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Effects of High Temperatures on the Properties of Hardened Concrete

M. SAMARAI, S. POPOVICS, AND V.M. MALHOTRA

The effects of high temperatures on the properties of hardened concrete and the reactions involved in the hardening process are discussed. The undesirable effects of hot weather on the properties of hardened concrete include decreased strength, increased tendency for drying shrinkage and differential thermal cracking, decreased durability, and increased creep. Recommendations for further research are given.

The effects of a hot climate are not so conspicuous on the properties of hardened concrete as they are on concrete in the fresh state. Nevertheless, such effects are important enough to require attention.

The organized summary presented below emphasizes the engineering aspects of the subject instead of the scientific point of view. Besides this, some of the currently unknown aspects are outlined in the form of recommendations for further research.

EFFECTS OF TEMPERATURE ON HARDENING

Reactions in Hardening Process

After the final set, chemical reactions between cement and water continue at a diminishing rate until one or more of the conditions necessary to the reaction are lacking. This stage of hydration is called the hardening process, during which the predominant reaction is the continuing hydration of the calcium silicates. The decrease in rate is the result of two effects: (a) the surface area of unhydrated cement particles decreases as the smaller particles become completely hydrated and the larger particles become smaller, and (b) a layer of CSH gel forms on the surfaces of the cement particles, slowing down further reaction by forming a protective coating.

Measurements indicate that the kinetics of hydration are influenced by several factors, including the fineness and composition of the cement, temperature, and water/cement ratio of the paste, and admixtures (1, pp. 259-273). It is important to note here that if any of these factors increase the specific rate of hydration, the same change simultaneously intensifies the deceleration of the hydra-

Figure 1. Effect on concrete compressive strength of elevated casting and moist curing temperatures: type I cement up to 1 yr.

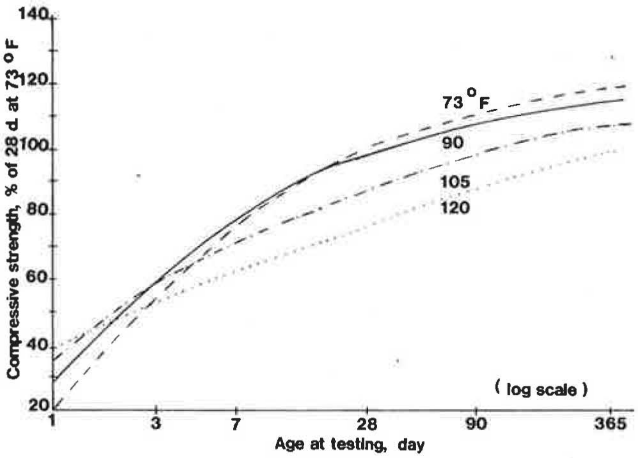
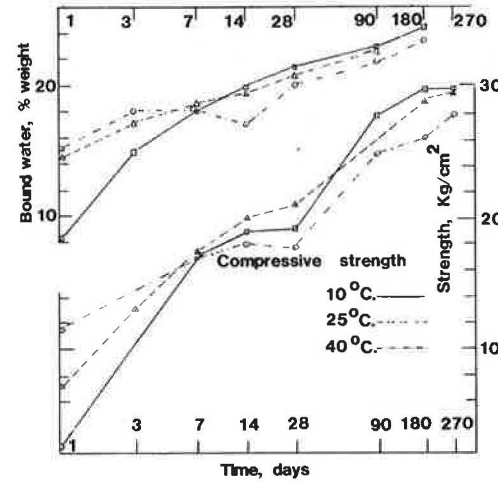


Figure 2. Compressive strength and bound water content of cement containing 12.5 percent C_3A.



tion to a greater degree. Thus, the hydration will begin more strongly but will also level off sooner. The kinetics are important not only because they control the quantity of the hydration products at early ages but also because they influence to a certain extent the quality of hydration (2).

General Description of Effects of Temperature

When concrete specimens are cured at various constant temperatures, the temperature has a double effect on their strengths. On the one hand, a higher curing temperature increases the strengths at early ages, which is expected, but on the other hand, it hinders the strength development later on, which is unexpected. This is illustrated quantitatively in Figure 1 (2,3), which shows the development of compressive strength of an ASTM type I portland cement.

In more general terms, the ultimate strength of a cement paste, mortar, or concrete is frequently lowered by factors that increase the early strengths (4). The term "ultimate strength" is used as the strength obtained after a long duration of moist curing.

There are quite a few analogies in nature for such an inverse relationship: The speed of the sprinter does not carry him as far as the lower speed does the distance runner; a low rate of growth results in larger crystals than a high rate; and so forth. Nevertheless, such cases represent the minority, and perhaps this is why one finds perplexing the existing inverse correlation between early strength and ultimate strength of portland-cement pastes.

From the standpoint of kinetics, the inverse relationship between the early strength and the ultimate strength means that an increase, for instance, in the curing temperature intensifies the rate reduction (deceleration) of hardening. Consequently, if a factor increases linearly the specific rates of the hardening process, it will intensify the specific decelerations more than linearly; that is, the hardening will start out stronger but will also level off sooner.

A possible physical explanation for the unexpected correlation between high early strength and relatively low final strength is the hypothesis that certain strength-affecting properties of the hydration products are modified by a change in the rate of hardening. The essence of this mechanism is that a change in the rate of hardening per se affects inversely the final strength, and the cause of the rate of change is secondary at most. For instance, cementlike CSH gels under the effect of intensifying physical or chemical factors produce a somewhat higher specific surface at early ages (5, pp. 199-219). This means finer texture and, presumably, lower porosity at early ages, which trend may reverse itself at later ages. So the rate of early hardening appears to influence, per se, the strengths at later ages through its influence on the structure of cement gel.

In brief, the inverse relationship between early strengths and final strengths is not quite understood yet. The hydration products formed, say, during curing at 122°F (50°C) do not differ greatly from those formed at 68°F (20°C). The elevated temperature modifies somewhat the morphology of the calcium silicate hydrates, but this effect does not appear to be large enough to have a major effect on the final strength. Thus, the main reason for the relatively low final strengths of the steam-cured and other accelerated concretes seems to be mechanical: The rapid hydration may produce higher final porosity and more microcracks in the gel (6).

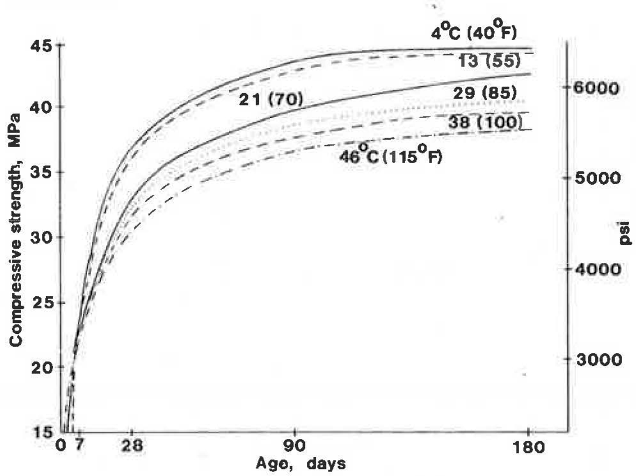
EFFECTS OF TEMPERATURE ON STRENGTH

Curing Temperature and Compressive Strength

The extent of the effects of curing temperature on the compressive strength of portland-cement concretes is illustrated quantitatively through several cases.

1. The magnitude of the effect of temperature on the strength development depends not only on the magnitude of temperature change but also on the type of cement used. Note also that when calcium chloride is added to the concrete, the adverse effect of high curing temperature on the late strengths is reduced (7).
2. The primary reason for higher early strengths with increasing temperatures is that the rate of chemical reactions between the cement and water--that is, hydration--increases with increasing temperature. This is demonstrated in Figure 2 (1), where the degree of hydration is characterized by the quantity of the chemically bound water in the hydration products of cement. The strength-reducing effect of higher curing temperatures at later ages is also illustrated.

Figure 3. Effect of temperature on strength development during first 2 hr after casting.



3. When concrete is cast and maintained at a given temperature for several hours and then cured at 70°F (22°C), the higher the initial temperature (within limits), the lower the 28-day strength, as illustrated in Figure 3 (8). The relative strengths at 28 days are maintained at later ages.

4. It may be generalized from the previous paragraph that if the curing temperature is higher than the initial temperature of casting, the resulting 28-day strength will be higher than that for a curing temperature equal to or lower than the initial temperature (9).

5. It appears that there is a curing temperature during the early life of the concrete that may be considered optimum with regard to the strength at later ages, or more strictly, at comparable degrees of hydration. This temperature is influenced somewhat by the cement type. For ASTM types I and II portland cements this temperature is 55°F (13°C); for type III it is 40°F (4°C) (7).

6. The 28-day concrete strength can be increased by using a suitable water-reducing admixture. It is also demonstrated that this beneficial effect is more pronounced when the concrete is mixed at 90 to 95°F (32 to 35°C) than at 70 to 75°F (22 to 25°C) (10).

Maturity Concept

Because strength of concrete depends on both age and temperature, it can be said that strength is a function of Σ (time times temperature), and this summation is called maturity. The temperature is reckoned from an origin found experimentally to be between 11 and 14°F (-12 and -10°C).

When maturity is measured in degrees Fahrenheit times hours or times days, strength plotted against the logarithm of maturity gives a straight line. Experiments by Ramakrishnan also support this finding within practical limits (11, pp. 1-8). It is therefore possible to express strength at any maturity as a percentage of strength of concrete at any other maturity; the latter is often taken as 35,000°F x hr (19,800°C x hr, which is the maturity of concrete cured at 64°F (18°C) for 28 days. The ratio of strengths--that is, relative strength (f_{rel})--can then be written as follows:

$$f_{rel} = A + B \operatorname{Log}_{10} (\text{maturity} \times 10^{-3}) \quad (1)$$

The value of the coefficients A and B depends on the strength level of concrete; those suggested by Plowman are given in Table 1. It can be seen that the strength-maturity relation depends on the properties of the cement and on the general quality of the concrete and is valid only within a range of temperatures. The severe limitation of the temperature ranges is apparent, for instance, from Figure 4 (7), obtained by Klieger, who tested ordinary portland-cement concrete with a water/cement ratio of 0.43 and an air content of 4.5 percent and that was cured at 73°F (23°C) from the age of 28 days. The separate relationships for each initial curing temperature indicate poor correlation of strength with maturity. A further complication arises because the effects of a period of exposure to a higher temperature are not the same when this occurs immediately after casting or later in the life of the concrete. Specifically, early high temperature leads to a lower strength for a given total maturity than when heating is delayed for at least a week or is absent.

Malhotra points out in this connection that the maturity rule is applicable only if

1. 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;
2. The initial temperature of the concrete is between 60 and 80°F (15.5 and 26.6°C); and
3. No loss of moisture by drying occurs during the curing period, which is a difficult condition to fulfill in the field (12).

Flexural Strength of Concrete

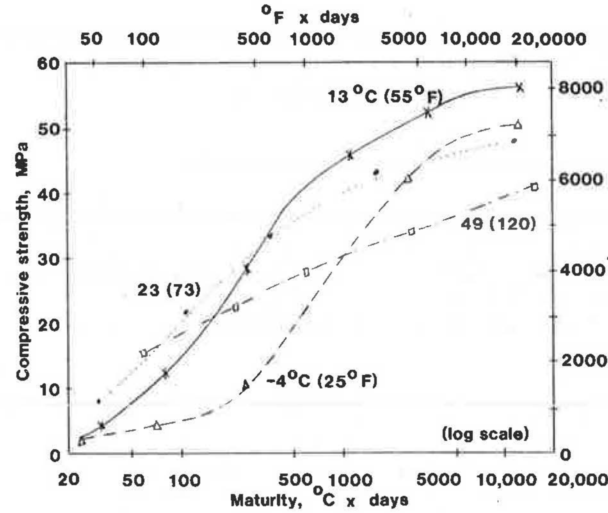
The preceding discussion of compressive-strength

Table 1. Plowman's coefficients for maturity equation.

Strength After 28 Days at 64°F[a] (psi)	Coefficient A	Coefficient B
2,500	-7	68
2,500-5,000	6	61
5,000-7,500	18	54
7,500-10,000	30	46.5

Note: t°F = (t°C ÷ 0.55) + 32; 1 psi = 145 MPa.
[a]Maturity of 35,600°F x hr.

Figure 4. Influence of temperature on strength versus maturity relationship of type I cement during first 28 days after casting.



data applies equally to the flexural-strength data. Flexural strengths at early ages increased with increase in temperature. At later ages, the effect of temperature was reversed. These concretes made and cured at the lower temperatures showed highest flexural strengths at 1 yr. The optimum temperatures for flexural-strength development appear to be the same as those for compressive strength (7).

The use of calcium chloride frequently resulted in flexural strengths at later ages somewhat lower than for comparable concretes at the same temperature but without calcium chloride.

EFFECTS OF CURING

Effects of Wetness

The strength of a hardening cement paste is the consequence of the hydration process. Therefore, the strength development stops when the paste in the concrete dries out, that is, when the amount of free water in the paste decreases below a level critical for the hydration. Because this has a great significance in concrete construction, especially in a hot climate, it should be discussed here.

The loss of water in concrete is the result of two actions: evaporation and the gradual using up of the mixing water by the hydration of cement, which is called self-desiccation. Thus, a long-enough strength development in mortars and concretes requires two countermeasures: (a) the elimination or at least reduction of the early evaporation of water from the concrete and (b) replacement of the water lost by self-desiccation and evaporation with water from outside. This double countermeasure is called curing; the (b) portion is the wet or moist curing. Self-desiccation has an important role in stopping the strength development when the water/cement ratio is below about 0.50 by weight. Therefore, moist curing is particularly important for such concretes.

It should be stressed that for a satisfactory strength development it is not necessary for all cement to hydrate; indeed, this is only rarely achieved in practice. If, however, the water-filled or empty porosity in the fresh cement paste of the concrete is greater than the volume that can be filled by the hydration products, greater hydration leads to a higher strength and lower permeability.

The rate and extent of drying through evaporation depend on a number of factors, such as the area of the exposed concrete surface relative to its volume, the humidity of the surrounding air [Figure 5 (13)], the temperatures of the air and concrete [Figure 6 (13)], the difference between the temperatures of concrete and air, and the wind velocity [Figure 7 (13)]. [In Figures 5-7 air temperature is 70°F (21°C), wind velocity is 10 mph (4.5 m/sec), and relative humidity is 70 percent.]

Curing Methods

A means of reducing the drying is to use an impermeable membrane or waterproof paper. A membrane, provided it is not punctured or damaged, will effectively prevent evaporation of water from the concrete but will not allow ingress of water to replenish that lost by self-desiccation. The membrane is formed by sealing compounds, which may be clear, white, or black. The opaque compounds have the effect of shading the concrete, and a light color leads to a lower absorption of the heat from the sun and hence to a smaller rise in the temperature of the concrete. ASTM C 156 prescribes tests for the efficiency of curing compounds.

Except when used on concrete with a high water/cement ratio, sealing compounds reduce the degree and rate of hydration compared with efficient wet curing. Wet curing is often applied only intermittently, however, so that in practice sealing may lead to better results.

The other usual way of curing, the wet curing, can be provided by keeping the concrete in contact with a source of water. This may be achieved by spraying or flooding (ponding) or by covering the concrete with wet sand or earth, sawdust, or straw.

Figure 5. Influence of relative humidity on loss of water from concrete in early stages after placement.

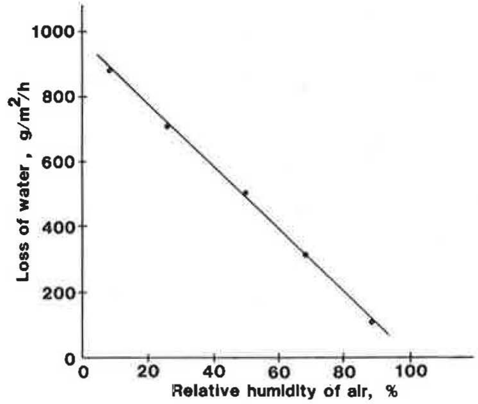


Figure 6. Influence of air and concrete temperature on loss of water from concrete in early stages after placement.

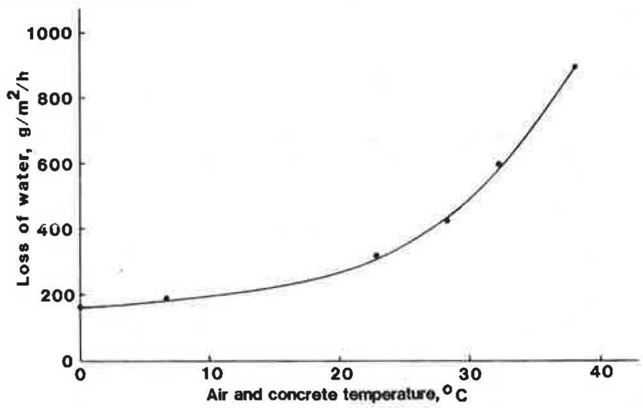


Figure 7. Influence of wind velocity on loss of water from concrete in early stages after placement.

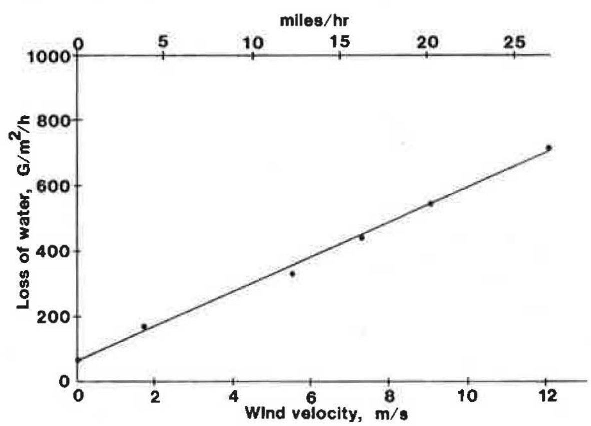
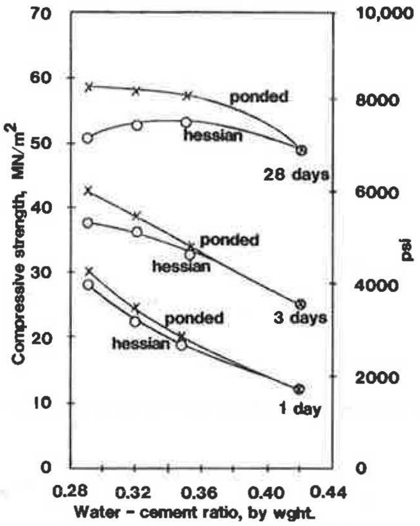


Figure 8. Influence of curing conditions on strength of test cylinders.



Periodically wetted hessian or cotton mats may be used, or alternatively an absorbent covering with access to water may be placed over the concrete. A continuous supply of water is naturally more efficient than an intermittent one, and Figure 8 compares the strength development of concrete cylinders whose top surface was flooded during the first 24 hr with that of cylinders covered with wet hessian. The difference is greatest at low water/cement ratios where self-desiccation operates rapidly. The influence of curing conditions on strength is lower in the case of air-entrained than non-air-entrained concrete (14).

The magnitude of the influence of wet curing on the strength has also been demonstrated. It has been shown clearly that the development of strength stops at early ages if the concrete specimen is exposed to dry air with no previous wet curing. Concrete exposed to dry air from the time of its placement is about 50 percent as strong at 3 months as concrete that has been moist cured continuously. Resumption of moist curing after a period of air drying results in resumption of hydration, although at a slower rate than that in progress when drying was begun. Note also that the measured concrete strength is influenced by the moisture content of the concrete at the time of testing. Specimens exposed to air and tested in the air-dry condition are one-quarter to one-third stronger than corresponding specimens exposed to air for the same period but saturated just before being tested. In general, the more dense and strong the concrete, the greater is this influence.

Large surfaces of concrete, such as road slabs, present a serious curing problem. In order to prevent crazing of the surface on drying out, loss of water must be prevented even before setting. Because the concrete is at that time mechanically weak, it is necessary to suspend a covering above the concrete surface. This protection is required only in dry weather but may also be useful in preventing rain from marring the surface of fresh concrete.

The period of curing cannot be prescribed simply, but it is usual to specify a minimum of 7 days for type I portland-cement concrete. With slower-hardening cements a longer curing period is desirable. The temperature also affects the length of the required period of curing, and the British Code of Practice for the Structural Use of Concrete (CP 110, 1972) lays down the normal curing periods for different cements and exposure conditions in terms of maturity of concrete (13).

High-strength concrete should be cured at an early age because partial hydration may make porosity discontinuous; on renewal of curing, water would not be able to enter the interior of the concrete and no further hydration would result. Nevertheless, mixes with a high water/cement ratio always retain a large volume of capillaries so that curing can be effectively resumed at any time.

SHRINKAGE AND CREEP

It is worthwhile to mention shrinkage and creep of the hardened concrete here because both of these deformation mechanisms are based on drying and other moisture movements and also because they play an important role in the cracking of concrete.

Cracks in concrete structures can indicate major structural problems and can mar the appearance of monolithic construction. They can expose reinforcing steel to oxygen and moisture and make the steel more susceptible to corrosion.

When concrete dries, it contracts or shrinks, and when it is wetted again, it expands. These volume changes, with changes in moisture content, are inherent characteristics of hydraulic cement concretes. It is the change in moisture content of the cement paste that causes the shrinkage or swelling of concrete, whereas the aggregates provide an internal restraint that significantly reduces the magnitude of these volume changes.

Why does concrete crack due to shrinkage? If the shrinkage of concrete caused by drying could take place without any restraint, the concrete would not crack. In a structure, however, the concrete is always subject to some degree of restraint by either the foundation or another part of the structure or by the reinforcing steel embedded in the concrete. This combination of shrinkage and restraint develops tensile stress. When this tensile stress reaches the tensile strength, the concrete will crack.

Another type of restraint is developed by the difference in the shrinkage at the surface and that in the interior of a concrete member, especially at early ages. Because the drying shrinkage is always larger at the exposed surface, the interior portion of the member restrains the shrinkage of the surface concrete, thus developing tensile stresses. This may cause surface cracking, in which cracks do not penetrate deep into the concrete. These surface cracks may with time penetrate deeper into the concrete member as the interior portion of the concrete is subject to additional drying.

The influence of temperature on creep has become of increased interest in connection with the use of concrete in the construction of prestressed concrete nuclear pressure vessels, but the problem is of significance also in other types of structures, e.g., bridges. The rate of creep increases with temperature up to about 160°F (70°C) when, at least for a 1:7 mixture with a water/cement ratio of 0.60, it is approximately 3.5 times higher than at 70°F (21°C). Between 160°F and 205°F (96°C) the rate drops off to 1.7 times the rate at 70°F. These differences in rate persist at least for 15 months under load. Figure 9 (13) illustrates the progress of creep (ratio of stress to strength is 0.70). This behavior is believed to be due to desorption of water from the surface of the gel so that gradually the gel itself becomes the sole phase subject to molecular diffusion shear flow; consequently the rate of creep decreases. The behavior over a wide range of temperatures is shown in Figure 10 (15).

Figure 9. Relationship between creep and time under load for concretes stored at different temperatures.

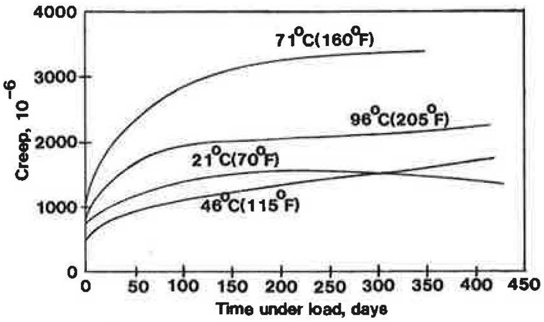
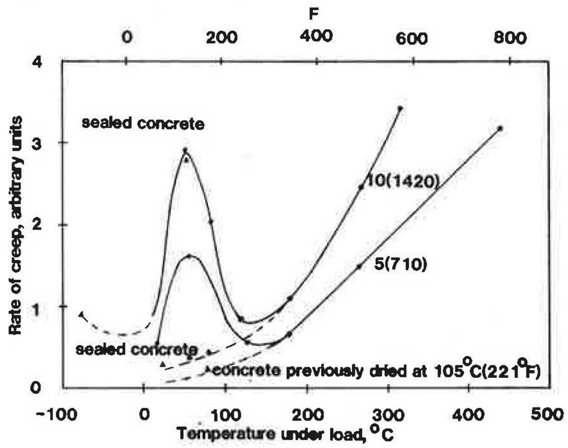


Figure 10. Influence of temperature on rate of creep.



RECOMMENDATIONS FOR FURTHER RESEARCH

The development of a numerical method is desirable that provides the strength development of portland cement in terms of compound composition, fineness, age, and curing temperature. Although certain efforts have been made in this direction (4), much more work is needed for a general, reliable theory and formulas for the prediction of concrete strength cured at elevated temperatures.

A recent committee report by the Réunion Internationale des Laboratoires d'Essais et de Recherches sur les Matériaux et les Constructions (RILEM) recommended the following topics for further investigation concerning hardened concrete (16):

1. Studies of the influence of hot and dry and hot and humid environments on strength, shrinkage, and creep of portland-cement concretes in relation to the composition of the cement;
2. Long-term study of shrinkage and creep of concrete exposed to elevated temperature combined with different amounts of relative humidity, intermittently or permanently;
3. Study of durability of building materials in a hot and humid environment;
4. Long-term field observations of corrosion of reinforcement in structures exposed to elevated temperatures and different amounts of relative humidity;
5. Systematic field measurements of thermal stresses in structures in a hot environment (supported by appropriate analysis and tests);
6. Study of thermal stresses in concrete structures in relation to cracking and deformation; and
7. Field observations of structures with a view to systematic information relating climatic conditions (hot and dry and hot and humid) to satisfactory performance.

CONCLUSIONS

Undesirable hot-weather effects on concrete in the hardened state may include

1. Decreased strength resulting from higher water demand and increased temperature level,
2. Increased tendency for drying shrinkage and differential thermal cracking,
3. Decreased durability,
4. Decreased uniformity of surface appearance, and
5. Increased creep.

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Effects of High Temperatures on the Properties of Fresh and Hardened Concrete: A Bibliography (1915-1983)

M. SAMARAI, S. POPOVICS, AND V.M. MALHOTRA

This bibliography covers the international literature up to the early part of 1983 on the effects of high temperature [up to 140°F (60°C)] on the properties of fresh and hardened concrete. The following topics are covered: the workability of concrete, including setting, slump loss, and admixtures; curing and the cracking tendency of fresh concrete in hot climates; strength development of concrete, including early strengths, later-age strengths, and maturity of concrete; other properties of hardened concrete, such as shrinkage and creep; and construction practices in hot climates, including selection of materials, especially admixtures; protective measures; construction methods; and pertinent specifications. Steam and autoclave curing and other accelerating treatments of concrete are not covered.

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