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Estimation of Strength Gain of Concrete

by
E. G. Swenson

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CALCUL DES GAINS DE RÉSISTANCE DU BÉTON

SOMMAIRE

L'auteur a utilisé une fonction du temps et de la température pour calculer les gains de résistance du béton d'un ouvrage extérieur soumis à des températures variables en-dessous de la normale. Il a obtenu une bonne correspondance entre les chiffres obtenus et les résistances réelles des parties centrales en début de vieillissement, en dépit des valeurs hypothétiques assignées à la durée de la coulée, aux températures réelles régnant à l'intérieur du béton et à ses caractéristiques de résistance. L'utilité de la formule de maturation de Nurse-Saul a été démontrée dans ce cas.

L'auteur étudie également les facteurs influençant la précision de la formule de maturation et en déterminant les champs d'application pratique.



Estimation of Strength Gain of Concrete

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Ottawa

EIC-67-BR & STR 8

Cast in-situ concrete provides no strength at the time it is placed and so must be fully and adequately contained and supported by the formwork and falsework until it develops some load-carrying ability. This feature is always a strong and overriding determinant of the ways in which the construction process can be carried out, and gives rise to a number of important design and supervisory considerations requiring a high degree of engineering competence.

The supporting structure must be adequate initially to carry all the loads which will be imposed on it. Since it is always an important item in construction costs and may pose restrictions on the freedom with which subsequent operations can be carried on, it is usually desirable to remove it at the earliest possible time. This poses the critical engineering consideration of judging when and to what extent the concrete construction has gained strength so that loads can be transferred to it. At the same time continuing and careful attention must be paid to all other loads in addition to those represented by the weight of the structure, which result from the continuing construction operation, to see that the combined load-carrying capacity of the existing falsework plus the developing strength of the concrete structure is never exceeded. An alarming number of serious failures during construction in recent years serve as a reminder that this whole matter is of vital importance and that there is still much room for improvement in dealing with it.

One of the critical estimations which must always be made is that of the growth of strength of the concrete so that estimations may be made for any given time during construction of the load-carrying capacity of the structure. Strength values based on compression tests on concrete cylinders are normally used as standard criteria. Situations do arise, however, when such test results are not available, or it is not possible to wait until the tests are made. Such strength values are often developed under conditions of temperature which differ from those occurring in the struc-

ture and may therefore be misleading.

Prediction of concrete strengths at different times and under changing temperature conditions can be made with a high degree of confidence by means of the "maturity function". This is an established relationship based on the product of temperature and time. The quantitative character of this empirical function, which is approximate in the elementary form, can be improved by modifications for individual cases. Its usefulness can be extended to a considerable number of practical problems.

This paper presents a brief review of the development of the maturity relations, describes a case of practical application, and presents a discussion of its uses and limitations.

The Temperature-Time Relation

Portland cement paste hardens and develops strength as a result of products formed by chemical reactions between water and the compounds present in the clinker material. The separate influences of temperature and time on strength development of portland cement products have been extensively studied and reported since the earliest use of cement. Attempts to express the combined effects of temperature and time as a single function were made by Nurse,¹ Saul,² and Rastrup.³ These relations are based on the product of temperature and time, the product corresponding to a degree of maturity of the cement paste or concrete.

The so-called Nurse-Saul relation is the most generally accepted; it takes the form

$$M = \sum (C + 10) \Delta t$$

where

M = maturity factor
C = degrees centigrade
t = time

Rastrup's formula is given by

$$t_1 = 2 \left(\frac{C_2 - C_1}{10} \right) t_2$$

where

t_1 and t_2 are two curing times, and C_1 and C_2 are the corresponding curing temperatures.

Nykanen^{4c} has suggested a modification of the Nurse-Saul function for temperatures below 0°C, namely,

$$M = \sum K(C + 15) \Delta t,$$

where the coefficient K varies from 0.2 to 0.4 depending on the cement. Bernhard^{4e} developed a similar modification.

Bergstrom⁵ used extensive American and European strength data to support the general validity of the Nurse-Saul function. Bergstrom's plot using one set of strength results⁸ is reproduced in Fig. 1. The very slight dispersion of the points indicates the good quantitative character of this maturity relation. Similar plots by Bergstrom using the strength values reported by others gave equally strong support to the Nurse-Saul function. Lyse¹¹ reported similar good correlation.

The various forms of the maturity function have been discussed extensively in the literature ^{4a} to ^{4f}. There is general agreement that temperature-time formulae are of value provided they are used with care.^{4f} The Nurse-Saul function is the most widely accepted as a useful tool for practical purposes. It is generally conceded, however, that it fails in accuracy at very high or very low temperatures. Some fear is expressed in its use at varying temperatures.^{4f} It is regarded as applicable only to portland cements.

McIntosh^{4d} considers that the Nurse-Saul function tends to overestimate strengths at low maturities and to underestimate them at high maturities. He suggests that the time during which the concrete is in the plastic state should not be included in the calculations.

Klieger⁶ reported poor correlation between strength and "degree-days." Alexander and Taplin⁷ found "important systematic deviations" from the maturity rule.

Examination of the bases of these adverse criticisms suggests that while deviations of the maturity relation from the strictly quantitative may not be tolerable where high precision is required, it can be used to obtain values which are adequate for many practical purposes. The accuracy of such estimations can be greatly improved if the strength curve for the particular concrete under consideration is available and if the formula is modified to fit this curve and the temperature conditions.

Among the individual criticisms of the maturity function which were available in this study it was not possible to find a case where it had actually been applied to a field problem.

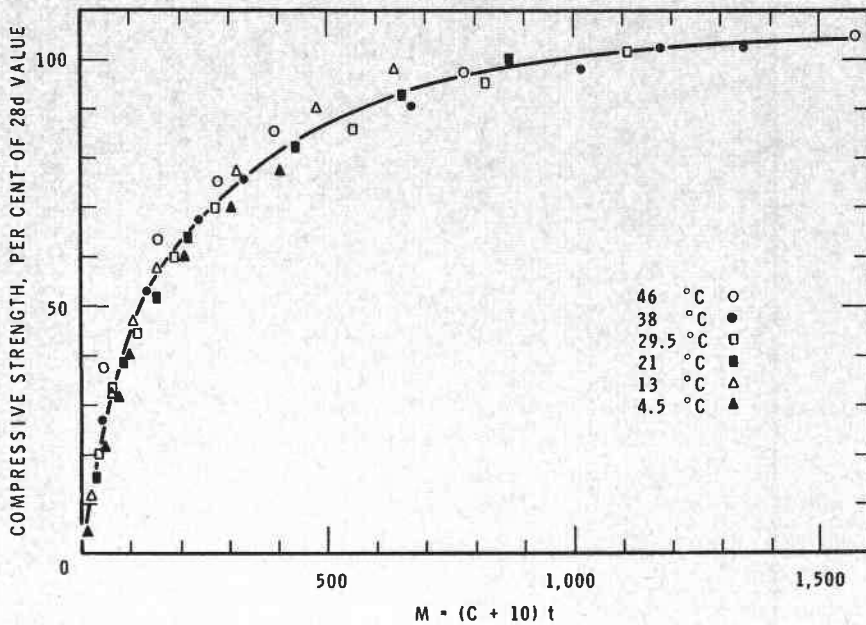


Fig. 1. Correlation of maturity values with strengths determined at various temperatures⁵ ($C = ^\circ C$; $t = \text{time in days}$).

Application to a Field Case

The Problem

A concrete floor slab placed during March failed during removal of some of the shoring at lower floor levels. Failure may have occurred first in the top slabs which had been placed one and two days before. This appeared to have generated further failure in older slabs below. It was important to know the strength of the concrete at the time of collapse in order to determine if the concrete had or had not developed the strength expected or required.

Public safety measures forbade coring at the site and it was necessary to break off large pieces of concrete, transport these to the laboratory, and core them there. Considerable time elapsed

between the time of failure and the time of final testing of the cores. These times varied greatly between samples.

These delays in time became highly significant because some of the critical concretes were only 1 to 2 days old at the time of failure, the strength gain had been retarded because of exposure to low outside temperatures, and because the laboratory temperature produced rapid strength gain of the sampled specimens at these early ages.

To arrive at the true strength of the concrete at the time of failure it was necessary to employ the maturity relation; in this case the Nurse-Saul formula was used. For technical and other reasons

the older slab sections were also tested and the maturity calculations applied to them.

The significance of the results as they relate to the specification requirements and safety regulations for removal of shoring or support of load are not considered in this treatment.

Assumptions

The problem of estimating strengths was made unusually difficult in this case because much of the pertinent information on mix proportions, times of placing, and methods of curing and protection, was not available or was rather uncertain. As a result, many assumptions had to be made, all of which affected the calculated values of strength to a greater or lesser extent. The following assumptions were made:

(a) Mix proportions were not obtainable, nor was it possible to obtain the strength curves for the concretes used on the job. The nominal strengths specified were 3000 psi for the slabs and 5000 psi for the columns. Taking into account the normal margins allowed by the ready-mix producer, it was assumed that the actual 28-day strengths were 4000 and 6000 psi, respectively.

(b) CaCl_2 was used as an accelerator but the dosage was uncertain. For reasons which appear below, 1 and 2 per cent by weight of the cement were assumed for the slab and the column concretes, respectively.

(c) On the basis of these assumptions, and because the strength data on the concrete were not available, a curve was selected which was considered to be representative of the slab concrete. This curve, the 40°F plot shown in Fig. 2,

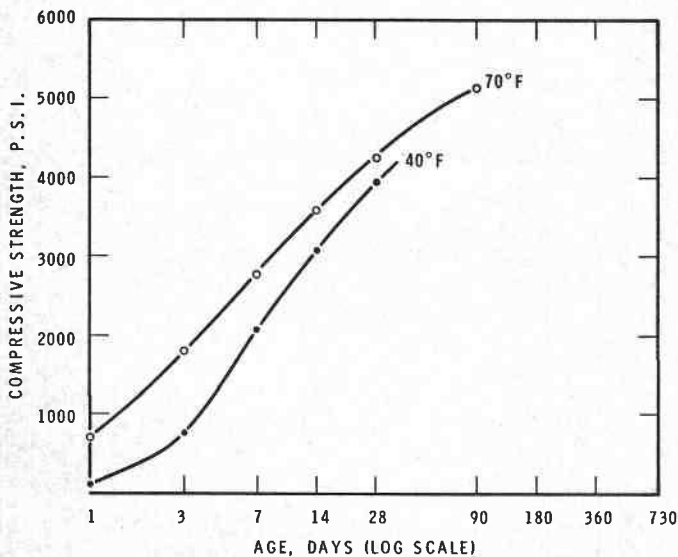


Fig. 2. Strength curve for 4000 psi concrete containing 1 per cent CaCl_2 ⁸ at two temperatures.

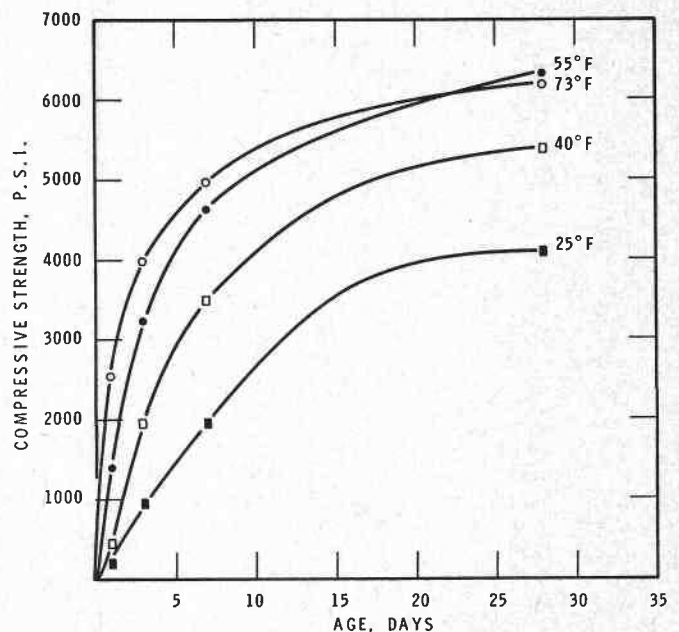


Fig. 3. Strength curves for a 6000 psi concrete with Type 1 cement and 2 per cent CaCl_2 (from Klieger⁶).

is taken from reliable literature.¹² This curve was based on concrete made with a Type II cement but this was considered acceptable under this temperature condition. At the time this was the only curve readily available which described a 4000 psi concrete containing 1 per cent CaCl_2 and which gave strengths at a temperature approaching that of the concrete on this job. It was not known what type of cement had been used on the job. The curve in Fig. 3 was used as a basis for the column concrete. It has been plotted from results published by Klieger⁶ for a concrete of approximately the required strength and containing 2 per cent CaCl_2 .

(d) The time of day of placement of the concrete could not be established. For convenience, 12 noon was taken in each case. The need for more exact times increases with increasing temperatures and shorter hydration periods.

(e) There appeared to have been no covering after placement of the concrete, or covering for one night at the most. The ambient temperatures recorded for this period are shown in Table I. It was assumed that the concrete slabs, with very high surface-to-volume ratio, underwent very rapid heat loss. The temperatures in the concrete for each day were assumed as shown in Tables II and III. It is possible that the slabs reached a temperature considerably lower than the official recorded night temperature because of microclimatic factors and possibly heat loss through radiation. It is equally possible that during the day the temperatures may have been higher because of sunshine or proximity to heated buildings. Attempts to adjust temperature further on these bases, however, were not considered as warranted. The temperatures in the columns were assigned a higher level because of low surface-to-

volume ratio and because forms are usually left in place for extended periods. (f) It was not possible to obtain reliable information as to the moist cure treatment. It was assumed likely that little or no wetting was carried out. Drying of the slabs would seriously affect mature concrete insofar as predictions of strength are concerned, but probably would not be a serious matter for young concretes. The core strengths might be expected to reflect this influence, although the inner parts of the slab sections from which cores were taken may not have lost significant amounts of moisture.

(g) The core samples were 2.7 in. in diameter. This was considered adequate as the maximum size coarse aggregate was in the order of $\frac{5}{8}$ in. The ends were trimmed by saw. It was possible in most cases to retain close to a 2 to 1 ratio of height to diameter. The cores were capped using a quick hardening capping

Table I
Weather Bureau Air Temperatures
in Area of Affected Concrete
Structure, °F

Date	Max.	Min.
Mar. 17	36	18
" 18	60	30
" 19	52	39
" 20	37	33
" 21	37	26
" 22	40	27
" 23	47	37
" 24	43	39
" 25	32	28
" 26	26	19
" 27	20	7
" 28	23	13
" 29	38	14
" 30	37	29
" 31	40	24
Apr. 1	39	23
" 2	46	24

Table III
Estimation of Concrete Strengths of
a Section of Slab B

Slab	Dates	Est'd Concr. Temp.		Maturity Period	$(C_1 + 10)\Delta t_1$, degree-days	Equiv. days (Δt_2) at 40°F		Strength, psi. (Fig. 2)	
		°F	°C			Indiv.	Totals		
B-4	Cast, Mar. 22	—	—	—	—	—	—	—	
	Mar. 23	45	7	1 day	17	1.17	—	—	
	Mar. 24	45	7	1 day	17	1.17	—	—	
	Mar. 25	35	1.5	1 day	11½	0.79	—	—	
	Mar. 26	30	-1	1 day	9	0.62	—	—	
	Mar. 27	20	-7	1 day	3	0.21	—	—	
	Mar. 28	20	-7	1 day	3	0.21	—	—	
	Mar. 29	20	-7	1 day	3	0.21	—	—	
	Mar. 30	30	-1	1 day	9	0.62	—	—	
	Failure Mar. 31	30	-1	1 day	9	0.62	5.62	1700	
Samples to lab.									
Samples tested									
(Apr. 1)		70	21	25 hr.	32.2	2.23	7.85	2150	

Table II
Estimation of Concrete Strengths of Slab A
Based on Nurse-Saul Maturity Relation

Slab	Dates	Est'd Concr. Temp.		Maturity Period	$(C_1 + 10)\Delta t_1$, degree-days	Equiv. days (Δt_2) at 40°F		Strength, psi. (Fig. 2)	
		°F	°C			Indiv.	Totals		
A-1	Cast, Mar. 30	—	—	—	—	—	—	—	
	Failed, Mar. 31	45	7	1 day	17	1.17	1.17	150	
	Apr. 1	40	4.5	1 day	14½	1.00	—	—	
	(Apr. 2)	35	1.5	1 day	11½	0.79	—	—	
Samples to lab.									
Samples tested									
(Apr. 2)		70	21	1 hr.	1½	0.10	3.06	775	
A-2	Cast, Mar. 29	—	—	—	—	—	—	—	
	Mar. 30	45	7	1 day	17	1.17	—	—	
	Failed, Mar. 31	40	4.5	1 day	14½	1.00	2.17	450	
	Samples to lab.								
Samples tested									
(Apr. 1)		70	21	30½ hr.	39½	2.72	4.89	1350	

compound. They were then broken in compression, with a minimum of delay between coring and final testing. The strength values were then corrected to a height-to-diameter ratio of exactly 2, and strengths equivalent to 6 by 12-in. cylinders. The correction factors used were those given in the U.S. Bureau of Reclamation Manual¹².

Calculations of Strengths

In Tables II to V inclusive are recorded sample calculations leading to an estimation of the strengths of the concretes placed at various times, and a summary of such strengths for all the samples taken. Temperatures (in °C) are taken to the nearest half degree; strengths are taken to the nearest 5 psi.

Table II gives the sequence of steps for predicting strengths in slab A at time

of core testing and at time of failure. Columns 3 and 4 give the assumed temperatures in the slab, as an average value over a 24-hr. hydration period of outside exposure. The time in the laboratory was taken to the nearest half hour (column 5). In column 6 are listed the degree-days calculated from the Nurse-Saul expression $(C_1 + 10) \Delta t_1$, where C_1 is the average temperature in degrees centigrade for the maturity period Δt_1 .

Using the 40°F curve in Fig. 2 as a basis, this temperature in degrees C is introduced into the second half of the Nurse-Saul formula, $(C_1 + 10) \Delta t_1 = (C_2 + 10) \Delta t_2$, as $C_2 = 4\frac{1}{2}$. Δt_2 is now calculated for each maturity period, the value for slab A being given in columns 7 and 8 of Table II. These values of Δt_2 represent the number of days at 40°F required to produce the same maturity (or strength) as the actual temperature produced in hydration periods shown in column 5.

The summation of the "equivalent days" for time of failure and time of test, given in column 8, are now applied to the 40°F curve of Fig. 2, and the corresponding strengths recorded in the last columns. These are the actual strengths of the concretes at these times as predicted by the maturity relation.

In Table III are recorded similar results for a section of an older slab. Table IV gives corresponding calculations for the two columns, but with the strength curves of Fig. 3 as a basis. Such data were developed for all other samples tested but are not recorded here.

In Table V are summarized all the strength results as obtained from the cores and from the maturity calculations. There are 3 floor slab sections, A, B, and C, for which 4000 psi concrete was assumed, and two columns. The number of cores taken from each section is shown in column 2.

The corrected core strengths in column 4 are considered to represent the actual strengths of the concrete at the time of test, in terms of 6- by 12-in. cylinders. These may be compared directly with the calculated strengths in column 5 (derived as in Tables II and III). The differences between the calculated values at time of test and time of failure (column 7) are subtracted from the corrected core strengths to obtain final, semi-direct values for the strength of the concrete at the time of failure (column 8).

Because of the relatively few data, no attempt was made to treat them statistically.

Discussion of Results

The corrected core strengths in column 4 of Table V are considered to represent the actual strengths of the concrete at time of test, in terms of the strengths of

Table IV
Estimation of Concrete Strengths of Columns

Column	Dates	Est'd		Maturity Period	$(C_1 + 10)\Delta t_1$, degree-days	Equiv. days (Δt_2) at 40°F		Strength, psi. (Fig. 2)
		Concr. Temp. °F	°C			Indiv.	Totals	
1	Cast, Mar. 29	—	—	—	—	—	—	—
	Mar. 30	55	13	1 day	23	1.55	—	—
	Failure Mar. 31	50	10	1 day	20	1.38	2.93	1950
	Samples to lab.							
	Apr. 1	70	21	—	—	—	—	—
2	Tested Apr. 2	70	21	43½ hr.	56.2	3.88	6.81	3450
	Cast, Mar. 26	—	—	—	—	—	—	—
	Mar. 27	55	13	1 day	23	1.55	—	—
	Mar. 28	45	7	1 day	17	1.17	—	—
	Mar. 29	45	7	1 day	17	1.17	—	—
	Mar. 30	40	4.5	1 day	14½	1.00	—	—
	Mar. 31	40	4.5	1 day	14½	1.00	5.89	3175
	Samples to lab.							
Samples tested								
	Apr. 1	70	21	27 hr.	34.9	2.41	8.30	3750

6- by 12-in. cylinders, and should correspond with the calculated strengths at time of test (column 5), except insofar as moisture loss had adversely affected the former. In the very young concretes of slab A no significant drying had occurred and the correlation between the two sets of values is remarkably good. It must also be kept in mind that results of a limited number of core tests may not be completely reliable or entirely representative of the concrete.

The hydration periods in the laboratory varied from 1 hr to 52½ hr. This did not appear to have any discernible influence on the degree of correlation.

Because of the generally good correlation between core strengths and calculated strengths at time of test, the cal-

culated strengths at time of failure were considered reliable (column 6).

It can also be concluded that the difference between the calculated strengths at these two times is a value which must be very close to the true difference (column 7 in Table V). This difference was subtracted from the corrected core value in each case to obtain a value for the strength of the concrete at time of failure which is of added interest in that it represents a further correction of the core strength. These values (column 8) should not be considered as in any way more significant than the calculated values in columns 5 and 6.

When it is recalled that the number of assumptions that had to be made was much greater than would normally be

Table V
Summary of Concrete Strengths Derived from Cores and from Maturity Calculations (3 Slab Sections and Two Columns)

Concrete Element	No. of Cores	Days from Casting to Failure		Core Strength, psi Corrected	Calculated Strength, psi, (Nurse-Saul)		Difference (Col. 5 minus Col. 6)	Est'd psi at Failure (Col. 4 minus Col. 7)
		Col. 2	Col. 3		At Test	At Failure		
		Col. 1	Col. 3		Col. 5	Col. 6		
A-1	3	1		800	775	150	625	175
A-2	5	2		1250	1350	450	900	470
A-2	2		1385					
A-2	1			1470				
B-1	2	6		1160	1425	775	650	510
B-2	3	8		1775	1800	1400	400	1375
B-3	1	9		2010	2050	1700	350	1660
B-4	6	9		2100	2150	1700	450	1650
B-5	2	14		1790	2800	2600	200	1590
C-1	2	12		2295	3050	2250	800	1495
C-2	3	21		2320	3500	3100	400	1920
Column A	2	2		3525	3450	1950	1500	2025
Column B	6	5		3930	3750	3175	575	3355

the case, the degree of correlation shown in the above results warrants confidence in the application of the maturity relation in practical cases of this type.

Factors Affecting Precision

The quantitative character of the Nurse-Saul maturity relation can be improved by the two methods already suggested: (a) use of strength graphs of the particular concrete in question and modification of the formula to suit this graph; and (b) by obtaining more and accurate information on mix characteristics, procedures and times of casting, and degree and duration of curing and protection.

It is clear from the studies of Nykanen,^{4c} Bernhardt,^{4e} and others that it is possible and often desirable to modify the empirical temperature-time relation to fit better a particular case. This is especially important for concretes made with accelerators or retarders in which the character of the strength curves is directly affected, particularly at low maturities. Two different formulae may be required for a single curve, one applicable to low maturity and the other to high maturity. The latter case may be illustrated in an over-simplified way using some data of Klieger⁶ and calculated as in Table VI. This shows that for these strength results, the expression $(C + 10)t$ holds reasonably well for maturities of 7 to 14 days, but at lower maturities the expression $(C + 0)t$ is better.

Similar trends hold for Klieger's results for concrete made with Type I cement and 2 per cent CaCl_2 , and for Types II and III cements. Price's results,⁸ however, tend to be in agreement with the expression $(C + 10)t$ for ages up to 28 days and more. An examination of strength results of others, for example, Davey⁹ and Gruenwald,¹⁰ shows deviations from the maturity rule which, when significant from a practical point of view, can be reduced or eliminated by some simple modification as illustrated above. This is a sound procedure because such deviations are systematic.⁷ It can be shown from the same sources of strength results that the deviations of the formula can be significantly reduced if one uses a strength curve developed at a temperature close to that for which calculations for strength are to be made. All ready-mixed concrete suppliers should have strength results on each of their mixes for 1, 3, 7, 14, and 28 days. These should be readily available.

In comparing published strength data it is well to note the differences in certain factors which may affect the results derived from the maturity relation. Examples of obvious ones are water-cement ratio and method of compaction. Less obvious ones are: temperature conditions

of ingredients prior to mixing, change in placing and curing temperatures, type of test specimens, whether prisms or cylinders, etc. The influence of such variables is essentially eliminated if one can use the strength curves for the particular concrete to which the maturity calculations are applied.

Areas of Application

Granholm^{4f} suggests that situations can arise at a building site where it is necessary to have a method of predicting strengths without resort to compressive strength tests. In some instances it is not possible to wait for such strength tests. It is also the case, all too often, that preparation and conditioning of test samples at the site can be less than satisfactory and that the results of such tests may not only be poor but may even be misleading.

ing the maturity function is complicated¹⁴. It may be adequate to estimate temperatures at intervals as in the case described in this paper. Because of the large surface to volume ratio the moisture loss in slabs can seriously affect the value of predicted strengths, except at early ages. In cases of "massive" concrete elements, the heat rise in the interior may be very considerable and thus affect the calculated results.

Predictions of strength can be useful in cases such as transfer of load, determination of time to apply post-tensioning or release of prestress, and prediction of specification strengths of precast elements. In such cases, where predictions are made before the job is carried out, all information requisite to accurate predictions can be available. Maturity calculations can also be useful as a check in cylinder testing.

The function can be useful in the pre-

Table VI
Example of Effect of Modification of Maturity Relation
from Data of Klieger (6) (Table 5, Page 1068) Type I Cement,
No Admixture

Temperatures	Equivalent Age Δt_2 (at C_2), days; using			
	Age t_1 (at C_1), days	$t_2 = \frac{(C_1 + 10)t_1}{(C_2 + 10)}$	$t_2 = \frac{(C_1 + 0)t_1}{(C_2 + 0)}$	Strengths (Fig. 3)
$C_1 = 73^\circ\text{F}$ (22.8°C).....	1	1½	2	2
to	3	4½	5½	5½
$C_2 = 55^\circ\text{F}$ (12.8°C).....	7	10	12	11½
	14	20	25	17
$C_1 = 73^\circ\text{F}$ (22.8°C).....	1	2	4½	5
to	3	6½	13½	10
$C_2 = 40^\circ\text{F}$ (4.4°C).....	7	15½	32	17
	14	30½	64	35

Quantitative guides are usually lacking in job decisions regarding the use of an accelerator or a high early strength cement to obtain high early concrete strengths. This is also true of cases where a decision has to be made as to the degree of protection required at low temperatures. The maturity function enables one to calculate concrete strengths at various ages and under varying temperature conditions. This can result in reduction in costs and in greater assurance in meeting safety requirements.

The degree of maturity of concrete required before it can be safely exposed to frost action has been reasonably well established.¹³ The maturity function enables one to calculate the curing time needed to meet such requirements under various temperature conditions. Slab construction is particularly susceptible to heat loss during cool weather and the rate of strength gain may be seriously affected. Although cooling formulae for predicting concrete temperatures under cooling conditions have been developed, their application in calculations involv-

paration of curing conditions to meet a particular scheduling program. It ought to be used as a regular tool on all jobs of any consequence, particularly in predicting time for removal of shoring and other supporting falsework.

Perhaps the serious limitation in the practical use of the maturity relation is the drying of the concrete and its effect on strength. Cases of excessive drying are not usually hard to distinguish. In such instances, maturity calculations must be limited to low maturities, perhaps up to 3 or 4 days. It is the young concretes, however, that pose most site problems.

The examples considered illustrate the two categories of possible use of the temperature-time function: (a) predictions before the job, and (b) calculations and estimations after the job. In the former case a high degree of accuracy can be achieved because all pertinent information can be available. In the latter case, as for the field case described in this paper, assumptions may have to be made which may reduce accuracy to a considerable extent.

Summary and Conclusions

Examination of recent literature would indicate that there is practical usefulness to be found in the Nurse-Saul maturity function in calculation of strengths of concrete, particularly where temperatures are low or variable. The function can be improved by modifications to fit particular concrete curves, or parts of such curves. The quantitative value of calculated strengths is improved as the accuracy of the temperatures and placing times is improved.

The maturity function is given a severe test in the field case described in the paper. Despite a lack of much pertinent information, and the many assumptions that had to be made as a consequence, the strength values predicted by this function showed good correlation with core strengths at the age of test. It was thus possible to predict strengths at another age with a high degree of confidence.

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