6. There ia a paucity of data concerning strengths at low maturities which are usually associated with accelerated strength testing. Ramakrishnan et al. [19] and Malhotra's data[23] do provide some information but further research is needed in this field. This is especially so for the various accelerated strength tests which are being standardized.

7. There are few reported case histories where the time x temperature functions have been used to solve problems in this field. Swenson[20] has reported one such case history.

8. There appears to be some degree of correlation between the maturity achieved in various accelerated strength tests which are currently in the process of being standardized by the ASTM and the corresponding compressive strength obtained in these tests[23]. This appears to be true for a wide range of water/cement ratios, although for each water/cement there is a different correlation.

9. Conventional age:strength relationships cannot be plotted when accelerated strength testing is being employed. This problem is easily overcome by the use of maturity:strength relationships.

10. In general, maturity functions have found little acceptance among concrete technologists. This is probably due to the narrow limites of time, temperature and curing conditions within which these functions give valid results. Furthermore, estimation of concrete strength from maturity functions may depend on the water/cement and aggregate/cement ratio of concrete and the brand of the same type of cement.

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