

is, the lower is the initial slump and the higher is the rate of loss of slump.

6. The compressive strength and the dry unit weight are higher for cylinders that were cast long after the mixing compared with the cylinders that were cast immediately after mixing. The gain in compressive strengths and dry unit weights can be attributed to the loss in air content with time.

ACKNOWLEDGMENT

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Notice: The opinions expressed in this paper are those of the authors and not necessarily those of the U.S. Department of Transportation.

Effects of High Temperatures on the Properties of Fresh Concrete

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

The effects of high temperature on the properties of fresh concrete and the mechanism of the setting of cement paste and concrete are described. The undesirable effects of high temperature on fresh concrete mentioned include increased water demand, increased rate of slump loss, increased rate of setting, and increased tendency for plastic shrinkage cracking. This is followed by a discussion of the methods to minimize the above effects; the roles of water-reducing and set-retarding admixtures, superplasticizers, and retempering of concrete are described.

The effects of high temperatures (that is, a hot climate) on the properties of fresh concrete are usually undesirable from the standpoint of construction. Frequently occurring phenomena such as accelerated slump loss or increased possibility of excessive moisture loss and the resulting shrinkage cause extra problems for the construction engineer. Such problems can be eliminated only by careful and sometimes expensive preventive measures.

The current status of the knowledge is still incomplete concerning the effects of high temperatures on the behavior of fresh cement paste or concrete. Some aspects have been published, such as those related to setting or effects of admixtures (1,2). Nevertheless, the seriousness of the problems of construction in tropical climates makes it worthwhile to provide additional details in a systematic fashion. In addition, the emphasis in this paper is on new aspects of the temperature effects.

EFFECTS OF TEMPERATURE ON HYDRATION OF CEMENT

Definitions

When portland cement is mixed with a limited amount

of water, the cement particles become dispersed in the water. The result is cement paste, which is a material of considerable plasticity.

The setting and hardening processes are the results of a series of simultaneous and consecutive reactions between water and the constituents of portland cement. These reactions are described as the hydration of portland cement. The hydration of cement compounds is exothermic. The heat developed is called the heat of hydration.

Reactions in Early Hydration and Setting

The measurement of heat evolution is particularly suitable for the investigation of the early stages of hydration (3). During a short period beginning when portland cement and water are first brought into contact at room temperature and during the time of mixing, relatively rapid chemical reactions occur, primarily between the water and the tricalcium aluminate (C_3A) of the cement.

When portland cement is insufficiently retarded, the time of initial setting is considerably less than 1 hr at normal temperature.

Another factor that can cause rapid setting is elevated temperature. The higher the curing temperature is, the faster are the reactions between cement and water, and consequently the shorter becomes the setting time. The effects of curing temperature on the intensity (rate) of hydration can be seen in Figures 1 through 4 (4,5, pp. 1-32; 6, pp. 259-273). It can also be seen from Figure 1 that a change appears in the hydration process at a temper-

Figure 1. Hydration of tricalcium silicate: effect of temperature.

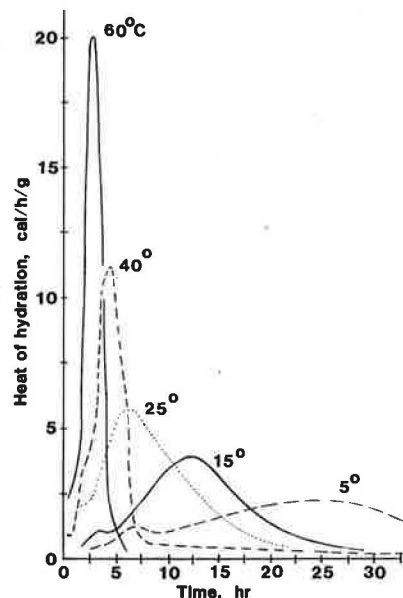
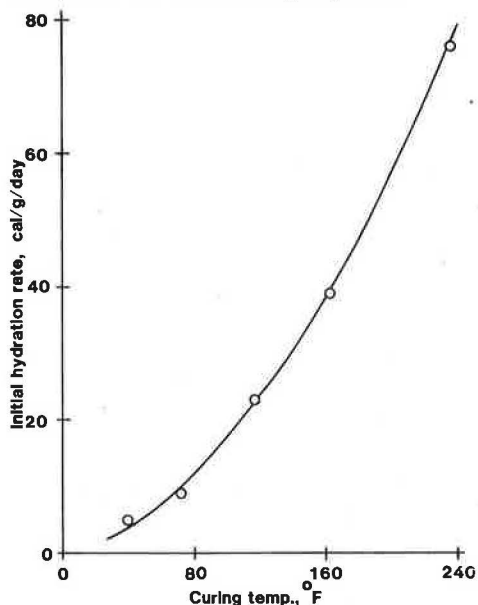


Figure 2. Initial rate of cement hydration as measured by the rate of heat development as a function of curing temperature.



ature of about 95°F (35°C), which is manifested in a decrease in the apparent activation energy from 8.45 to 5.70 kcal/mole (4).

Methods for counterbalancing the acceleration of setting are discussed in the following sections.

SETTING OF CEMENT PASTE AND CONCRETE

Definitions

When cement is mixed with approximately 20 to 35 percent of water, the result is a paste. This mixture displays considerable plasticity that is maintained for a period of time called the dormant period. After a while, however, the paste starts to stiffen, less and less plasticity can be observed,

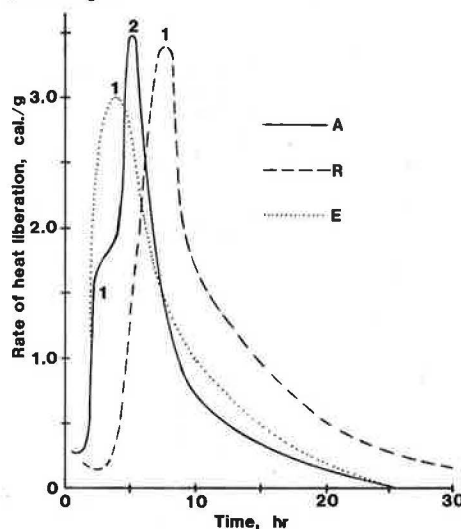
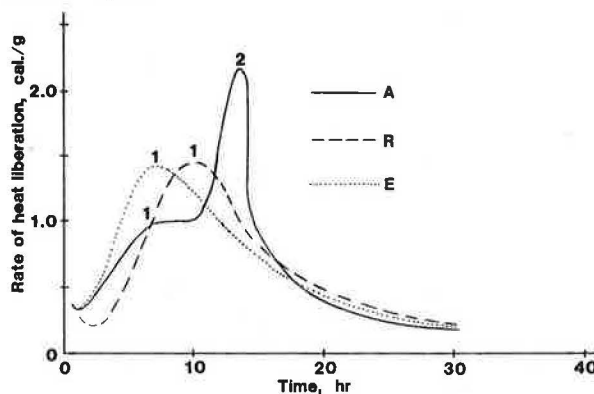
Figure 3. Rate of heat of hydration of three portland cements of different C_3A contents at 104°F (40°C): 1, reactions of silicate phase; 2, reactions of aluminate phase (A, 12.5 percent C_3A ; R, 7.6 percent C_3A ; E, 3.7 percent C_3A).

Figure 4. Rate of heat of hydration at 77°F (25°C) of three portland cements shown in Figure 3.



and finally all the plasticity is gone and the paste becomes brittle, although still without any great strength. This stiffening process is called setting and is the result of a series of reactions between the cement and the water, which was discussed earlier. One should recognize that the stiffening is not a drying process; it takes place even if the fresh cement paste is kept under water. The gain of strength—that is, the hardening process—takes place subsequent to the setting.

It is customary to refer to initial setting, which is basically the beginning of the stiffening, and final setting, which is marked by the disappearance of plasticity. The setting process should not start too early because the freshly mixed concrete should remain in a plastic condition for a sufficient period to permit satisfactory compaction and finishing after transportation and placement. On the other hand, too long a setting process is also undesirable because this would cause a useless delay in the strength development after the finishing. Of the two concepts the initial setting has far greater significance.

There is no strict dividing line between setting and hardening. Any distinction is more or less arbitrary and poorly defined. So are the terms ini-

tial setting and final setting. Nevertheless, for practical purposes, it is convenient to have test methods for the approximate determination of the time when the stiffening starts and when the plasticity is gone.

The time of set of a paste or concrete is usually determined by measuring repeatedly the changes in its resistance to penetration by specified small rods or needles, although slump, heat development, pulse velocity, shearing test, and electrical resistivity measurements are also applicable for this purpose (1,2). There are two standard penetration methods for portland-cement pastes in the United States. One applies the Vicat apparatus (ASTM C 191-74), the other the Gillmore needles (ASTM C 266-74). The Vicat apparatus is primarily for laboratory use, whereas the Gillmore needles are for field tests. For blended portland cement only the Vicat method is specified.

ASTM C 403-70 provides a procedure for determining the time of setting of concrete with slump greater than zero by measuring the penetration resistance of the mortar that is sieved from the concrete mixture by specified rods. The penetration resistance is calculated as the force required to cause a 1-in. (2.54-cm) depth of penetration of the needle divided by the area of the bearing face of the needle. Time of initial setting is defined as the time elapsed after initial contact of cement and water that is required for the mortar to reach a penetration resistance of 500 psi (3.45 MPa). Time of final setting is the elapsed time required for the mortar to reach a penetration resistance of 4,000 psi (27.6 MPa).

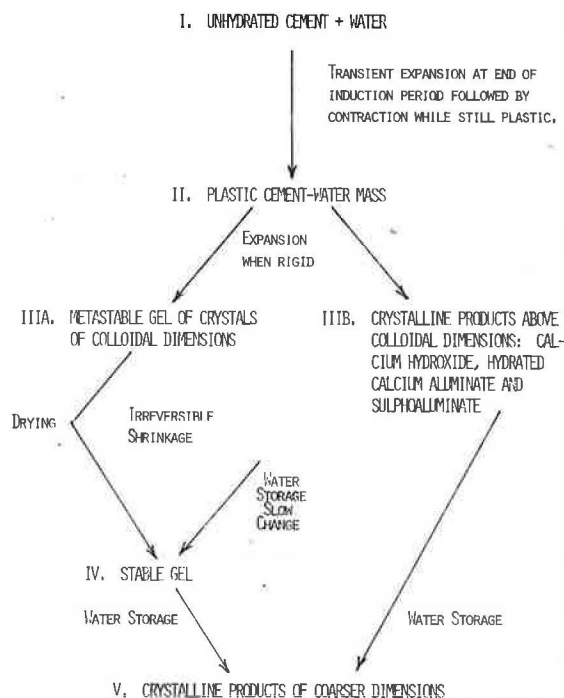
Mechanism of Setting

Lea summarizes the setting mechanism as follows (7). The cement grains are acted on by water to form a supersaturated solution from which the gel-like mass of crystals precipitates. Diffusion of water molecules to the surface, or even into the crystal lattice, to react in situ must also play a part, at least in the later stages of hydration. While still in a plastic condition, the cement paste shrinks slightly because there is a contraction in volume of the system of cement plus water on hydration. Once the mass becomes rigid, a small expansion sets in because the gel mass deposits around the cement grains and causes them to swell and to exert an outward pressure. The quality of the gel mass increases progressively with time, and it spreads into the intergranular spaces.

The cement gel must be regarded as being formed initially in an unstable condition; the fiber crystals of the gel particles, or the gel particles themselves, are farther apart and occupy a greater volume and enclose more water than in their stable state. The gel thus has an inherent tendency to shrink and give off some of the water it contains. In water no measurable contraction occurs, but in any case it would be offset by the effects of continued hydration of previously unattacked cement. During drying, the set cement undergoes an irreversible contraction and reduction in water content as the gel changes into its more stable form. The expansion during subsequent wetting and the amount of water taken up then become reversible and are reproduced in successive cycles of wetting and drying. During prolonged aging under wet conditions, a further slow change may occur by crystal growth. There is, however, a reduction in the surface area with aging, indicating that irreversible changes toward a more stable state are occurring.

The setting, hardening, and aging processes are shown in Figure 5 (7).

Figure 5. Diagram of setting process of portland-cement paste.



The changes from I to IIIA and IIIB (Figure 5) are part of the setting process. The change from stage IIIA to IV occurs when the set cement is allowed to dry in air, but when stored under water, the cement persists longer in stage III although a slow change during aging in water from stage IIIA to IV occurs. The final change from stage IV to V appears to be exceedingly slow and does not appear to occur in mortars or concretes under normal conditions.

Setting of Cement Paste

The most conspicuous change that takes place in the cement-and-water mixture is the gradual stiffening. The stiffening of a cement paste can be demonstrated quantitatively by the decreasing penetration depths of the needle of the standard Vicat apparatus as a function of elapsed time. Typical results obtained with a type III cement are shown in Figure 6 (8).

Setting of Concrete

Results of three series of the standard penetration test (ASTM C 403) obtained on concrete are plotted in the log-log system in Figure 7 (data from Master Builders Laboratory) (8). It can be seen that the three different kinds of concrete provided a common slope with a good approximation within resistance limits of 300 psi (2.07 MPa) and 4,000 psi. The 4,000-psi resistance corresponds to an approximately 100-psi compressive strength (8).

Further analysis of published data (9, pp. 97-117) reveals that the cement brand, curing temperature, water/cement ratio, and certain admixtures do not significantly influence either the straight-line approximation or the slope, whereas other admixtures, particularly certain retarders and water-reducing admixtures, may increase the slope (10, pp. 195-221). When this happens, it indicates that the early stiffening (initial set) is retarded relatively more than the concluding part of the setting (final set); thus the stiffening starts later but

Figure 6. Typical curves of Vicat penetration for cement pastes setting at room temperature.

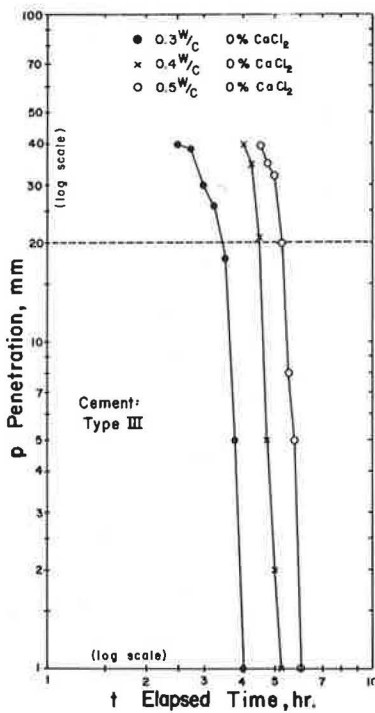
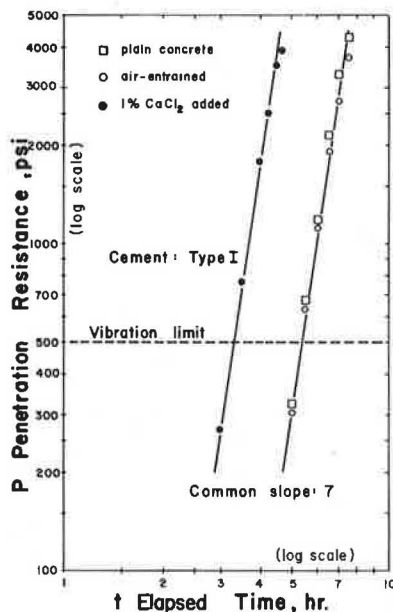


Figure 7. Typical curves of standard penetration for mortars sieved from concretes and setting at room temperature.



the rate of stiffening is higher and the process is more intensive.

Consecutive repetitions of a consistency test on a concrete sample can also be used for the characterization of the stiffening process. An example is shown in Figure 8 (8) in which several typical results of the standard slump test (ASTM C 143) are plotted against the elapsed time [curing temperature, 90 to 95°F (32.2 to 35°C); cement content, 520 lb/yd³ (310 kg/m³)]. In these tests the concrete was not remixed after each slump test. As

Figure 8. Slump loss of concrete with and without a given water-reducing admixture as a function of elapsed time.

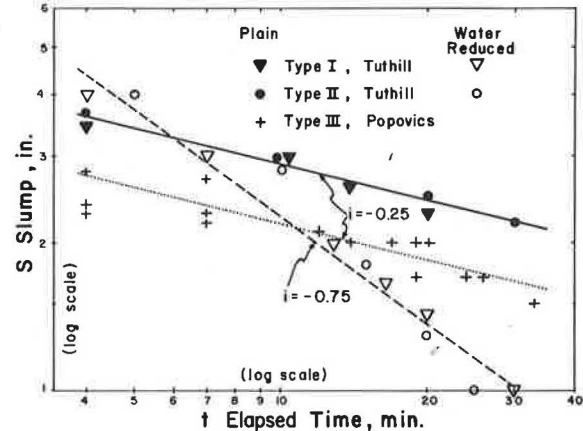
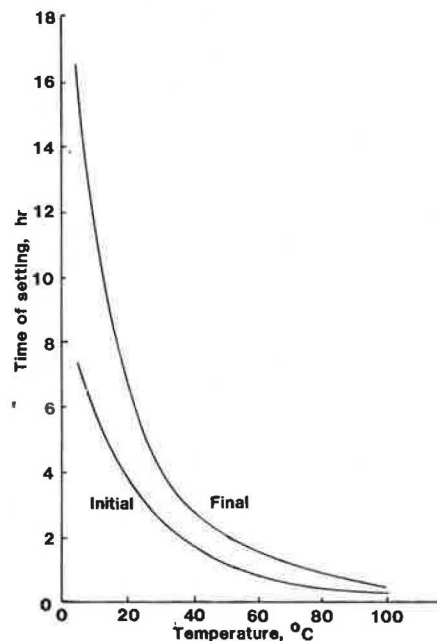


Figure 9. Effect of temperature on initial and final sets of portland-cement mortar (mix proportion, 1:3 by weight).



shown in Figure 8, standard slump results in general form straight lines in the log slump versus log (elapsed-time) system. The degree of approximation shown is fairly good, considering the usual fluctuation of the slump results.

Effect of Temperature on Setting

The standard initial set of commercial portland cements ranges from approximately 2 to 4 hr and the final set from 5 to 8 hr. In concrete mixtures the set usually occurs later because of the higher water/cement ratios in concretes. Under special conditions, however, such as construction at high temperature, a concrete may set early. This accelerating effect of elevated temperatures is demonstrated in Figure 9 (4) not only qualitatively but also quantitatively. In this figure it is shown that an increase in temperature from 59 to 86°F (15 to 30°C) reduces the time of initial set by approximately half. Further details concerning the effects

Table 1. Effects of admixtures on setting at various temperatures: type I cement DI.

Mix	Admixture	Sugars in Admixture	Dosage of Admixture per Sack (lb)	Reduction in Water ^a (%)	Time (hr) to Penetration Resistance of		Compressive Strength (psi)	Air Content		
					500 psi	4,000 psi		Air (%)	Air-Entraining Agent (ml/yd ³)	Air-Detraining Agent (ml/yd ³)
Initial Concrete Temperature 50° to 55°F										
R50										
1	None	—	—	—	7.2	12.6	64 at 16 hr	4.0	58	0
2	SO	High	1/4	8.3	10.1	13.8	29 at 16 hr	4.6	0	0
3	DP	Low	1/4	8.3	9.2	13.0	57 at 16 hr	4.8	0	0
4	OP	Low	1/4 _b	9.5	8.5	12.7	57 at 16 hr	4.9	0	0
5	RW	Low	—	4.1	7.2	9.8	115 at 16 hr	3.9	0	0
9	None	—	—	—	8.2	12.5	32 at 12 hr	3.4	37	0
10	QA	High	1/8	4.7	8.5	12.6	20 at 12 hr	3.4	0	0
11	QA	High	1/4	7.1	10.2	15.3	15 at 12 hr	3.8	0	2.0
12	QA	High	3/8	7.9	13.2	20.4	6 at 12 hr	3.5	0	3.0
Initial Concrete Temperature 70° to 75°F										
R										
1	None	—	—	—	4.3	6.9	530 at 16 hr	3.6	80	0
5	SO	High	1/4	6.7	6.4	8.8	527 at 16 hr	3.8	0	0
4	DP	Low	1/4	9.0	5.8	8.0	584 at 16 hr	4.6	0	0
2	OP	Low	1/4 _b	8.6	5.8	7.9	623 at 16 hr	3.6	0	0
3	RW	Low	—	3.5	4.4	6.2	760 at 16 hr	3.6	26	0
13	None	—	—	—	5.3	7.8	172 at 16 hr	3.5	55	0
14	QA	High	1/8	3.5	5.4	7.7	200 at 16 hr	3.5	10	0
15	QA	High	1/4	7.8	6.3	8.8	192 at 16 hr	3.4	0	1.0
16	QA	High	3/8	7.4	7.7	10.5	135 at 16 hr	3.5	0	2.0
Initial Concrete Temperature 90° to 95°F										
R90										
1	None	—	—	—	3.3	4.8	541 at 10 hr	3.4	88	0
2	SO	High	1/4	9.5	5.3	7.0	480 at 10 hr	4.0	21	0
3	DP	Low	1/4	8.3	5.0	6.7	566 at 10 hr	4.7	0	0
4	OP	Low	1/4 _b	7.1	4.9	6.6	462 at 10 hr	3.7	16	0
5	RW	Low	—	3.6	3.7	5.0	595 at 10 hr	3.4	29	0
12	None	—	—	—	4.4	6.0	441 at 12 hr	3.0	60	0
13	QA	High	1/4	5.3	5.7	7.4	520 at 12 hr	3.5	0	0
14	QA	High	3/8	7.9	7.9	9.5	376 at 12 hr	3.3	0	1.0
15	QA	High	1/2	7.6	8.8	10.8	262 at 12 hr	3.8	0	2.0

Notes: 1 lb = 0.45 kg, 1 psi = 145 MPa, $t^{\circ}\text{F} = (t^{\circ}\text{C} \div 0.55) + 32$. DI is the identifying mark of the cement; SO, DP, and so on, are the identifying marks of the admixtures used.

^aThe plain concrete used as a basis of comparison is in all cases air-entrained concrete. The water reduction was computed after adjusting all mixes to the same slump and air content.

^bDosage was 6 fluid oz.

of temperature on setting may be found in the literature (1,2).

Cement stored in sealed containers at ordinary temperatures is usually little changed after long periods, but at high temperatures some effect is produced, because although the cement appears normal, it may rapidly develop a flash set if subsequently exposed to air. Trouble with rapid setting is occasionally experienced with cements shipped from temperate to tropical climates. Development of a flash set also occurs occasionally in cement stored in bulk (7).

Special cements may require different criteria for the evaluation of the setting process. For instance, setting of oil-well cements is usually measured in terms of change in viscosity at elevated temperature.

Effects of Retarders and Plasticizers

One way to counteract the rapid setting caused by elevated temperature is to use a set-retarding admixture, or retarder, in concrete. The effects of such an admixture depend on a number of factors, including the temperature. These factors may interfere with one another, changing the effectiveness of the admixture. For instance, use of retarders and water-reducing admixtures, including superplasticizers, may make the slope of the consistency line steeper, the degree of which depends on the type and quantity of the admixture employed as well as on the

SO₃, C₃A, alkali, and free lime contents of the cement. This reflects the usual experience that certain admixtures increase the time of initial setting or reduce the amount of water needed for a given initial slump or both, but such concretes may stiffen faster, sometimes too fast even for a cement and an admixture that separately meet all specifications. This happens whenever the composition of the cement and that of the admixture are incompatible either because the readily soluble SO₃ content in the cement is lower or because it is high relative to the C₃A content.

Despite the availability of remedial actions, it is better to check the compatibility of the job cement and the job admixture before the construction starts. A simplified test method is ASTM C 359 for the determination of false set in Ottawa-sand mortar. A more complete test can be made from trial concrete mixes with the job materials in the proper amounts as described in ASTM C 494.

The effects of admixtures on delaying the time of setting are shown by the data in Table 1 (9) and in Figures 10 and 11 (9) (cement type I). The cement content for Figure 11 was 470 lb/yd³ (280 kg/m³).

Expanding or shrinkage-compensating cements may also provide excessive slump loss when combined with certain water-reducing admixtures. In one series of experiments the use of type D lignins of ASTM C 494 proved to be the most effective with type K cement (11). Further details concerning the effects of admixtures on setting may be found in the literature (1,2).

Figure 10. Concretes of similar vibration limit made at various temperatures by varying dosages of set-retarding admixture.

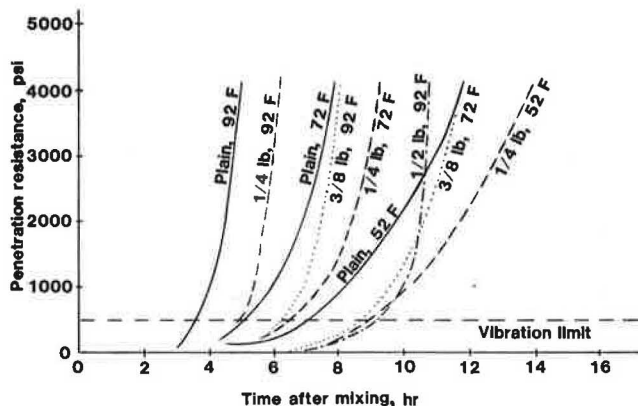
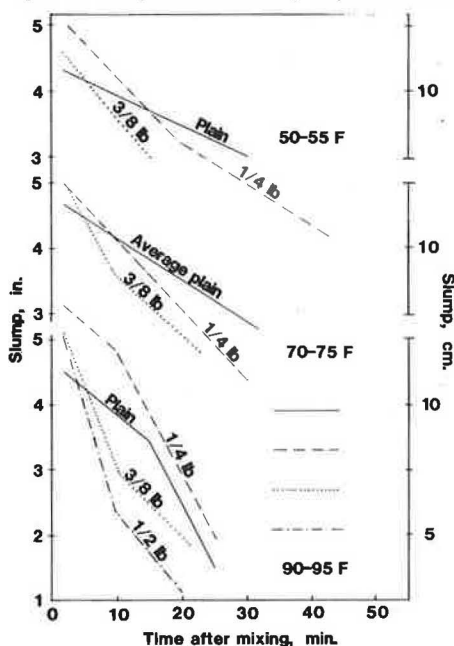


Figure 11. Slump loss as affected by temperature and dosage of retarder.



MECHANISM OF CHEMICAL RETARDATION OF SETTING TIME

Gypsum for Retardation of Setting

Powders of cement clinkers, especially those with a high $\text{Fe}_2\text{O}_3:\text{Al}_2\text{O}_3$ ratio, show a rapid but not a flash set, yet the final set may be unduly slow. This undesirable situation can be eliminated by the addition of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). Gypsum retards the initial set properly and speeds up the final set.

Any system that contains sufficient retarder to be on the plateau for time of set is properly retarded. Such a system is properly retarded as far as control of flash set is concerned, but there are other factors that must be considered. Many physical properties of hardened paste are affected by the quantity of gypsum that is present in the cement. Four of the most important of these are (a) compressive strength, (b) contraction on drying, (c) delayed expansion, and (d) heat liberation.

Lerch used this last property for the definition of properly retarded cement (12). In his opinion, a

properly retarded cement can be considered one that contains the minimum quantity of gypsum required to give a curve that shows two cycles of ascending and descending rates of heat liberation and shows no appreciable change with larger additions of gypsum during the first 30 hr of hydration. The quantity of gypsum determined in this way is essentially the same as the quantity of gypsum required for maximum strength and minimum shrinkage, and it avoids abnormal expansion. Thus it can be called optimum.

Unfortunately, it is not clear whether the optimum defined in this way is also optimum from the standpoint of adequate retardation at higher curing temperatures. It has been observed, however, that an excess of gypsum above the traditional optimum amount may produce unfavorable results such as lower strength and delayed expansion (13) on the cement properties when the cement is cured at standard temperature.

The influence of various clinker properties on the optimum gypsum content can readily be seen by examining the rate of heat-liberation curves. The specific surface of the cement and the alkali content of the clinker, as well as the C_3A content of the clinker, affect the amount of gypsum required for proper retardation. In any case, the basic rule appears to be that the maximum (optimum) amount of gypsum permissible in the cement should be such that no or little unreached gypsum remains in the specimen of paste at 24 hr. This rule may help develop an optimum gypsum content specifically for cement to be used for concreting in hot countries.

Action of Set-Retarding Admixtures

Because in many cases the quantity of gypsum in the cement is not enough to assure an adequately long setting time when the concreting takes place at high temperatures, other protective measures are needed. The most commonly used measure is a suitable admixture.

It is important to recognize that admixtures are no substitute for sound concrete-making practices. The proper utilization of admixtures requires increased care, for instance, in batching. The other aspects of the concrete-making procedure should also be kept as constant as possible.

Certain organic compounds or mixtures of organic and inorganic compounds can be used as admixtures to reduce the water requirement of a concrete (ASTM C 494, type A) or to retard the setting (type B) or both (type D).

The new generation of water-reducing admixtures is called superplasticizers because of their improved effectiveness (14-16). These are usually low-molecular-weight polymers; the typical molecular structure is similar to that of lignosulfonates (17). Superplasticizers per se do not markedly affect the setting or the hardening of the cement paste (18).

Set-retarding admixtures are used primarily to offset the accelerating effects of high temperature and to keep concrete workable during the entire placement period. This method is of particular value to maintain the workability of the concrete during a long hauling distance in hot weather and to prevent cracking resulting from form deflection of concrete beams, bridge decks, or composite construction work. Set retarders are also used to keep concrete plastic for a sufficiently long period so that succeeding lifts can be placed without development of discontinuities in the structural unit. Retarders meeting ASTM C 494, type B and type D, delay the setting time of concrete as measured by the standard penetration test (ASTM C 403) but do not retard the slump loss with elapsed time. It has been reported

that concrete slump loss was not reduced even when type D admixtures were added to concrete at dosage levels that extended the setting time beyond 24 hr (19).

The amount of retardation obtained is dependent on the specific admixture used, its dosage, the brand and type of cement, temperature, mixing sequence, and other job conditions. For instance, set retarders appear more effective with cements that have lower alkali and C_3A contents. The quantity of admixture added must be accurately determined and measured because a heavy overdosage can seriously damage the setting and hardening of concrete, particularly when an excess of air is entrained in the concrete by the overdosage (1).

There are water-reducing admixtures that also have a set-retarding effect and set-retarding admixtures with a secondary water-reducing effect. For instance, refined white granulated sugar in the quantity of 0.1 percent by weight of the cement not only retards the setting effectively but also provides a more workable mixture and increases the strength at 7 days and later.

The principal role in the mechanism of water reduction and set retardation of the admixtures considered in the classification discussion previously belongs to so-called surface-active agents. These substances are usually composed of long-chain organic molecules that are hydrophobic (no affinity for water) at one end and hydrophilic (strong affinity for water) at the other. Such molecules tend to become concentrated and form a film at the interface between two immiscible phases, such as cement and water, and alter the physiochemical forces acting at this interface. It appears that the group $H-C-OH$ is the active component in the set retardation.

Inadvertent prolonged retardation of cements with high iron contents (types II and V) has been attributed to a water-reducing admixture (lignosulfonate). Publicized instances of retardation apparently are attributable to insufficient sulfate in the cement to retard the deleterious effect of iron on setting and strength. Without the admixture these cements set normally (20). Other incompatibilities of admixtures with some cements have also

Figure 12. Effect of different dosage levels of a retarder on slump loss.

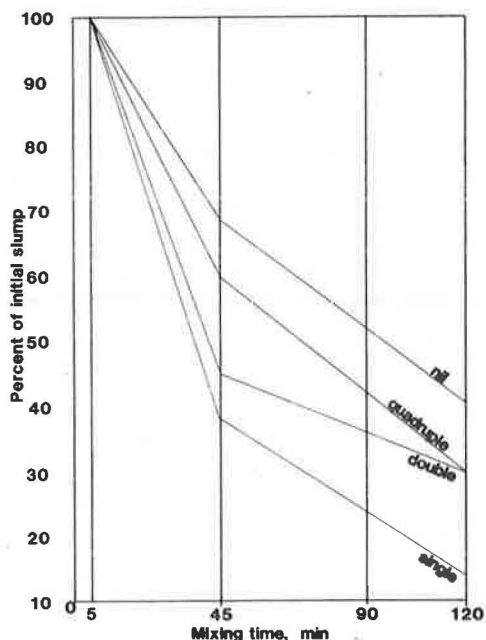
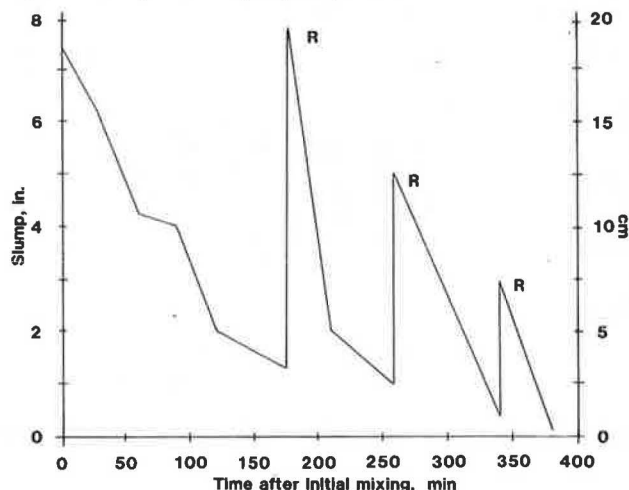


Figure 13. Slump-time retempering study.



been experienced with concrete in laboratory and field.

RETEMPERING

Another method for counterbalancing the stiffening of the cement paste or concrete is to soften its consistency during or after delivery by the addition of a suitable material. Such material can be water, a water-reducing admixture, cement paste, or any combination of these. This procedure is called retempering. It should be noted, however, that the undesirable effect of high temperature starts before retempering because the quantity of mixing water needed for a specified consistency (slump) increases with an increase in temperature (2).

It is not desirable to compensate for expected slump loss by using an initial slump higher than the required final slump when prolonged delays are encountered. Experimental results have shown that the retempering of a concrete will still result in a higher total water/cement ratio when there is initially a higher slump value than when there is a lower slump value (19).

Continuous agitation, such as mixing, does not eliminate the slump loss. Neither does the use of admixtures. Retarders meeting ASTM C 494, type B and type D, delay the setting time of concrete as measured by the standard penetration test (ASTM C 403) but do not retard the slump loss with elapsed time [Figure 12 (21)]. The advantage of the application of water-reducing admixtures is that it allows a reduction in the total water required after retempering.

Retempering with water is not the best practice either, because it increases the original water/cement ratio and reduces the quality of concrete. Nevertheless, it may be tolerable because of its simplicity, provided that the increased water/cement ratio is still below the specified limit.

Better results have been obtained by retempering with superplasticizers. It was reported by Ramakrishnan et al. (22) that the slump of retempered concrete both with and without superplasticizer decreased about equally with time; nevertheless, large increases in slumps can be maintained for several hours by repeated retempering with superplasticizer [Figure 13 (R = repeated retempering)], which does not reduce the concrete strength. Ramakrishnan also drew the following conclusions:

1. The slump loss is proportional to the initial slump level for all the mixes; the higher the initial slump, the higher the slump loss. The total time span during which concrete could be kept workable is, however, longer for concrete with higher initial slump.

2. About 60 to 80 percent of the slump of control and retempered control concrete is lost in 60 to 90 min.

3. The ability of the superplasticizer to keep the concrete workable is reduced as the number of retemperings is increased. Higher dosages of superplasticizer lead to segregation. The rate of slump loss is higher for retempered concretes.

4. Repeated dosages of superplasticizer cause a loss in entrained air.

5. An extended period of mixing does not have an adverse effect on the strength of superplasticized concrete; however, extended mixing time does affect the workability of the mix.

6. The properties of hardened retempered concrete such as compressive strength, dry unit weight, and modulus of elasticity are not adversely affected for the mixes both with and without the addition of the superplasticizer.

Recently Malhotra performed a thorough investigation with a standard type I portland cement concern-

ing retempering concrete with superplasticizer (23). His findings support essentially the large slump increases reported by Ramakrishnan. He also pointed out several additional facts, as follows [Figure 14 (superplasticizer used consists of sulfonated naphthalene formaldehyde condensations)].

1. The plasticizing effect depends on the type of superplasticizer used.

2. The size and character of the change in air content in the concrete caused by retempering with superplasticizer are a function of the type of superplasticizer used.

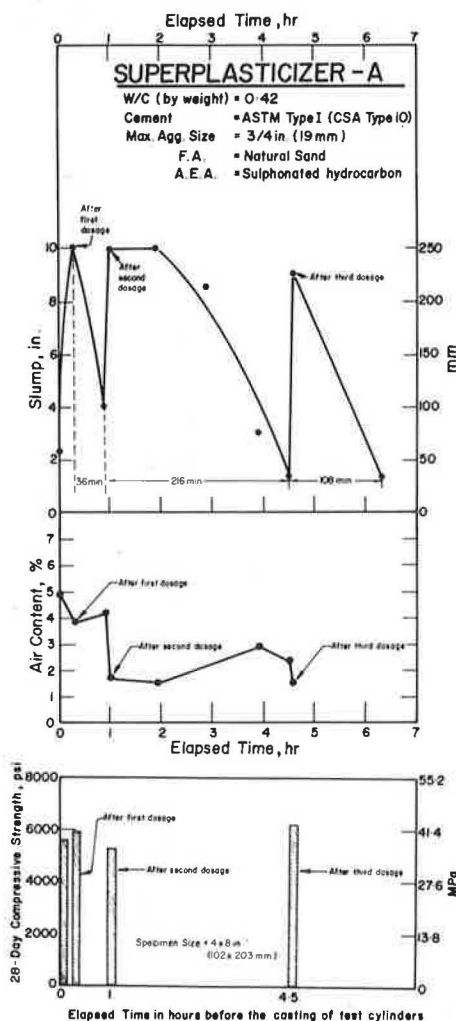
3. The size and character of the change in concrete strength caused by such retempering are also dependent on the type of superplasticizer. These strength changes do not always run parallel to the changes in air content.

4. Repeated retemperings produce a diminishing rate of return. Thus, it is usually not worthwhile to retemper the same concrete mixture more than twice.

Another form of retempering is to add cement paste with the appropriate water/cement ratio to the stiffening concrete to regain the specified slump.

Note that the opposite of excessive slump loss--that is, too slow stiffening--can also be a problem because it may result in low strengths, at least in the early ages, and in a delay in the construction.

Figure 14. Elapsed time from initial mixing versus slump, air content, and compressive strength.



CONCLUSIONS

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

1. Increased water demand;
2. Increased rate of slump loss and corresponding need to add water at the job site;
3. Increased rate of setting resulting in greater difficulty with handling, finishing, and curing and increasing the possibility of cold joints;
4. Increased tendency for plastic cracking; and
5. Increased difficulty in controlling entrained-air content.

Those effects can be mitigated by several methods, including water-reducing admixtures, set-retarding admixtures, or a suitable method of retempering.

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Effects of High Temperatures on the Properties of Hardened Concrete

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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 ce-

ment 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-