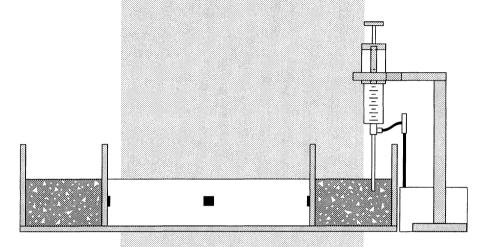# PRELIMINARY INVESTIGATION OF THE RELATIONSHIP BETWEEN CAPILLARY PORE PRESSURE AND EARLY SHRINKAGE CRACKING OF CONCRETE

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Supplementary Notes

Abstract

The purpose of this study was to design experimental laboratory equipment and perform experiments to investigate the basic physical processes that occur in concrete for periods of several hours to several days after mixing. The study was conducted in the laboratory, with controlled variations in concrete materials, mixture proportions, and curing regimes. Mortar was used because concrete containing aggregates produces less measurable shrinkage.

The development of capillary pore pressure at early stages in a concrete mass appears to be a basic physical parameter controlling the occurrence of plastic cracking. Equipment was designed to monitor capillary pore pressure and shrinkage strains developing in setting mortar or concrete. Five tests were conducted using the equipment, and the results were interpreted with respect to the physical-chemical processes occurring in the hydrating mortar.

The results show that the equipment can monitor capillary pore pressure and shrinkage strains that develop in hydraulic cement-based materials in the early ages after mixing. The equipment will be used in future experiments to investigate the interrelationships between materials properties and environmental factors and their effect on the occurrence of plastic cracking of concrete.

FINAL REPORT

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INTRODUCTION

Plastic shrinkage cracking of concrete is one of the vexing problems of concrete construction. These cracks occur during the hardening process while the concrete is still plastic. Although in some cases plastic cracks are merely cosmetic faults, in the case of reinforced concrete elements such as bridge decks and deck overlays where the concrete serves as a barrier to protect the reinforcement from corrosion, the cracks are unacceptable because they provide a direct pathway for chlorides through at least a portion of the barrier.

A consensus exists that plastic shrinkage cracking occurs when the rate of evaporation of water from the surface of the concrete exceeds the rate at which the concrete mass can provide water through the bleeding process.[1] Consequently, construction practices for preventing plastic shrinkage cracking are geared toward minimizing the rate of evaporation from the concrete surface and the length of time the concrete surface remains unprotected. Preventive measures commonly used are nighttime placements, particularly during the summer months; the use of fogging misters; and quick application of curing materials after the finishing operation.

In some cases, as with plastic shrinkage cracking in a newly constructed bridge deck, the cause can be readily traced to inadequate curing.[2] In other cases, as with some deck overlays, reports of the construction operations suggest that evaporative conditions were not severe and that no serious fault occurred; yet, when the initial curing was complete, the deck was cracked.

One explanation is that the reports may not provide an accurate reflection of the situation during construction or sufficient detail to assess it. Usually, the conclusion drawn is that the plastic cracking resulted from excessive evaporation of water from the concrete surface. However, in a discussion of Lerch's study,[1] Tuthill[3] cited field investigations where plastic cracking apparently occurred under nonevaporative conditions. Tuthill suggested that several

factors may act alone or in concert to result in plastic cracking: evaporation rate, subgrade conditions, and cement characteristics. He also indicated that delayed finishing or a second finishing operation may sufficiently relieve the developing tension in the concrete mass to prevent plastic cracking, although it is quite possible that this serves only to close the crack at the surface.

Spindel[4] discussed laboratory techniques for measuring the shrinkage of cement pastes and concretes during the setting or hardening process. In his experiments, significant shrinkage or contraction was measured in specimens placed under water, conditions that preclude evaporation. He indicated that such shrinkage can be of sufficient magnitude to cause field problems and that knowledge of such a tendency in a concrete mixture can be useful in planning construction operations to avoid cracking problems.

Shalon's and Ravina's[5] findings from tests conducted in an outdoor exposure area indicated that either the evaporation rate is related to plastic shrinking irrespective of the rate of bleeding or the evaporation rate is not the decisive issue. Their findings also indicated that several commonly suggested preventive measures, such as nighttime placements and sunshades, were not effective, although in these respects, they failed to convince the concrete construction industry.

Regarding cracking during the setting of hydraulic cements, Acker and Moranville-Regourd[6] counterposed the issues of self-desiccation (loss of water through hydration of cements) and desiccation (loss of water from the mass to the outside through evaporation or bleeding). The products of cement hydration occupy significantly less volume than the sum volume of anhydrous cement and water (Le Chatelier contraction or chemical shrinkage), which leads to endogenous shrinkage. The volume change varies with different cementing materials, as noted by Tuthill[3] and Spindel.[4] Because of its nature, shrinkage of this type affects the concrete mass somewhat uniformly, whereas shrinkage related to desiccation is localized near the surfaces from which the water is lost. However, with respect to deck overlays with thicknesses on the order of 30 mm, no part of the mass is far removed from the surface.

In the simple sense, plastic cracking of concrete occurs when the mass shrinks because of a combination of factors at a rate that exceeds the capacity of the concrete to adjust its volume and before it develops strength that exceeds the tensile stresses resulting from the shrinkage. These stresses would seem to develop initially from interparticle capillary tension in the solid framework of the mass as water is lost.

Wittman[7] conducted experiments on ordinary portland cement concretes, simultaneously measuring capillary pore pressure and shrinkage. His results indicated a relation between capillary pore pressure and plastic shrinkage of concrete. His investigation of the effect of the water–cementitous material ratio (w/cm) suggested that contraction is maximal with a w/cm between 0.5 and 0.6 and minimal at a w/cm below 0.4.

Wittman's results showed a means to measure some of the fundamental processes occurring in freshly mixed concrete related to the phenomenon of plastic shrinkage. It is known

that concrete containing silica fume is more susceptible to plastic cracking than ordinary concrete.[8] This increased tendency is often simply ascribed to the failure of such low w/cm concretes to bleed, but it can be described mechanistically as resulting from the very high interparticle surface area existing in silica fume concretes and the development of correspondingly high capillary pore tensile pressures relative to the strength of the material at very early ages.[9] Theoretical equations for the capillary tensile pressure are reported in which the pressure is directly related to the specific surface area of the cement (or cementitious materials) in the mixture and the surface tension of the water and inversely related to the w/cm.[9] Calculations for a typical portland cement fineness (350 kg/m^2) with a water surface tension of 7.3 x 10^{-2} N/m at a w/cm of 0.35 yield capillary tensile pressure between 0.021 and 0.073 MPa.[9]

Low w/cm and silica fume concretes require the use of high-range water-reducing admixtures (HRWRA). Commercially available HRWRA act by altering the electrostatic surface charges on the cementitious particles, thus promoting dispersion of the particles and lowering of the viscosity of the paste.[10] It is speculated that the action of the HRWRA also alters the surface tension of the mixing water. Further, it is known that the effectiveness of HRWRA in lowering paste viscosity diminishes abruptly and rapidly shortly after its introduction to the mixture, resulting in rapid stiffening of the mixture.[10] Such a loss in fluidity renders the material less able to adjust cohesively to volumetric changes that may be occurring simultaneously. Consequently, the use of HRWRA may affect the system in some manner regarding capillary pressures and plastic shrinkage cracking.

Radocea[11] developed a method to measure capillary pore pressure in concrete. His experimental setup consisted of a water-filled syringe inserted into the concrete and connected to a sensitive pressure transducer. Capillary pore pressures measured by this system in cement pastes and silica fume–fly ash slurries exposed to evaporative conditions were between 0 and 100 kPa. These pressures generally agree with those calculated from theoretical equations.[9] Radocea suggested that the development of capillary pore pressure, and thus the tendency for plastic cracking, is dependent on the pore geometry at the evaporative surface and the response of the material to water loss.

Sellevold[12] described the use of a test in which an annular specimen of concrete is cast around a rigid ring. The ring restrains the shrinkage of the concrete specimen, thus creating a situation reflective of field placements where boundary conditions (forms, base) and reinforcement provide restraint. This type of test specimen has been used in the evaluation of restrained drying shrinkage of concrete.[13,14] Instrumentation of the restraining ring with strain gages allows automated data collection and monitoring of the specimen for strain development and release through cracking.

In another study of early-age shrinkage of concretes, Bloom and Bentur[15] described the use of a longitudinal jig for measuring free and restrained shrinkage. This device used a concrete specimen 1 m long with one fixed and one free end. The free end is instrumented with a gage to measure shrinkage. It is also designed to permit incremental adjustments to the distance between the two ends of the specimen, thus providing a means to measure and restrain shrinkage. Their results suggested that the development of early-age cracking was dependent on a number of

3

interrelated factors including free shrinkage, time of setting, the w/cm, and the presence of silica fume.

Based on the foregoing, the phenomenon of plastic cracking can be described as follows:

- Capillary tensile pressures develop within the concrete as a consequence of water loss when the material has attained sufficient rigidity to resist contraction by fluid rearrangement.

- Cracking results when the capillary pressures exceed the tensile strength of the concrete.

The physical processes that may combine to result in plastic shrinkage cracking, capillary pressure and volume contraction, are affected by particular properties of materials and environmental factors. A more complete understanding of the parameters and relationships that affect the occurrence of plastic shrinkage cracking of concrete is needed to develop a comprehensive approach to preventing this construction fault.

PROBLEM STATEMENT

Plastic shrinkage of concrete is a major problem affecting the construction of bridge decks and overlays. This type of cracking incurs extra construction expenses for evaluation, repair, or removal and replacement as well as lost time and possible litigation. Although the basic physical process that leads to plastic cracking is known, it results from a complex interaction among a number of parameters that are not well understood.

PURPOSE AND SCOPE

The purpose of this research was to design experimental laboratory equipment and perform experiments to investigate the basic physical processes that occur in concrete for periods of several hours to several days after mixing. The study was conducted in the laboratory, with controlled variations in concrete materials, mixture proportions, and curing regimes. Mortar was used because concrete containing aggregates produces less measurable shrinkage.

RESEARCH DESIGN

Specimens were cast in PVC ring molds having a nominal inside diameter of 170 mm, an outside diameter of 300 mm, and a height of 65 mm. The molds were instrumented with strain

gages (Measurements Group, Type EA-30-125AC-350) that responded to the physical shrinkage of the mortar during early curing. A thin hollow-tube probe consisting of a 5-ml syringe-type pipetter (Popper & Sons) with a side outlet to which a pressure transducer (Omega, Model No. PX243-05BF5V) was attached was used to measure the development of capillary pore pressure within the specimen. A schematic and photographs of the experimental setup are presented in Figures 1-4.

Experimental mixtures were batched from combinations of a Type I portland cement, silica fume, water, fine aggregate, and a naphthalene sulfonate formaldehyde-based HRWRA. Mixture proportions are given in Table 1. The molds were filled with mortar to a depth of approximately 40 mm.

TABLE 1. MIXTURE PROPORTIONS

Test No.	W/cm	Water (% by mass)	Sand (% by mass)	Cement (% by mass)	Silica Fume (% of cement)	HRWRA (ml/kg)
1	0.5	12	64	24	NA	NA
3	0.5	12	64	24	NA	NA
4	0.42	10	66.5	23.5	15	9.9
5	0.35	9.3	64	26.7	15	15.3

Five tests were performed. In the first, eight strain gages were mounted on the interior of the mold. Four (referred to as circumferential gages) were mounted tangentially on the mold's circular interior, and four were mounted longitudinally (parallel with the central axis of the mold's concentric rings). Because the gages were positioned as shown in Figure 1, their relative locations were denoted by clock face positions (e.g.,12:00). In subsequent tests, four circumferential gages were used. The mortar pore pressure was monitored at the tip of the pipetter, which protruded to a depth of 1.5 cm in the mortar and was connected to the pressure transducer by deionized and deaerated water that filled the pipetter. WD-40 lubricant was applied to the walls of the mold to prevent the mortar from adhering to them. The tests were performed in a controlled laboratory environment where the temperature was maintained at approximately 22°C and 60 percent relative humidity. The top surface of the specimens was left uncovered. Tests 4 and 5 used a total mix mass of 8564 g. In the later tests, setting times of the mixtures were determined concurrently following ASTM C 403.
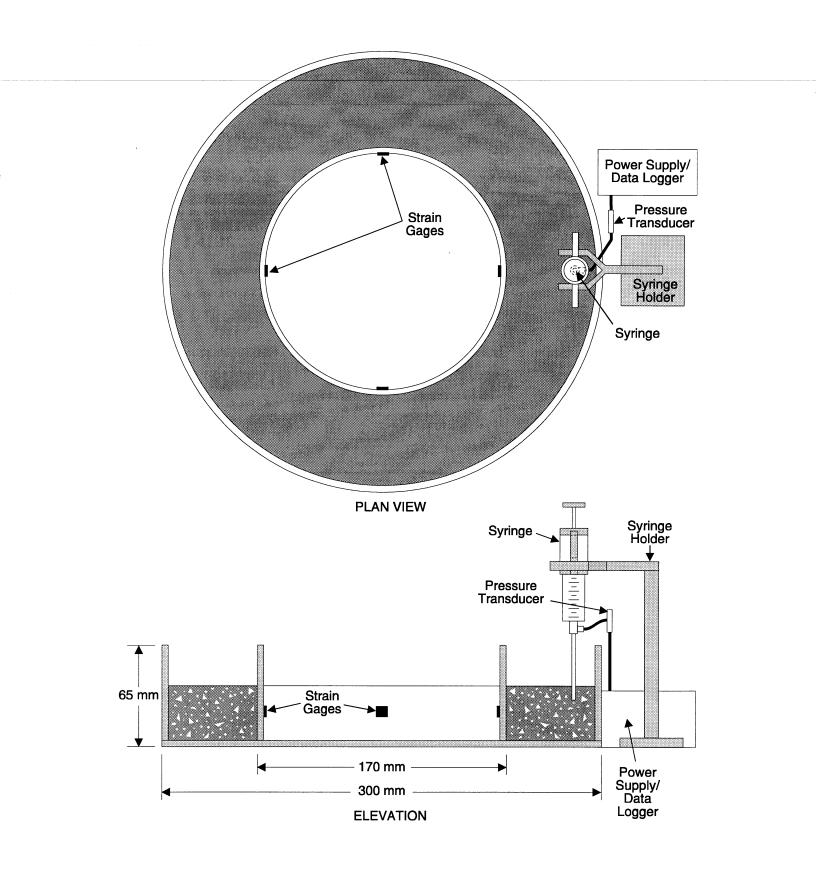
Strain Gages

Power Supply/
Data Logger

Pressure
Transducer

Syringe
Holder

Syringe

PLAN VIEW

Syringe

Syringe
Holder

Pressure
Transducer

65 mm

Strain
Gages

170 mm

300 mm

Power
Supply/
Data
Logger
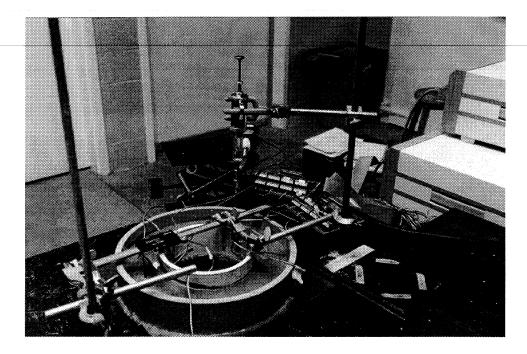
ELEVATION

Figure 1. Schematic of Experimental Setup
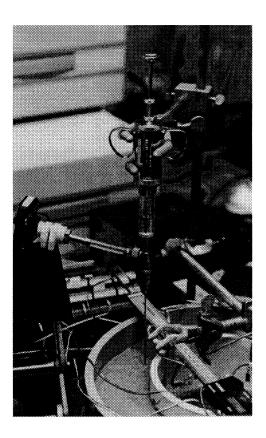
Figure 2. Test Setup Including Ring Mold and Pipetter
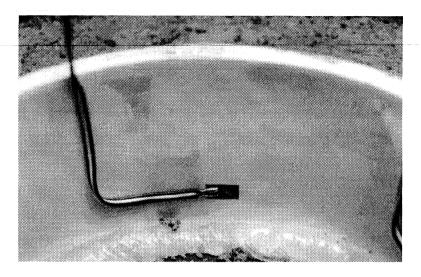

Figure 3. Pipetter and Pressure Transducer

Figure 4. Strain Gage on Mold's Inner Ring

RESULTS

The results of Test 2 are omitted because of errors in the experimental procedure.

Test 1

Figures 5 and 6 are graphs of the strain gage data. The data from the longitudinal strain gages had two distinct behaviors. First, the three monitored gages measured similar shrinkage in the mortar during the initial 4 hr of curing. Second, the data differed quantitatively after the first 4 hr. This difference was probably attributable to slippage of the mortar relative to the mold wall at the interface between the mortar and the mold. The fourth longitudinal strain gage was not monitored because not enough data collection channels were available.

The initial positive strain was attributable to a small expansion of the mortar early in the curing process, but we are unsure about the mechanism producing this expansion. Soon, the evaporation of water from the mortar surface and the surface tension of the water between the mortar particles caused bulk shrinkage of the entire mortar ring. This shrinkage continued until about 350 min had elapsed, when each gage measured a significant change in the trend of the data. The longitudinal gages showed that the mortar ring expanded slightly at this time. This brief expansion was probably caused by changes in the capillary pore pressure, which is discussed in more detail later. The amount of expansion differed for each gage, and from this time on each longitudinal gage recorded similar qualitative behavior but significantly different quantitative behavior.
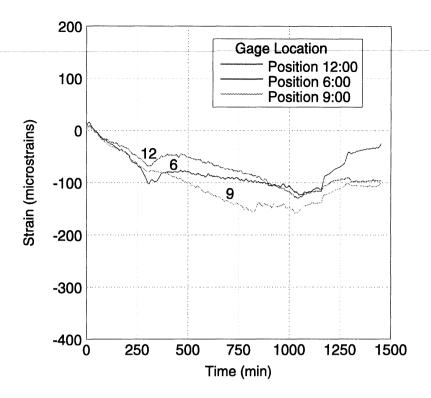
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Figure 5. Longitudinal Strains in Ring Mold Resulting from Mortar Curing in Mold (Test 1)
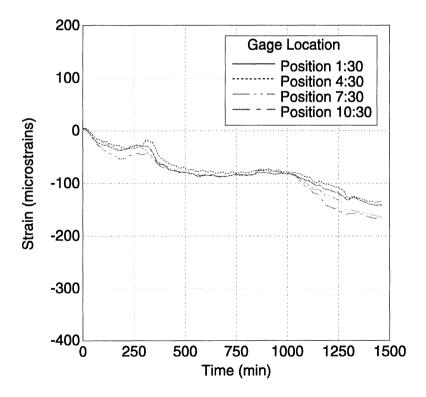

Figure 6. Circumferential Strains in Ring Mold Resulting from Mortar Curing in Mold (Test 1)

The longitudinal gages indicated that further shrinkage took place from 500 to 1050 min, when the inner ring of the PVC mold was forced to contract by the mortar. This period of contraction ended abruptly at 1050 min, when each gage began to indicate that the mortar ring was expanding. This apparent expansion probably resulted from slippage at the interface between the mold wall and the mortar, as mentioned earlier.

The four circumferential strain gages measured similar quantitative and qualitative behaviors as the curing mortar ring caused the inner ring of the PVC mold to deform. They indicated an initial expansion of the mortar ring, which was consistent with the longitudinal strain data. Soon after this expansion, however, the mortar ring began to contract because of the evaporation of water and the development of forces related to the surface tension of the water in the capillary pore system. This circumferential contraction progressed until approximately 200 min had elapsed.

At 200 min, the ring began to expand again. This trend continued until approximately 300 min had elapsed, indicating that the sporadic pressure release over this period caused the mortar to expand. After 300 min, the ring began to contract again significantly. This contraction progressed until approximately 500 min into the test, when the measured strains in the circumferential direction stabilized. The contraction was believed to have resulted from chemical shrinkage of the mortar material. The reason for this hypothesis is described in more detail as other tests are described. The constant strain starting at 500 min indicated that the chemical reactions in the mortar slow down at this time. At approximately 900 min, the ring began contracting significantly again. This trend continued until the end of the test, indicating continued chemical shrinkage.

The data from all seven strain gages became quite significant when compared with the capillary pore pressure data in Figure 7 obtained simultaneously. As the capillary pore pressure dropped throughout the first 200 min, all gages indicated significant shrinkage in the mortar. Shortly after 200 min, the capillary pore pressure began to increase abruptly. This change in pore pressure was reflected in the circumferential strain gage measurements, which indicated the mortar expanded from 200 until approximately 300 min. At about 300 min, the capillary pore pressure again began to increase abruptly. This pressure increase was accompanied by an expansion in the longitudinal direction and a relatively brief expansion in the circumferential direction. The pore pressure recovered to a zero value soon after the increase began but stabilized at a positive value of approximately 1.2 kPa. Because the capillary pressure recovery has been interpreted to indicate a breakdown of the continuity of water in the pore system,[16] the pressure was expected to equilibrate at zero; the reason for this discrepancy is uncertain. In subsequent tests, the capillary pore pressure did stabilize at zero. The development of pressure in the capillary pore system generally followed the trends described in the following discussion.

The capillary pore pressure measurements were expected to follow the three successive trends presented in Figure 8. In this figure, small vacuum pressures are developed in period 1 because of surface tension forces at the interfaces between the mortar particles and water. These forces increase significantly during period 2, when the menisci between mortar particles develop
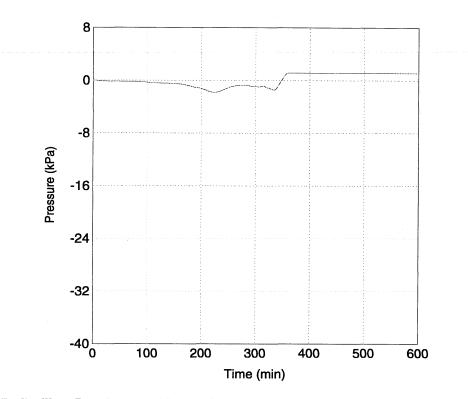
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Figure 7. Capillary Pore Pressure Measured as Function of Time During Mortar Curing (Test 1)
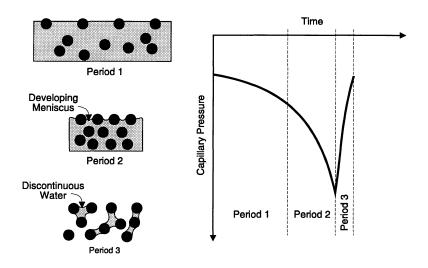

Figure 8. Three Major Periods of Development of Capillary Pore Pressure

very small radii. The capillary pore pressure is therefore moving toward a maximum vacuum pressure, called the breakthrough pressure, during period 2 as the mortar particles are brought closer together. Finally, in period 3, the capillary pore pressure increases quickly, recovering to a value near zero when it reaches equilibrium. The pressure recovery is often erratic in experimental data because of the lodging of solids in the pressure probe. The mortar continues to

11

hydrate and shrink after the pressure recovery, but these changes are not reflected in the capillary pore pressure measurement. In fact, the capillary pressure remains approximately constant with time after the pressure recovery. This description of the mechanism of plastic shrinkage as related to capillary pore pressure development was proposed by Wittman[7] and expanded upon by Radocea.[16]

Test 3

Test 3 allowed us to evaluate further the apparatus and procedure we developed in Test 1. Changing one element of the procedure, we did not apply lubricant to the walls of the ring mold. The circumferential strain data were affected significantly by this change (as shown in Figure 9), exhibiting positive strains when negative strains were expected because of shrinkage of the mortar. As further tests showed, this phenomenon occurred only when lubricant was not applied to the mold walls. We believe that these positive strains resulted from the adhesion of the mortar to the outer wall of the ring mold, which constrained the mortar and forced the inner ring of the mold to expand as curing progressed. Adhesion at the outer wall probably varied, causing the discrepancies in the data collected from the four strain gages.
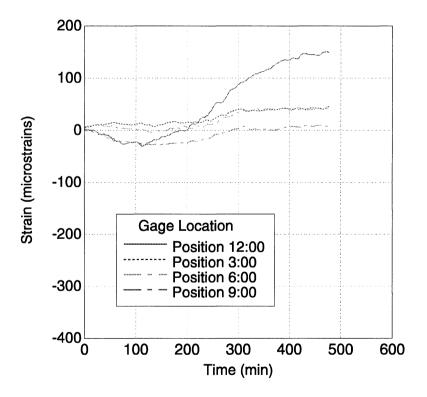

Figure 9. Circumferential Strains (Test 3)

12

The capillary pore pressure developed in the same three-part process observed in Test 1, as shown in Figure 10. This time, however, the second period of pressure development displayed a discontinuity. This was probably attributable to cement entering and clogging the tip of the probe, which was inserted to a depth of 23 mm for this test. Periods 1 and 2 of the pressure development lasted longer than in Test 1. This increased time was expected with the deeper insertion of the probe tip. The pressure recovery was smooth and returned to approximately zero, indicating that any blockage had been dislodged and the pressure transducer was responding properly. The breakthrough pressure was significantly greater than in Test 1, again because of the deeper insertion of the probe.

For this test, the temperature of the concrete was monitored at the mid-radius of the mold and at the interior and exterior walls of the inner PVC ring using thermocouples. These temperatures were quite stable, fluctuating around 22°C, indicating that strain measurements were not resulting from temperature gradients in the materials developing from the hydration reactions.
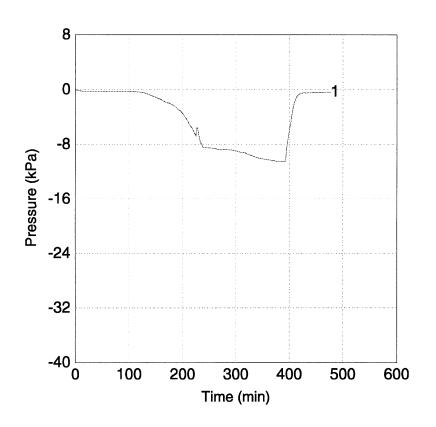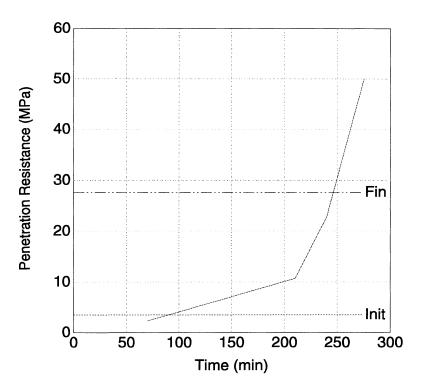

Figure 10. Capillary Pore Pressure (Test 3)

Tests 4 and 5

Figures 11 through 16 present the data collected during Tests 4 and 5. These tests had consistencies that made them interesting to compare. Both included silica fume in the mix but
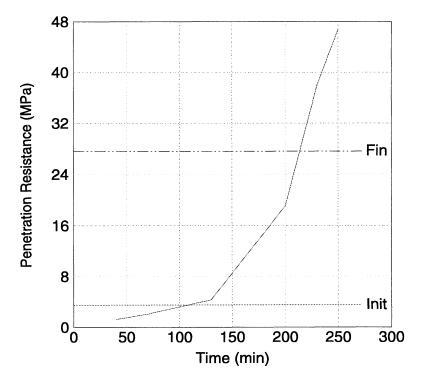
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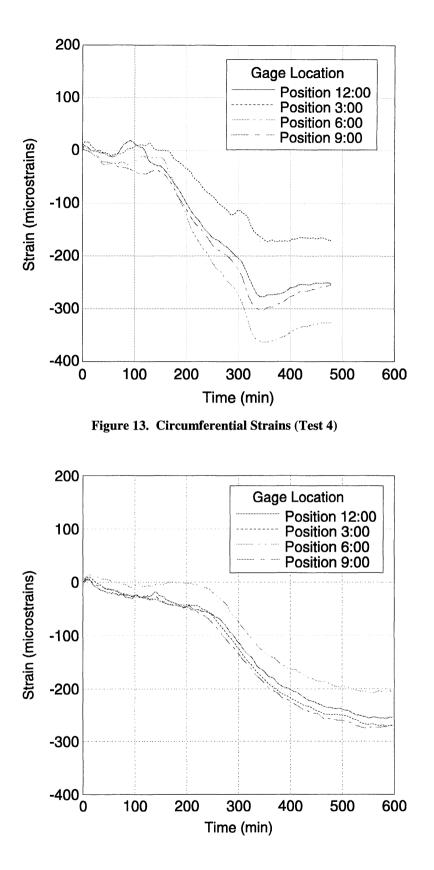**Figure 11. Penetration Resistance (Test 4)**

Figure 12. Penetration Resistance (Test 5)

14

Figure 13. Circumferential Strains (Test 4)

Figure 14. Circumferential Strains (Test 5)

15

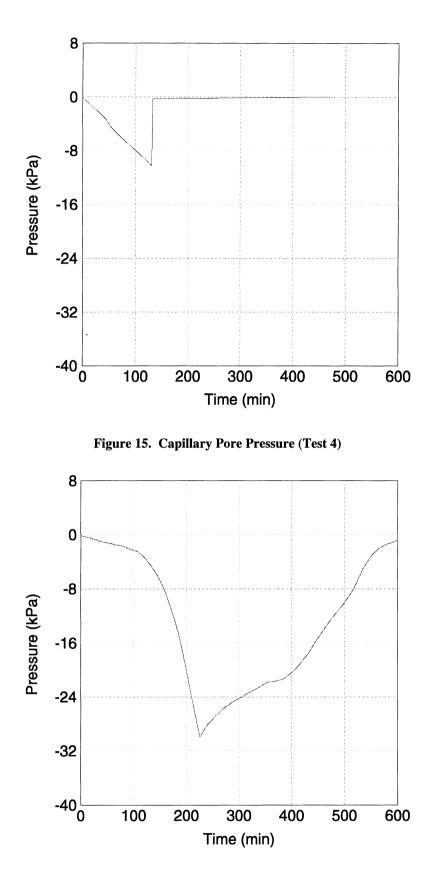**Figure 15. Capillary Pore Pressure (Test 4)**

Figure 16. Capillary Pore Pressure (Test 5)

16

had different w/cm and different quantities of HRWRA. High capillary pore pressures and large strains were expected in comparison with the first two tests, since silica fume is suspected to increase shrinkage and capillary pressures because of its very fine particle size.

After reviewing data from the previous tests, we decided that information regarding the time of set of the mixtures would be beneficial in interpreting the strain and pressure data. Figures 11 and 12 show the results of the penetration resistance tests (ASTM C 403) conducted in Tests 4 and 5. The mixtures reached initial set, defined as 3.5 MPa, at approximately 90 and 120 min, respectively. Initial set is considered the latest time at which true plastic cracking can occur. A final set of 27.6 MPa was reached in Tests 4 and 5 at 245 and 215 min, respectively.

The strain data presented in Figures 13 and 14 have three distinct trends as time progresses. In both cases, there is an initial slow rate of shrinkage, a subsequent high rate of shrinkage, and a third period when the mortar stabilizes and stops shrinking. These tests were run for shorter periods than in Test 1, in which this period of stability was followed by continued shrinkage. These three periods can be distinguished because of the interplay of physical and chemical phenomena in the mortar.

In the initial period of slowly developing shrinkage, the dominant phenomenon that causes the mortar to contract is the physical evaporation of water, which results in increasing capillary pore pressure and decreasing volume. Chemical reactions do not play a major role in mortar shrinkage during this period. This is known from measurements of the rate of heat evolution,[17] which indicate that few exothermic reactions take place in this interval. The second period, which is characterized by a high rate of shrinkage, is indicative of the chemical shrinkage resulting from the rapid hydration of cement in the mortar. In Tests 4 and 5, the onset of the second period occurred after the initial setting times of 90 and 120 min, respectively. This shrinkage takes place because the reactants in the mortar occupy more volume than the reaction products. This chemical shrinkage could be predicted by the relatively high heat of evolution expected during this interval. Finally, the chemical reactions in the mortar slow down and shrinkage ceases for a period of time. It is probable that the intervals between events are different for the two tests because of the differences in the mix design.

The graphs of pressure development with time (Figures 15 and 16) display the three basic periods defined earlier in this section. The graphs are similar in that the rate of pressure development is much higher during the first two periods than in the previous two tests. This distinction can be attributed to the addition of silica fume and HRWRA. It is suspected that Test 5 displays much greater vacuum pressures than Test 4 because of the lower w/cm and higher HRWRA dosage used. This hypothesis will be tested in future experiments. The pressure recovery is pronounced in Test 4 and much slower in Test 5. Experience has shown that the latter result is produced by clogging of the probe orifice with particulate matter from the mortar. If no clogging had taken place, the recovery periods would have probably appeared much more similar.

In general, the results of Tests 4 and 5 confirmed that the addition of silica fume and HRWRA to concrete results in more rapid development of capillary pore pressures and higher

shrinkage strains. However, breakthrough pressures were reached well after initial set of the mortar and no plastic cracking was noted. Current theory indicates that plastic shrinkage cracking would occur in situations where the capillary pressures develop rapidly in advance of the initial set. In future experiments, the goal will be to simulate conditions that result in the development of high vacuum pressures before initial set to confirm the relation between capillary pore pressure and plastic shrinkage cracking.

CONCLUSIONS

The results show that the experimental equipment can monitor capillary pore pressure and shrinkage strains that develop in hydraulic cement-based materials in the early ages after mixing. The behavior of capillary pore pressure in these tests followed trends reported by earlier investigators. The rate of development and magnitude of these pressures were affected by the particle size of the cementitious materials and the use of HRWRA. The shrinkage behaviors noted were related to capillary pore pressure development and the setting and hardening of the materials.

It is believed that plastic shrinkage cracking occurs as a result of unique interactions between these physical-chemical processes as they are affected by variations in environmental conditions and material properties. The ability to monitor these physical parameters thus permits investigation of these interrelationships to develop a better understanding of the phenomenon of plastic shrinkage cracking of concrete materials.

RECOMMENDATION

The equipment described in this study should be used in future research to investigate the effects of factors that influence capillary pore pressure and plastic shrinkage cracking of concrete. The factors investigated should include environmental and cuing conditions, materials properties (in particular, fineness of cementitious materials), and the use of HRWRA and other chemical admixtures.

ACKNOWLEDGMENTS

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