Evaluation of Rapid-Setting Concretes

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ABSTRACT

Rapid-setting materials are becoming widely available. Transportation agencies have a strong need for materials that will set rapidly yet provide a durable repair especially in urban areas. There are eight categories of rapid-setting concretes, and these possess a wide range of characteristics and properties. A survey of state transportation departments indicated that there are several preferred properties and characteristics of rapid-setting materials. A test program was conducted to evaluate test procedures for these materials and to determine the properties of a range of rapid-setting concretes. The results of this test program are summarized in this paper.

Rapid-setting repair materials have been in wide demand for the repair of portland cement concrete pavements and bridge decks. High traffic volumes in urban areas require materials that will cure rapidly yet provide adequate strength and durability.

Many types of repair materials are available:

- Portland cement,
- Other chemical-setting cements,
- Thermo-setting materials,
- Thermoplastics,
- Calcium sulfate,
- Bituminous materials,
- Composites, and
- Additives used to alter mix characteristics (1).

Many of the materials are proprietary and the formulations are not made available. Some are suitable only for temporary repairs, and others are designed for permanent repairs. Some can be used only in hot weather, and some can be used only in dry conditions.

A survey was conducted in Texas and nine other states to determine the desired characteristics and properties. Setting time, durability, and ease of mixing, placing, and finishing were considered to be the most important characteristics. Bond strength, flexural strength, and shrinkage were selected as the most important properties (2).

A test program has been conducted to evaluate test methods for rapid-setting materials and to evaluate selected rapid-setting materials. A summary of the results of this program follows.

MATERIALS

1. Magnesium phosphate (MPH). The magnesium phosphate material is packaged as a mortar mix; that is, fine aggregate is included. The material is water-activated and may be extended by the addition of coarse aggregate.

2. Magnesium polyphosphate (MPPH). The magnesium polyphosphate concrete is packaged as a two-component mortar mix. The dry magnesia component is activated by the liquid phosphate component. The mix may be extended by the addition of coarse aggregate.

3. Gypsum-modified portland cement (GPC). This mixture of gypsum (calcium sulfate) and portland cement is packaged neat and water-activated. Sand is added to obtain a mortar. Both sand and coarse aggregate are added to the material to obtain a concrete mix.

4. Modified portland cement (MPC). This modified portland cement is packaged as a mortar mix and is water-activated. The modifiers are proprietary. It may be extended by the addition of coarse aggregate.

5. Accelerated concrete. The accelerated concrete consists of portland cement concrete used in combination with an accelerating admixture. The concrete mix contains Type III cement with a low water-cement ratio (0.45) and a high cement content (7-sack mix). A high-range water reducer is added to improve workability when required. Accelerators used include: calcium chloride ($CaCl_2$), calcium nitrite [$Ca(NO_2)_2$], calcium nitrate [$Ca(NO_3)_2$], and sodium thiocyanate (Na SCN).

EVALUATION TESTS

Compressive Strength

Mortar Cubes

The mortar cube compressive strength test was run according to ASTM C109-80 "Compressive Strength of Hydraulic Cement Mortars" for the accelerated concrete mixes. For the prepackaged rapid-setting materials, the composition of the mortars was according to manufacturers' recommendations. The specimens were cast in 2 x 2 x 2-in. steel molds.

Cylinders

The compression cylinders were made and tested according to ASTM C39-81 "Compression Strength of Cylindrical Concrete Specimens." Specimens were cast in cardboard molds and capped to provide a smooth loading surface. Specimens containing 0.375-in. aggregate were 3 in. x 6 in. whereas specimens containing 0.75-in. aggregate were 6 in. x 12 in.

Modulus of Elasticity

The modulus of elasticity of the rapid-setting materials was determined according to ASTM C469-65 "Static Modulus of Elasticity of Concrete in Compression." A compressometer was attached to 7-day compression cylinders to determine strains.

Flexural Strength

The flexural strength of 2 in. x 2 in. x 12-in. beams was determined according to ASTM C78-75 "Flexural Strength of Concrete." The beams spanned 6 in. and were loaded at one-third points. Mixes containing 0.375-in. coarse aggregate were used.

Set Time

Gilmore Needle

Set times for the rapid-setting materials were determined according to ASTM C266-77 "Time of Setting of Hydraulic Cement by Gilmore Needles." Mortar mixes proportioned according to manufacturers' recommendations were used to form 3-in.-diameter x 0.5-in.-thick pats.

Penetration Resistance

The penetration resistance set time was performed according to ASTM C403-80 "Time of Setting of Concrete Mixtures by Penetration Resistance" for accelerated concretes. Mortar mixes were used for the packaged rapid-setting materials.

Peak Exotherm

Peak exothermic temperature was used to estimate set times of packaged rapid-setting materials. A thermocouple was used to measure the temperature at the center of 3-in. x 6-in. and 6-in. x 12-in. cylindrical specimens.

Bond

Direct Shear Bond

For the direct shear bond test, a 5 x 5 x 0.5-in. layer of rapid-setting mortar was cast onto a 5 x 5 x 1-in. cured portland-cement concrete plate. The bond surface of the PCC plate was troweled smooth and roughened by wirebrushing. Direct shear was then applied to the bond plane until failure.

Flexural Bond

The flexural bond strength of rapid-setting concrete to PCC was determined by casting a 2 x 2 x 6-in. section of rapid-setting concrete against a 2 x 2 x 6-in. cured PCC prism. The resulting 2 x 2 x 12-in. specimen was loaded at one-third points of the 6-in. span until failure.

Sandblast Abrasion

The abrasion resistance test was run according to ASTM C418-76 "Abrasion Resistance of Concrete by Sandblasting." Seven-day mortar specimens of 5 in. x 5 in. x 0.5 in. were used.

Length Change

The length change test was carried out according to ASTM C157-80 "Length Change of Hardened Cement Mortar and Concrete." For rapid-setting concretes, both 1 x 1 x 0.25-in. mortar specimens and 2 x 2 x 0.25-in. concrete specimens were used. For accelerated concretes, 2 x 2 x 11.25-in. concrete specimens were used. For the rapid-setting mortar and concrete specimens, measurement of length change was started immediately after removal of specimens from forms, approximately 1 hour after casting.

Freeze-Thaw Resistance

The freeze-thaw resistance test was run according to ASTM C666-80 "Resistance of Concrete to Rapid Freezing and Thawing." Concrete specimens of 3 x 3 x 16-in. were tested. Specimens were cured 7 days at the start of testing. Specimens were frozen and thawed in water at a rate of 4 cycles per day.

TEST VARIABLES

1. Temperature. For ambient temperatures of 40, 75, and 110°F, flexural strength, cylinder compressive strength, and set times were determined for all materials.
2. Aggregate type, size, and quantity. Concrete mixes with variable (a) type of aggregate (siliceous or limestone), (b) size of aggregate (0.375 in. or 0.75 in.) and (c) quantity of aggregate (coarse aggregate weight to total concrete weight ratios of 0.10, 0.20, and 0.30) were tested for cylinder compressive strength. These tests were performed on packaged rapid-setting materials only.
3. Type of cement. For accelerated concretes, the brand of Type III cement was examined as a variable. Flexural strength, cylinder and mortar cube compressive strength, and set times were determined.

TEST RESULTS

Compressive Strength

The effects of test variables on rapid-setting materials and accelerated concretes were determined from the relationship between compressive strength and time. Compressive strength versus time curves for accelerated concretes at ambient temperatures of 40, 75, and 110°F are shown in Figure 1. All accelerators tested are plotted for 75°F. The most rapid strength gain occurred in mixes containing calcium chloride and calcium nitrite.

Compressive strength versus time curves for the rapid-setting materials at 40, 75, and 110°F are shown in Figures 2-4. At all temperatures, the magnesium phosphate and magnesium polyphosphate exhibited the most rapid strength gain at early times.

In Figure 5, compressive strength versus time relationships for rapid-setting concrete mixes with varied quantities of coarse aggregate are shown. Mixes with ratios of coarse aggregate weight to total concrete of 0.10, 0.20, and 0.30 were evaluated. For all materials, the compressive strength was increased by reducing the percentage of coarse aggregate. The increase in strength was most dramatic in the magnesium phosphate material.

The effect of size and type of aggregate on compressive strength of rapid-setting materials is shown in Figure 6. In general, the mixes containing 0.375-in. limestone aggregate achieved higher strength.

Modulus of Elasticity

The modulus of elasticity and 7-day cylinder compressive strengths for rapid-setting materials are given in Table 1.

Flexural Strength

The effect of temperature on flexural strength was determined for rapid-setting materials and accelerated concretes. In Figure 7, flexural strength versus time curves for accelerated concretes are shown for temperatures of 40, 75, and 110°F. All accelerators tested are shown for 75°F. Mixes containing calcium chloride and calcium nitrite exhibited the most rapid strength gain. Only curves for mixes

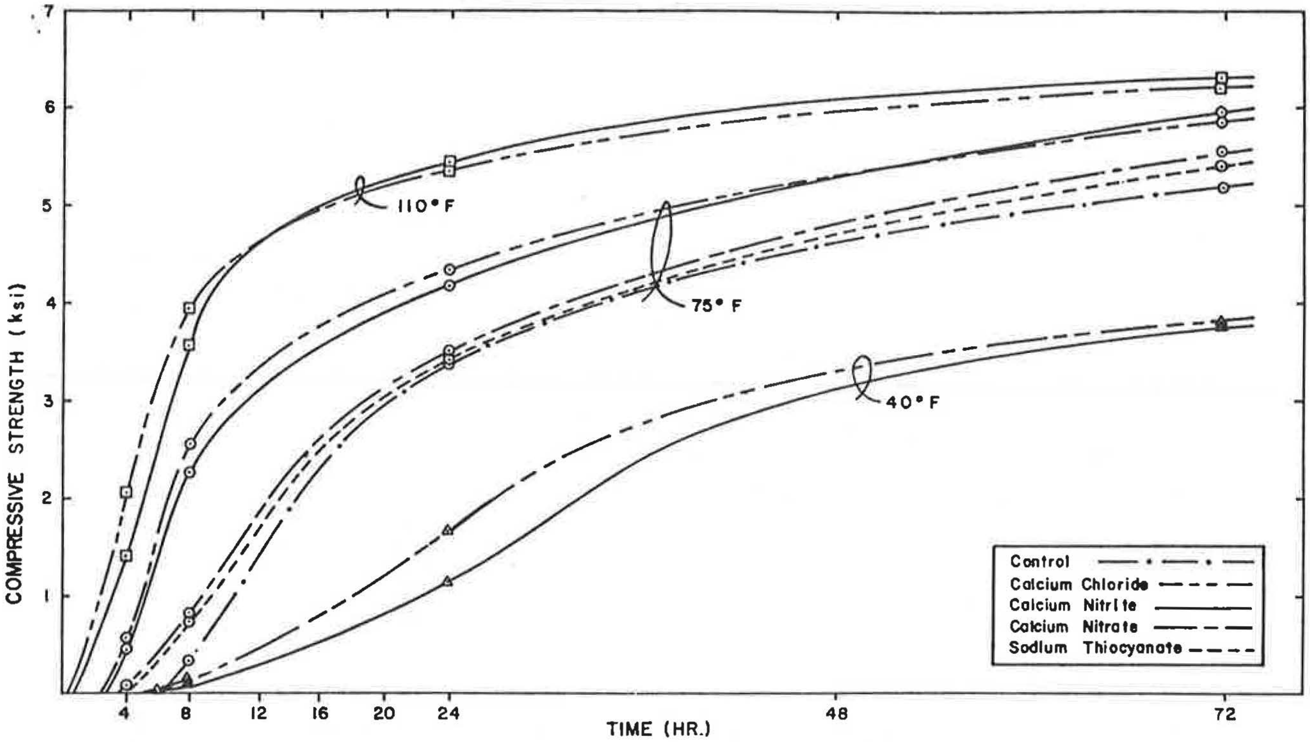

FIGURE 1 Compressive strength of accelerated concrete as a function of time and ambient temperature.

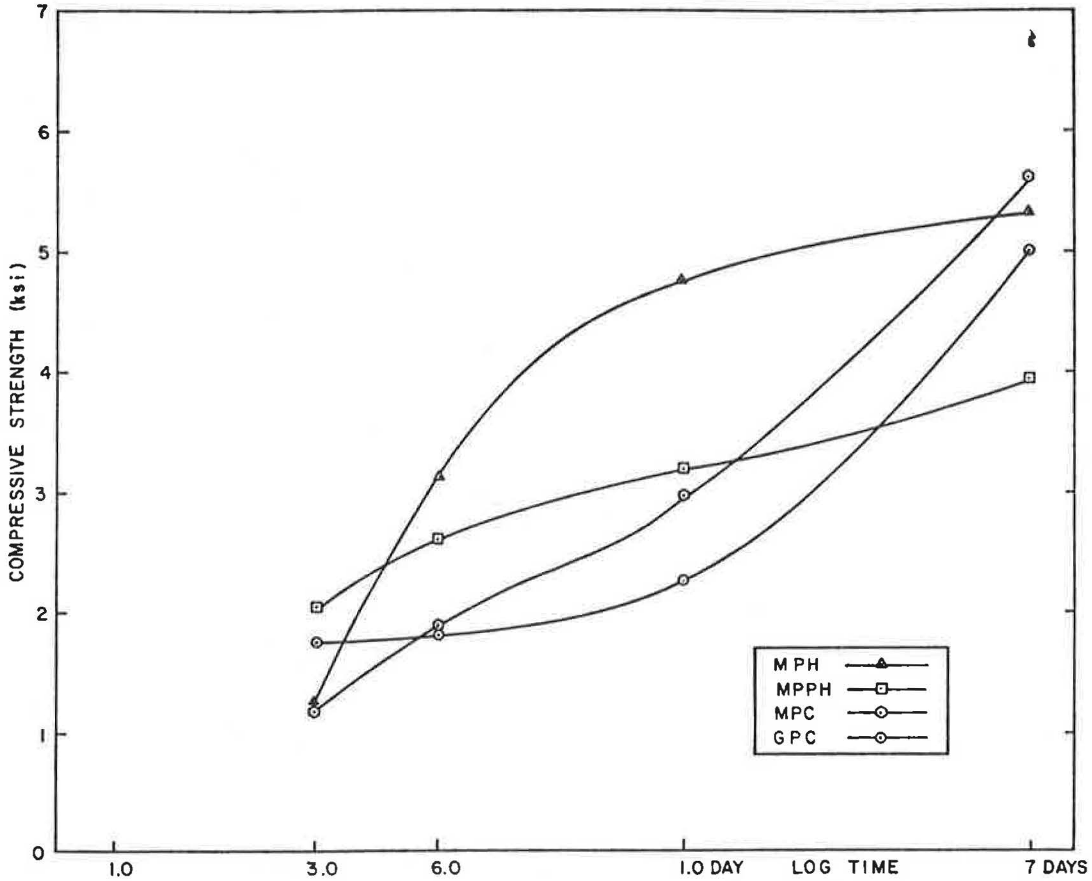

FIGURE 2 Compressive strength of rapid-setting concretes as a function of time at ambient temperature of 40° F.

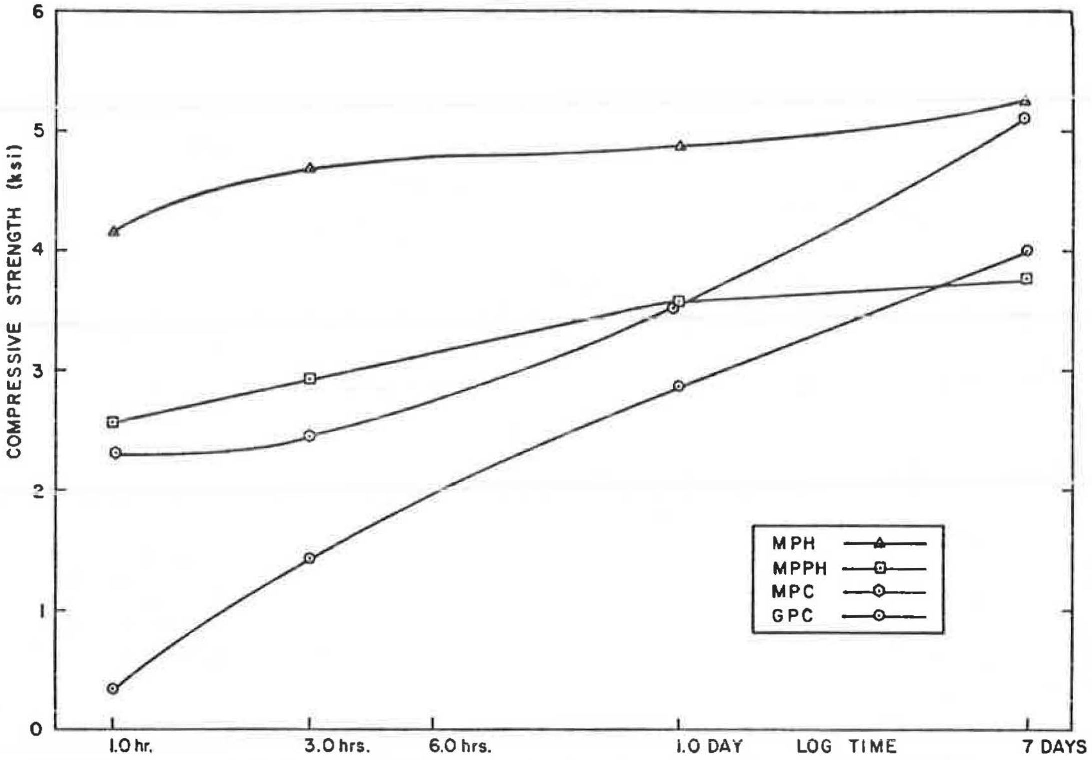

FIGURE 3 Compressive strength of rapid-setting concretes as a function of time at ambient temperature of 75° F.

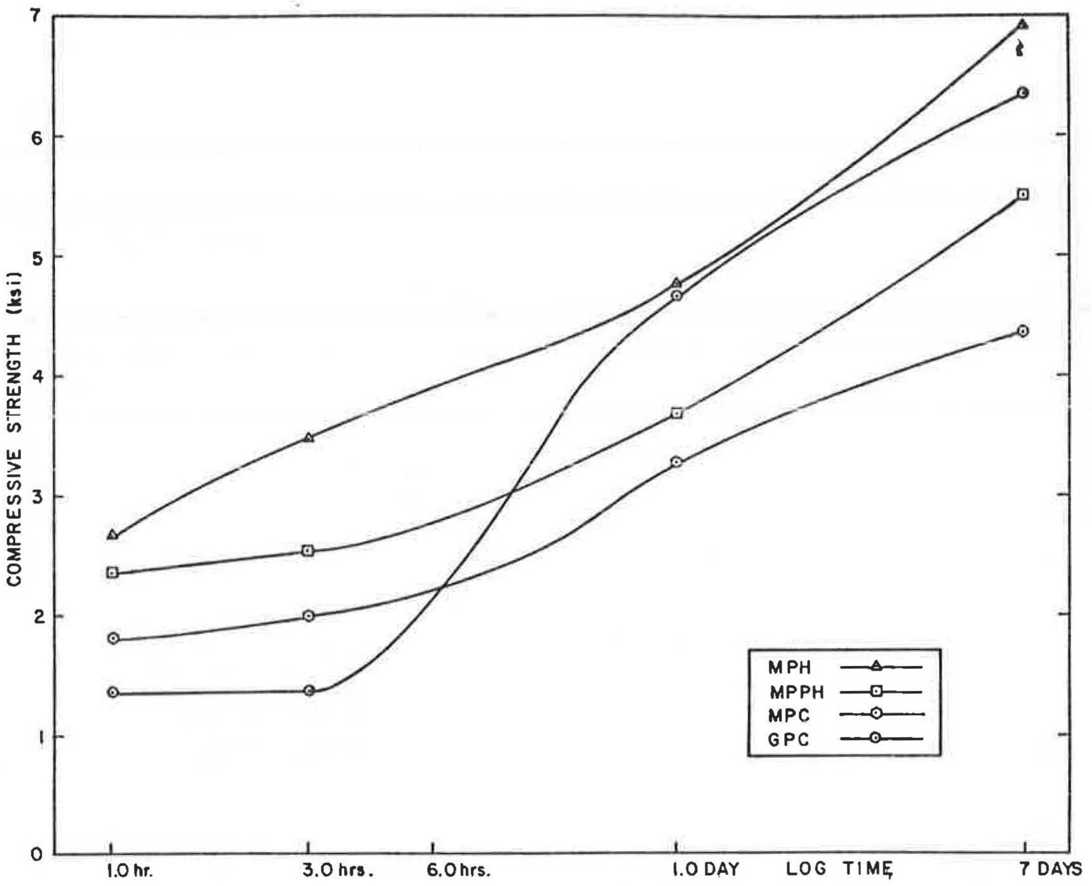

FIGURE 4 Compressive strength of rapid-setting concretes as a function of time at ambient temperature of 110° F.

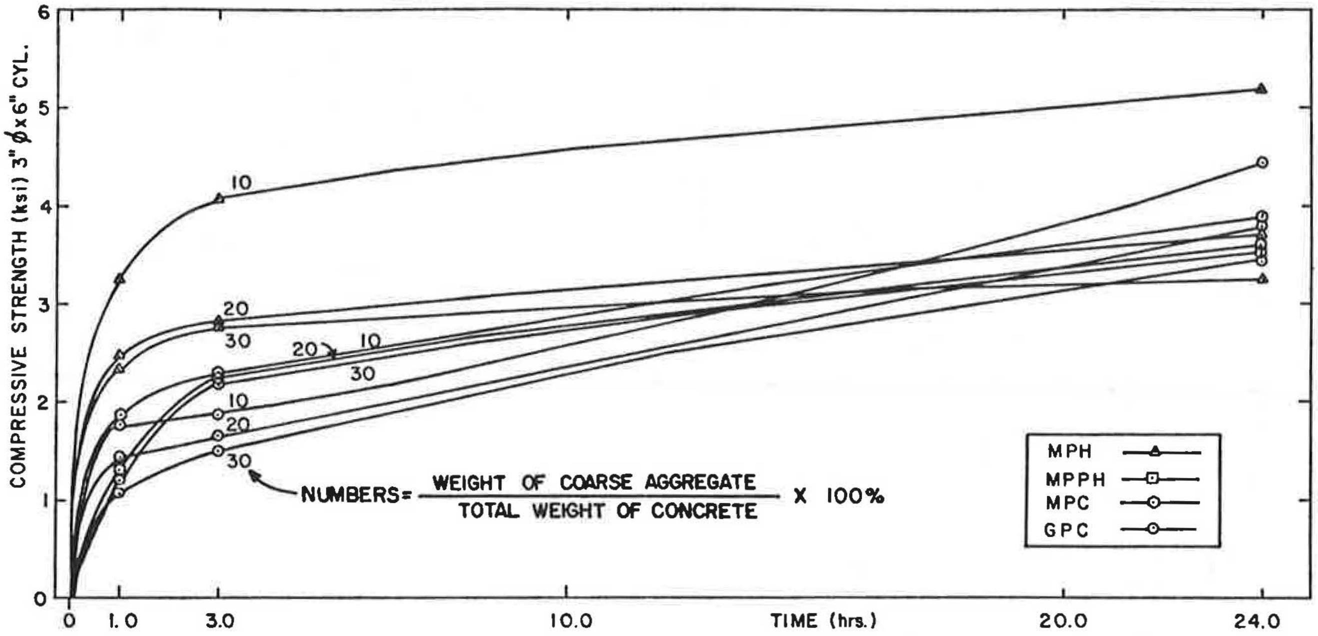

FIGURE 5 Compressive strength of rapid-setting concrete mixes with varied quantities of coarse aggregate.

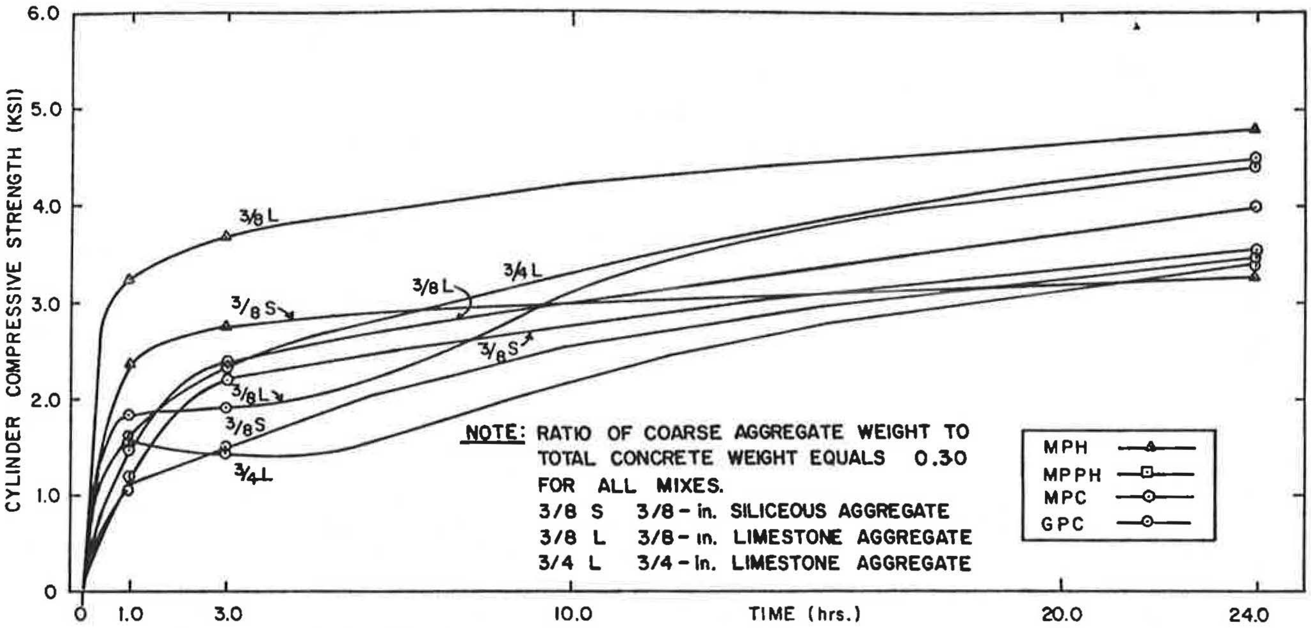

FIGURE 6 Compressive strength of rapid-setting concrete mixes with varying types of coarse aggregates.

TABLE 1 Compressive Strength and Modulus of Elasticity at Age of 7 Days

Material	Average 7-Day Compressive Strength (psi)	Average Modulus of Elasticity (1×10^6 psi)
Magnesium phosphate	5,230	4.51
Magnesium polyphosphate	3,730	6.41
Gypsum-based portland cement	4,000	4.75
Modified portland cement	5,100	3.97

using these accelerators were plotted for 40°F and 110°F.

Flexural strength versus time curves for the rapid-setting materials at 40°F, 75°F, and 110°F are shown in Figure 8. At 75°F and 110°F, the magnesium phosphate and magnesium polyphosphate exhibited the most rapid strength gain. At 40°F the gypsum-based portland cement and the modified portland cement had higher 6-hr strengths.

Set Time

Initial and final set times for accelerated concretes, determined by penetration resistance, are

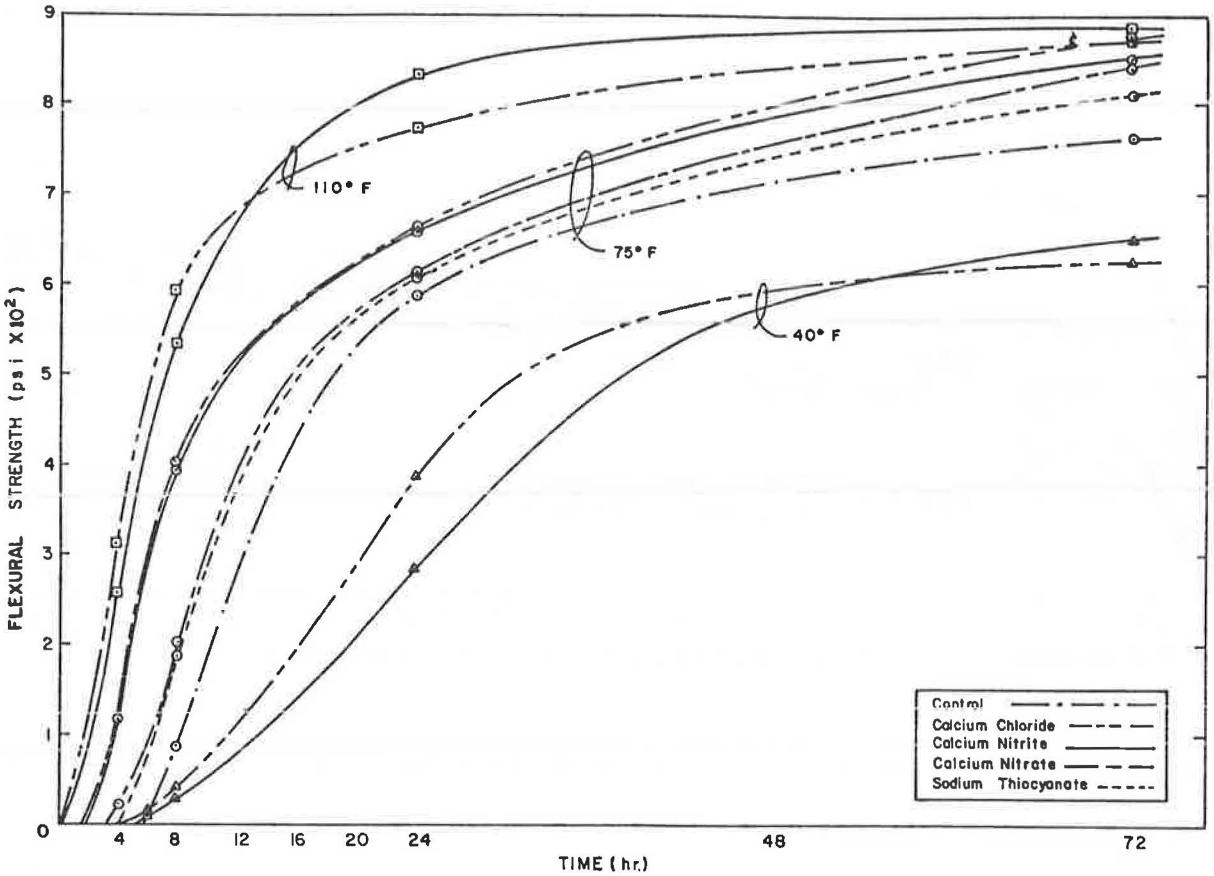

FIGURE 7 Flexural strength of accelerated concrete as a function of time and ambient temperature.

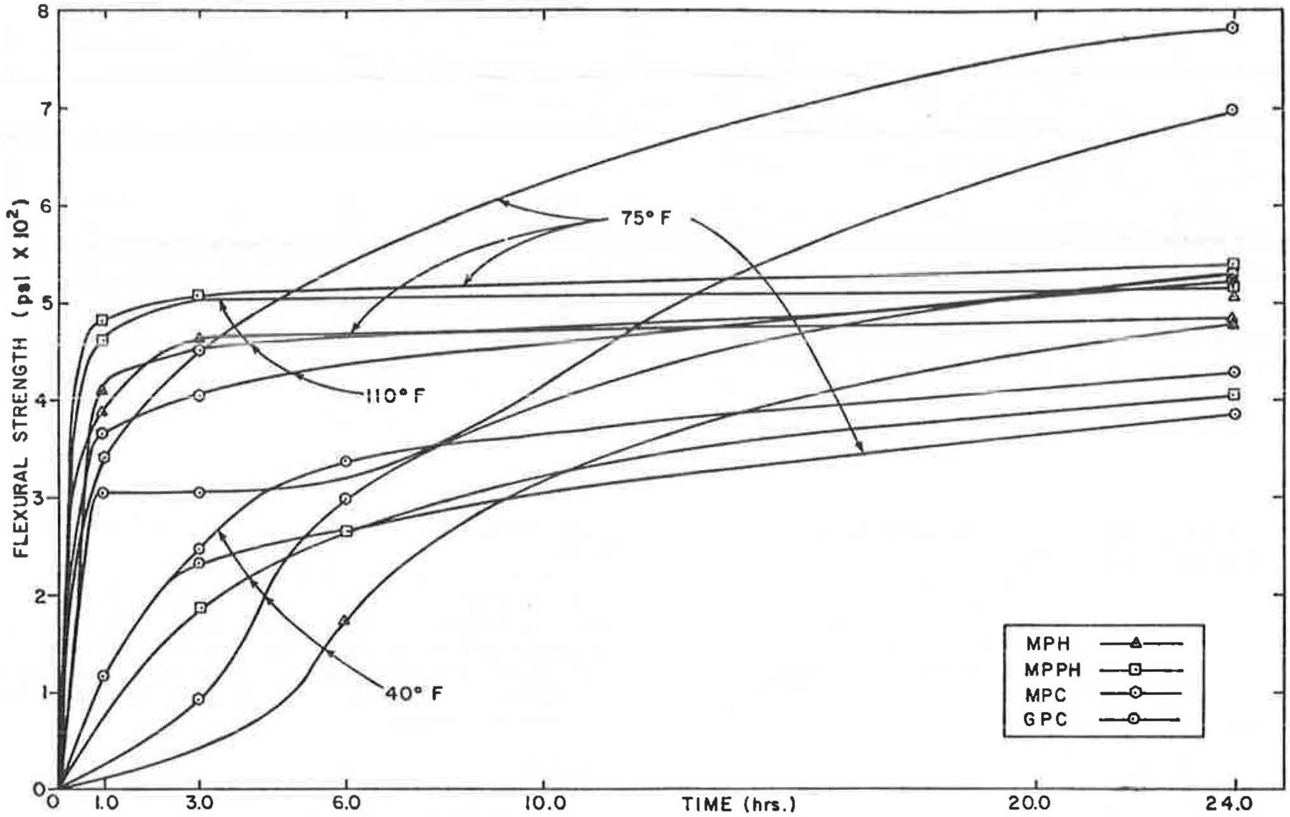

FIGURE 8 Flexural strength of rapid-setting concretes as a function of time and ambient temperature.

shown in Figure 9. Set times were determined at ambient temperatures of 40°F, 75°F, and 110°F. Calcium chloride and calcium nitrite provide the most rapid setting at all temperatures.

In Figure 10, the set times for the rapid-setting materials determined using the Gilmore needle are shown for temperatures of 40°, 75°, and 110°F. At all temperatures, the magnesium phosphate and magnesium polyphosphate set most rapidly. However, at higher temperatures these materials set too rapidly to allow adequate placing and finishing.

Bond

Direct shear bond and flexural bond tests have been performed on the magnesium phosphate and gypsum-based portland cement. The flexural bond strength of the magnesium phosphate was greater than that of the gypsum-based portland cement. The results were reversed for the direct shear bond test. The results appeared inconsistent and are not presented.

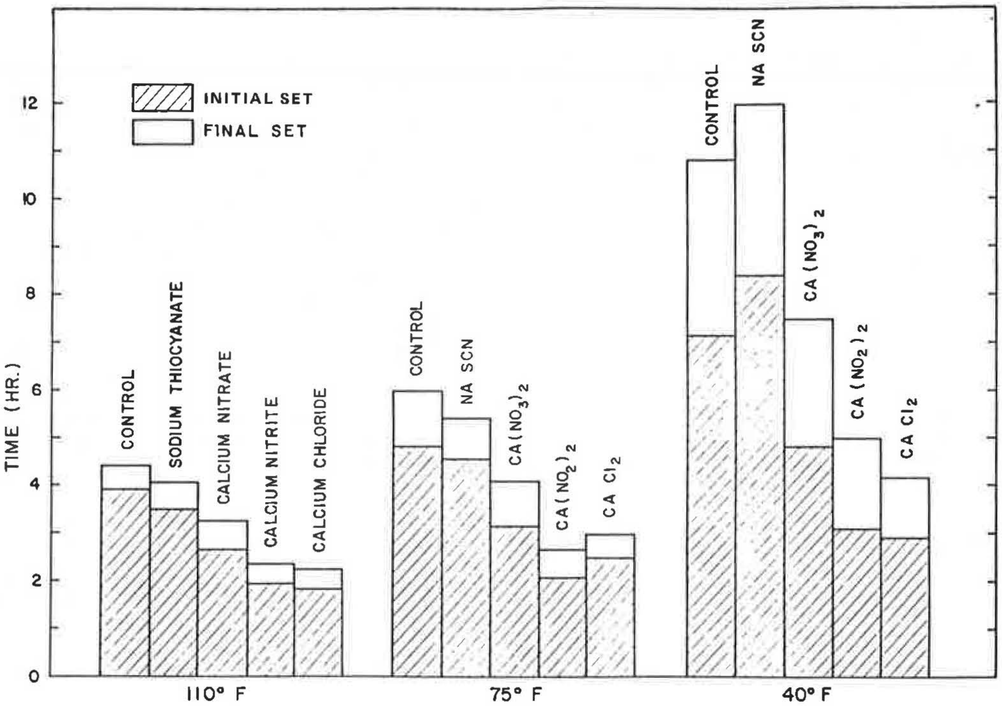

FIGURE 9 Set time of accelerated concretes by penetration resistance for various ambient temperatures.

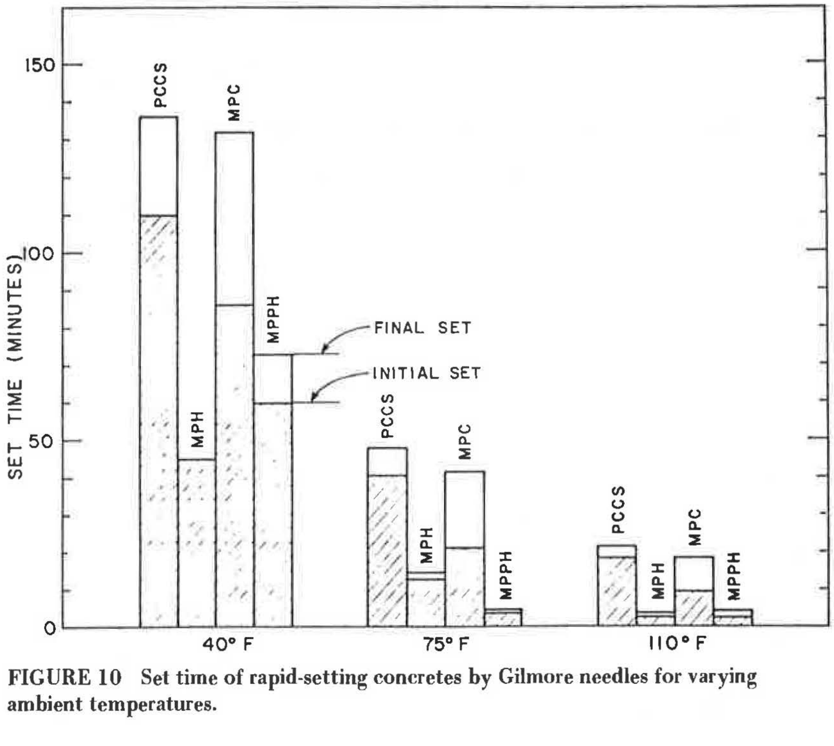

FIGURE 10 Set time of rapid-setting concretes by Gilmore needles for varying ambient temperatures.

Sandblast Abrasion

Sandblast abrasion coefficients are given in Table 2. The abrasion loss for the rapid-setting materials was significantly greater than that of the accelerated concretes.

Length Change

Change in length versus time relationships for the rapid-setting concretes are shown in Figure 11. The beams contain 0.375-in. siliceous coarse aggregate with a 0.30 ratio of coarse aggregate weight to total weight of concrete. The modified portland cement exhibited the most severe shrinkage. The gypsum-based portland cement expanded slightly.

In Figure 12, change in length versus time curves for accelerated concretes are shown. Most concretes exhibited expansion during the 7-day moist-curing period. The initial rate of shrinkage was greater for the accelerated concretes than for the control specimen.

TABLE 2 Sandblast Abrasion Coefficients

Material	Average Abrasion Coefficient (cm^3/cm^2)
Magnesium phosphate	0.164
Gypsum-based portland cement	0.117
Modified portland cement	0.007
Calcium chloride accelerated concrete	0.011
Calcium nitrite accelerated concrete	0.012

Freeze-Thaw

Results from the freeze-thaw tests on the rapid-setting materials are shown in Figure 13. Both the magnesium phosphate and the magnesium polyphosphate performed poorly with failure occurring at less than 100 cycles. The modified portland cement outperformed the other materials.

CONCLUSIONS

1. For evaluation of mechanical properties of the rapid-setting concretes and accelerated concretes, cylinder compressive strength, modulus of elasticity, and flexural strength appeared most appropriate.
2. The working time of the rapid-setting concretes was best evaluated using the Gilmore needle test. The set times of the accelerated concretes were best determined using the penetration resistance test.
3. The performance of both the rapid-setting concretes and the accelerated concretes appeared to be best evaluated using both the freeze-thaw resistance test and the shrinkage test.
4. The mortar cube compressive strength test, the peak exotherm test, the bond tests, and sandblast abrasion test appeared least appropriate in evaluating these materials.
5. In the evaluation of accelerated concretes, calcium chloride and calcium nitrite exhibited the most rapid strength gain in all tests performed.

In general, the magnesium phosphate and the magnesium polyphosphate display higher early strength

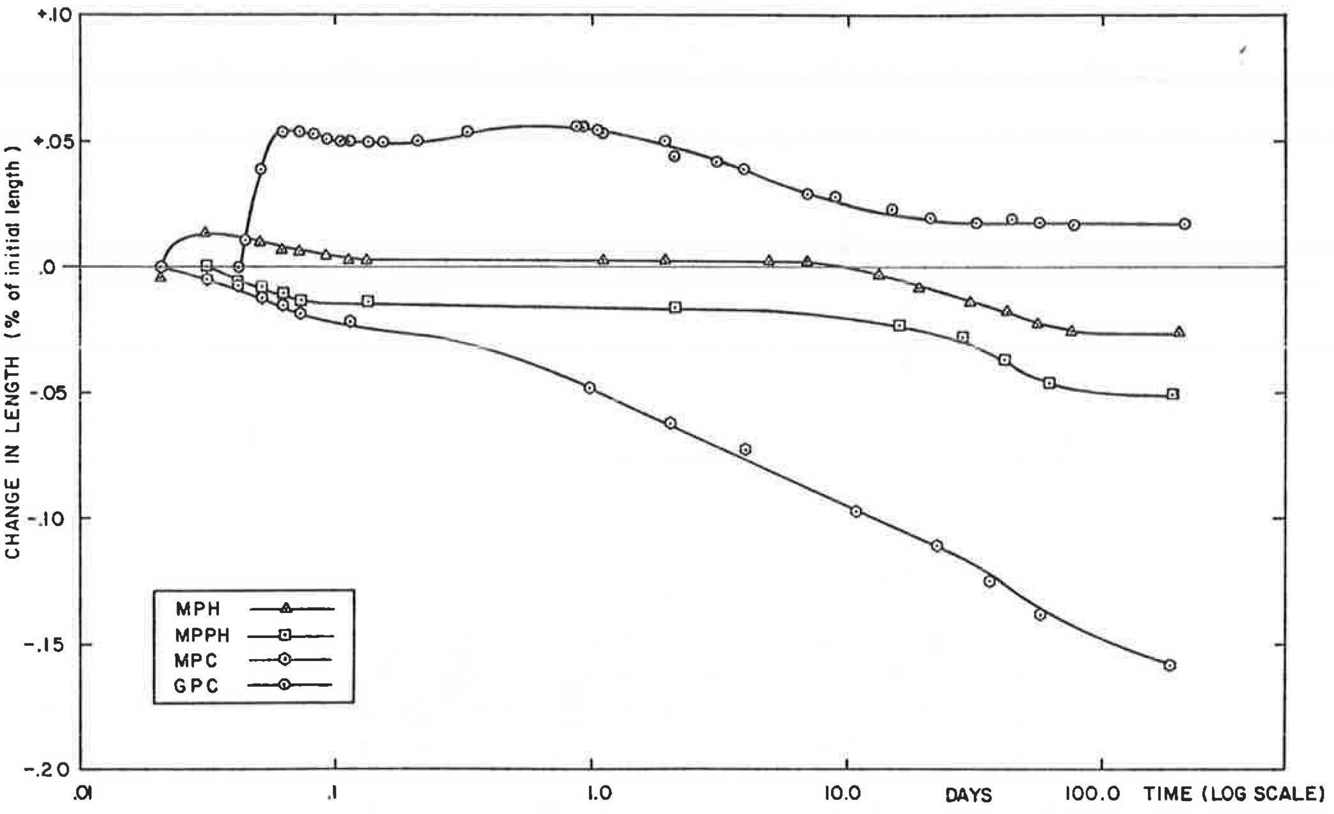

FIGURE 11 Change in length of rapid-setting concrete beams.

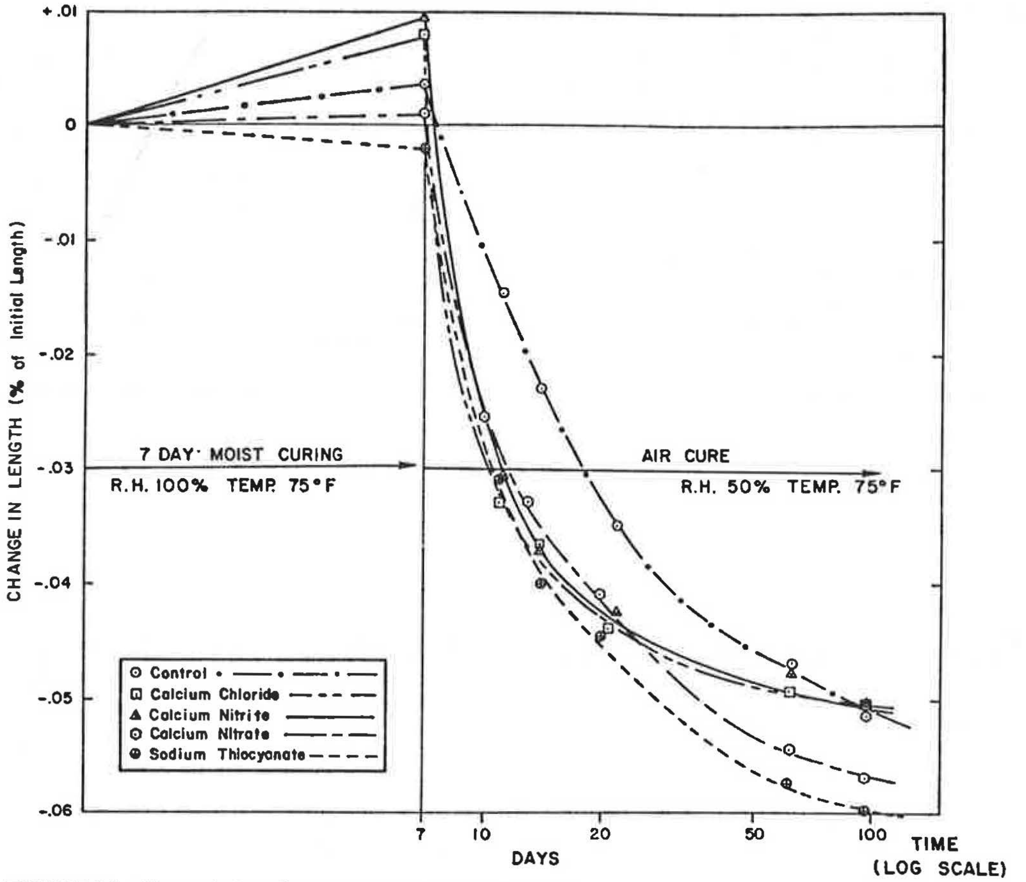

FIGURE 12 Change in length of accelerated concrete beams.

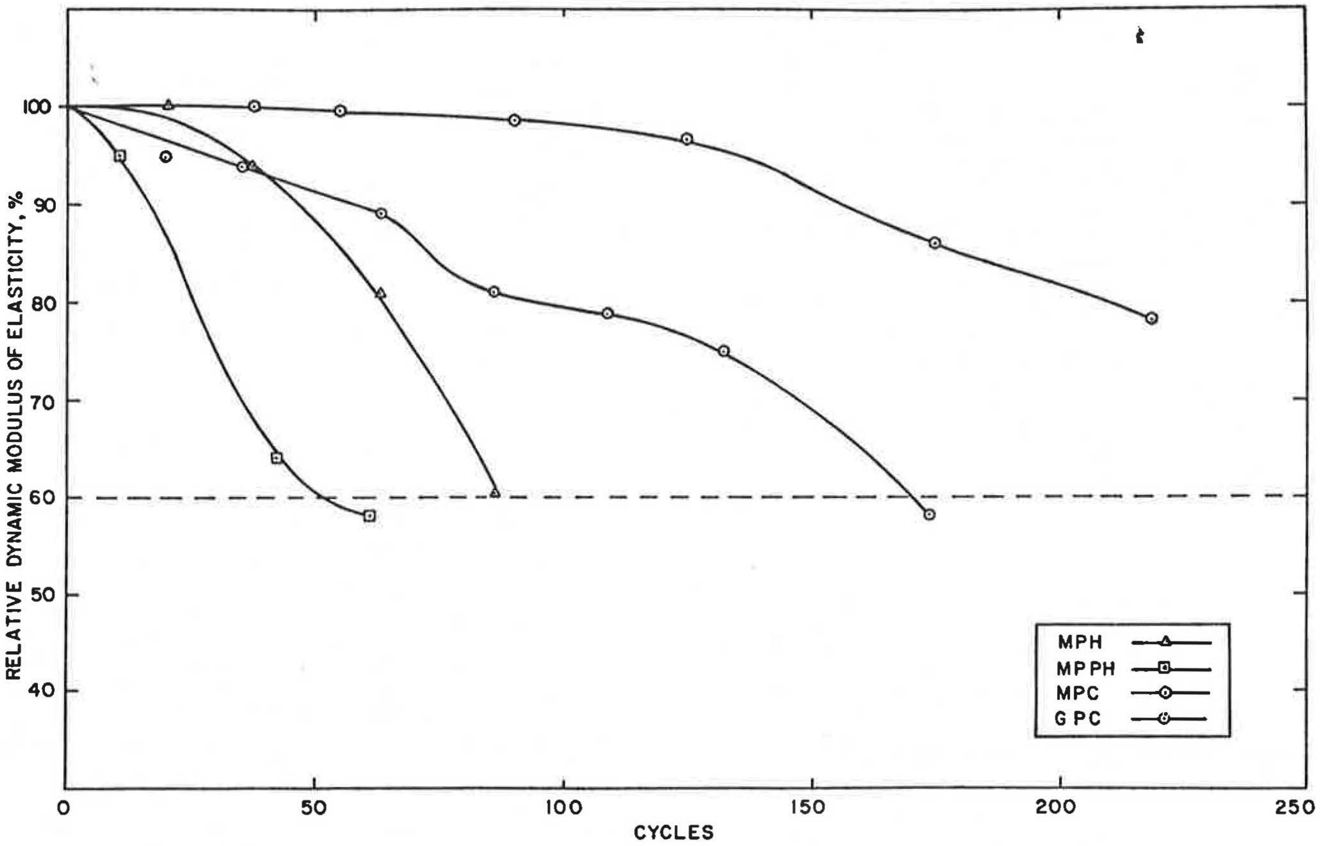

FIGURE 13 Change in dynamic modulus of rapid-setting concretes as a function of freeze-thaw cycles.

gains. However, these materials do not allow reasonable working time at higher temperatures. The freeze-thaw performance of the modified portland cement and the gypsum-modified portland cement was significantly better than for the magnesium phosphate and the magnesium polyphosphate.

ACKNOWLEDGMENTS

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Shear Transfer in Two-Layer Composite Systems

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ABSTRACT

Experiments were conducted to evaluate the shear transfer capacity of two-layered systems using polymer-modified concrete as the top layer. The experimental program was designed to verify the general theory of shear transfer mechanism for concrete and to evaluate the necessary constants of the theoretical expressions. The general theory presented covers structural members with (a) no shear reinforcement, (b) moderate shear reinforcement, and (c) high shear reinforcement. Four groups of specimens were tested. Group A specimens were used to investigate the relation between intrinsic bond shear transfer capacity and the strength of the composite materials. Group B specimens contained various amounts cast monolithically using ordinary concrete to serve as control specimens. Group C contained control specimens made up of totally cast-in-place concrete with no cold joints. Group D contained control specimens made up of cast-in-place concrete over precast concrete.

The problem of shear transfer in concrete structures arises when shearing loads must be transmitted across a definite and often weak plane. Typical situations are encountered in corbels, nonmonolithic joints in concrete, and composite elements where concrete is cast in place over a precast member.

Since the early 1950s, several researchers have studied this problem. It is generally recognized that the shear transfer capacity in concrete elements can be attributed to any of the following: friction at the shear plane, interlocking action of the aggregates, dowel action of any reinforcement, and bond forces (apparent cohesion) at the shear plane. However, there continues to be a great deal of debate regarding the relative importance of the various parameters.

Of the many expressions for shear transfer capacity (1-12), the simplest and most widely used has been that based on the shear friction hypothesis of Birkeland and Birkeland (1). This expression with minor modification (9) has been incorporated in the American Concrete Institute (ACI) code. Although the expression is useful in estimating shear transfer capacities, its very formulation ignores "apparent cohesion" (bond) and dowel action resistance.

This paper is a condensation of "Shear Transfer in Concrete and Polymer Modified Concrete Members Subjected to Shearing Loads" (2), which deals with the shear capacity of the normal concrete-polymer modified concrete interface. A general theory on the shear transfer mechanism is also presented correlating with the tests (13,14). The discussion covers any two-layered system.

A THEORY OF SHEAR TRANSFER MECHANISM FOR CONCRETE

It is hypothesized that the total shear transfer capacity in a concrete element is made up of: intrinsic bond shear resistance, ΔV_b; shear friction resistance, ΔV_f; aggregate interlock resistance, ΔV_i; and dowel resistance, ΔV_d.

Consider an element subjected to a shearing load (Figure 1). Initially, all shear resistance is provided by intrinsic bond. After cracking has started and some slip has occurred, resistance is developed through friction, aggregate interlock, and dowel action. Shear transfer through friction is due purely to the surface shear resistance to slip. Aggregate interlock is due to the interlocking action of the aggregates at the failure plane. Dowel action shear resistance is a result of the steel reinforcement as shown in part b of Figure 1.