

Viscoelastic Behavior of Concrete Containing Super Absorbent Polymers

by E.A.B. Koenders, H.W.M. van der Ham and K. van Breugel

Synopsis: Concrete mixtures, having a water/cement ratio below 0.4, may exhibit a considerable autogenous shrinkage induced by internal drying of the capillary pore structure. In order to compete with this issue and to avoid or compensate for the development of autogenous shrinkage of concrete, either the mix proportions have to be adapted or additional (internal) water has to be supplied with emphasis on the moisture state of the capillary pore system. Until recently, one of the most frequently used methods used to retain internal self-desiccation of concretes was by adding water saturated porous light weight coarse aggregates (i.e. Lytag) or wood pulp fibers to the cementitious matrix. One of the latest innovations in this area is the addition of shrinkage reducing additives such as Super Absorbent Polymers (SAP). In order to examine the pros and cons of SAP addition to a concrete mix, an extensive experimental programme considering eight different concrete mixtures have been tested at Delft University of Technology. It is investigated how the Super Absorbent Polymers influence the mechanical and viscoelastic properties of hardening concrete. Experiments are performed for water/cement ratios of 0.32, 0.39 and 0.5, for Portland cement as well as Blast Furnace Slag cement, with addition of three different percentages of SAP, i.e. 1, 1.5 and 2 kg/m³ (1.68, 2.53 and 3.37 lb/yd³). The mixtures are tested at isothermal conditions of 20 °C and the early-age autogenous shrinkage strains are measured over a testing period of about 300 hours. Besides, the tensile strength, compressive strength, the elastic modulus and the creep strains have been measured for the different mixtures as well. The tensile, compressive strength and elastic modulus are tested at 28 days of age. The early age creep of the mixtures was measured from prisms and tested under a sustained compressive load of 40% of the compressive strength and were loaded at an age of 3 and 7 days. In this paper, the results of the experimental program are described in detail. A significant effect of the reduction of autogenous shrinkage due to SAP addition was observed. However, results also show that SAP affects the tensile and compressive strength and the viscoelastic properties like elastic modulus and the early age creep.

Keywords: early-age concrete, super absorbent polymers (SAP), viscoelastic properties

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INTRODUCTION

Autogenous shrinkage of concrete is one of the materials' most unexpected cause of cracking during the early stage of hardening of concrete elements. Autogenous shrinkage occurs if the actual level of water in the pore system does not balance the volume of capillary pore water needed to achieve entire cement hydration. In other words, if there is insufficient water in the capillary pore system to hydrate all binder material, self-desiccation of the concrete will occur. As a result of this, and depending on the pore size distribution of the system, capillary contraction forces will develop that act on the internal pore wall area. This particular mechanism associates with an external volume reduction and is called autogenous shrinkage. In order to avoid autogenous shrinkage of concrete the mix proportions of concrete have to be adapted with emphasis on the moisture state in the capillary pore system. Until recently, one of the most frequently used methods used to retain the internal self-desiccation of the concretes was by adding water saturated porous light weight coarse aggregates (i.e. Lytag) or wood pulp fibers to the cementitious matrix by replacing certain percentages of the aggregate fractions. Due to the addition of additional water stored initially in the porous clay particles and released during hardening, more moisture will be available in the pore system during hydration, leading to lower capillary forces, and with this, to a less autogenous shrinkage. A state of the art (STAR) report on this issue has been prepared by the RILEM TC 196-ICC (Kovler and Jensen 2007) on Internal Curing of Concrete. One of the latest innovations in this respect is the addition of Super Absorbent Polymers (SAP). Super Absorbent Polymers (Fig. 1) can be used to mitigate autogenous shrinkage by means of internal curing via a mechanism of water binding and water releasing polymers. For this special kind of internal curing material a STAR report is currently under development being one of the main deliverables of the RILEM TC-SAP¹. SAPs are added to the concrete during the mixing stage bringing in an additional volume of hydration water into the mixture. The release of the water takes place during early hydration fostered by the under pressures developing in the capillary pore system. In order to become more insight in the effectiveness of Super Absorbent Polymers regarding its potential to reduce autogenous shrinkage an extended experimental programme has been conducted at Delft University of Technology in The Netherlands (Fig. 2). The program also addresses the effect of SAP on the viscoelastic properties of concrete. In total, eight different concrete mixtures are tested were three are reference mixtures without polymers and five are mixtures containing SAP. The mix design, the experimental program, and the test results are provided in this paper.

MIX DESIGN

Within the research project provided in this paper, eight different mixtures have been tested all having different characteristics with respect to SAP. A detailed description of the mix proportions is presented in detail in Table 1. The eight mixtures are based on three reference mixtures (indicated by REF) that do not include SAP. The other mixtures include different amounts of the Super Absorbent Polymers, i.e. 1, 1.5, and 2 kg/m³ (1.68, 2.53 and 3.37 lb/yd³), and are added with respect to these reference mixtures. In order to study the influence of the polymers on viscoelastic properties these mixtures are tested and results are compared with the plain reference mixtures. The reference mixtures have been used in Delft research projects before, i.e. such as in previously research conducted by (Koenders 1997; Lokhorst 2001; Sule 2003; Czerny 2004). The mechanism of SAP addition into concrete mixtures requires balancing the water uptake from the initial mix composition. The addition of polymers is affecting the initial water/cement ratio and should be corrected for. This leads to an increase of the amount of mixing water in the

¹ Mechtcherine and Reinhardt, State of the Art Report, RILEM TC SAP-SAP Committee, Under preparation, 2010.

concrete that compensates for the influence of the polymers on the workability. The reasoning behind the selection of the eight different mixtures studied in this research project is based on the fact that these mixtures cover a wide range of concretes frequently used in practice. It shows the effect of SAP on the viscoelastic properties. Therefore, three different types cements were selected, i.e. Portland cement - coarse and fine - and Blast furnace slag cement, which are either applied as single binders or as a blended binder composition. Besides this, the affect of SAP using a silica fume-based mixture is also selected as one of the eight mixtures. The mixtures cover a wide range of water/cement ratios ranging from 0.32 up to 0.5. With respect to the mixing water, the additional compensation water needed because of SAP turned out to lead to an additional amount of 8.3 liter water per kg of SAP. This had to be added to the mixtures which resulted in a relatively higher “real” water/cement ratio (see also Table 1). A detailed overview of the amount of extra water added per unit of SAP particles is provided in Table 2.

MIX PROCEDURE

In comparison with the regular mix procedure, the addition of super absorbent polymers to a concrete mixture requires an adjustment of the sequence and duration of the different mixing stages per constituent. Mixing SAP through the mixtures has to be done separately from the regular mix ingredients, as well as mixing the extra water through the concrete mix. Van der Ham developed the following procedure for mixing SAP-based mixtures:

Mix procedure (see Van der Ham, 2009):

Prepare mixer;

Mix sand and gravel for 1 minute;

Add dry polymers and mix for 2 minutes;

Add cement and mix for 1 minute;

Add water and additives and mix for 1.5 min.

In order to avoid flocculation of the polymers in the fresh mixture, and in order to avoid an inhomogeneous distribution of the polymers throughout the mixture, the polymers are added to the sand-gravel mix in a dry configuration. The polymers are considered to absorb all the extra water added to the mix for compensation of the water uptake caused by SAP. This means that in potential more water is available in the mixture (stored in SAP), which may release during cement hydration and helps to reduce the autogenous shrinkage by avoiding internal drying, i.e. self-desiccation. The release of the extra water during hardening will affect the actual level of water in the capillary pores, viz. the degree of saturation of the pore system. As a result of this, it will affect the autogenous shrinkage and other viscoelastic properties as well.

TESTING PROGRAM AND METHODS

For each of the eight mixtures, the development of tensile strength, the compressive strength, the elastic modulus and the autogenous shrinkage are measured with time. Besides this, also creep loaded under sustained compression was measured from two series of prisms placed on top of each other, and loaded after three and seven days of hardening. A schematic overview of the testing program is provided in Fig. 2. The tensile strength and compressive strength are measured from cubes $0.15 \times 0.15 \times 0.15 \text{ m}^3$ ($0.164 \times 0.164 \times 0.164 \text{ yd}^3$) (see Fig. 3, left). The elastic modulus is measured from prisms with dimensions $0.1 \times 0.1 \times 0.4 \text{ m}^3$ ($0.109 \times 0.109 \times 0.109 \text{ yd}^3$) (see Fig. 3, right) and the autogenous shrinkage is measured simultaneously from three parallel operating ADTM devices (Autogenous Deformation Testing Machine) as shown in Fig. 4a, b and c and as described in (Van der Ham 2009). All moulds are connected to a cryostat unit which enables the possibility to control the temperature regime during hardening via thermocouples actively. In this testing program all specimens are hardened under isothermal and sealed conditions at 20°C . After mixing the concrete was directly cast into the temperature controlled moulds (Fig. 3 and Fig. 4) and covered by a sealing foil. The temperature control was performed continuously during the hardening stage by pc-computer. The test specimens were demolded at the moment of testing, i.e. after three and seven days of hardening. All test results (tensile splitting strength, compressive strength, elastic modulus and autogenous shrinkage) were measured three times, from three different specimens. The results are provided in the figures as a mean value of these three specimens. An exception concerns the creep tests. Results measured from the creep tests are determined from two specimens placed on top of each other. The creep strain of each specimen is measured by a configuration of four linear variable differential transducers (LVDT), each measuring the strains at one side of the specimen (Fig. 5). The creep strains are compensated for autogenous shrinkage and temperature variations during testing by measuring the strains from an unloaded sealed dummy specimen.

TEST RESULTS

Tensile, compressive strength and elastic modulus

In Fig. 6, left, results are presented for the effect of SAP addition on the splitting tensile, compressive and the elastic modulus after 28 days of hardening. The results represent the mixtures indicated by:

- 32A100: water/cement ratio = 0.32 and SAP addition = 1.5 kg/m³ (1.68 lb/yd³)
- 39A100: water/cement ratio = 0.39 and SAP addition = 1.5 kg/m³ (1.68 lb/yd³)
- 50A100: water/cement ratio = 0.50 and SAP addition = 1.5 kg/m³ (1.68 lb/yd³)

From the results provided in Fig. 6, it can be observed that for a water/cement ratio (wcr) of 0.5 SAP addition leads to a small decrease of the tensile strength ($\pm 1\%$) and small increase of the compressive strength ($\pm 2\%$). The increase is most pronounced for the elastic modulus, viz. approx. 7%. However, for the wcr 0.39 and wcr 0.32 mixtures opposite results were found. The compressive strength reduces with about 3% and 8% respectively. The tensile strength suffers from SAP addition, i.e. about 8% reduction for the wcr 0.39 and about 9% reduction for the wcr 0.32 mixtures after 28 days of age. The effect of SAP addition for the elastic modulus shows a reduction of about 10 % for the wcr 0.39 mix and a reduction of about 8% for the wcr 0.32 mix.

Autogenous shrinkage

When coming down to the main reason for the SAP addition to the concrete mixtures, emphasis was on the ability of SAP to limit internal drying by internal curing and to reduce autogenous shrinkage. Based on the similar reference mixtures as used in the previous section for testing the tensile strength, compressive strength and elastic modulus the autogenous shrinkage reduction caused by SAP addition is measured for mixtures containing 1, 1.5 and 2 kg SAP per m³ (1.68, 2.53 and 3.37 lb/yd³). When considering the results provided in Fig. 6 (right), it can be observed that all mixtures containing 1.5 kg/m³ (2.53 lb/yd³) SAP, a significant reduction of the autogenous shrinkage was obtained. From Fig. 6 it can also be observed that for the wcr 0.39 and wcr 0.32 mixtures, adding this amount of SAP leads to an overall reduction of the autogenous shrinkage of about 50% for all three ages. For the mixture with a water/cement ratio of 0.5, the influence is very substantial and does not lead to a reduction of the shrinkage, but, on the contrary, to a significant swelling of more than 50% after 300 hrs of hardening, i.e. approx. 1.5 times its original swelling. This can be attributed to the fact that both the relatively high water in the mix caused by the water/cement ratio of 0.5 in combination to the extra water addition due to SAP addition. Both contributions lead to a relatively high amount of water in the mix causing swelling of the concrete. In Fig. 7 a more detailed overview of the autogenous shrinkage is given for different amounts of SAP, i.e. wcr 0.5, 0.39, and 0.32 with SAP content 1.0 kg/m³ (=67) (1.68 lb/yd³), 1.5 kg/m³ (=100) (2.52 lb/yd³), and 2 kg/m³ (=133) (3.37 lb/yd³). From the results it can be observed that, in general, adding SAP to a mixture associates with a reduction of the autogenous shrinkage.

Creep

For the mixtures containing SAP, creep tests have been conducted as well. The creep tests show the development of creep strains with time, while under a sustained compressive load. In general, the magnitude of the strains is depending on the compressive force applied to the specimen. In this research 40% of the actual compressive strength was applied to the specimen. Since the strength of the eight different mixtures at loading (3 or 7 days) was different, the absolute value of the compressive force applied to the creep specimens was not equal as well. However, all mixtures have experienced a 40% compressive stress relative to their actual strength. To make the results of the different creep tests comparable, creep coefficients have been determined for all tests. The creep coefficient can be calculated from the measured creep strains and from the elastic strain that develop during loading of the specimen. The creep coefficient is considered the ratio between the creep strain at sustained compressive loading and the elastic strain at loading (see Eq. 1):

$$\phi(t, t_c) = \frac{\varepsilon_c(t)}{\varepsilon_e} \quad (1)$$

where:

- $\varepsilon_c(t)$ creep strain after t hours of sustained compressive loading
- ε_e elastic strain corresponding to the strain after imposing the load

For the reference mixture with a water/cement ratio of 0.5 (50REF), the creep strain measured under a constant compressive loading is presented in Fig. 8. In this figure, the elastic strain of the specimen measured during loading ϵ_e , and the subsequent creep strain $\epsilon_c(t)$ are indicated as well. For a selection of mixtures as provided in Table 1 the results have been recalculated to creep coefficients. The development of the creep coefficients are presented in Fig. 9. Results are presented for the mixtures with the following characteristics: wcr 0.5, 0.39, and 0.32, SAP content 1.0 kg/m³ (=67) (1.68 lb/yd³), 1.5 kg/m³ (=100) (2.52 lb/yd³), and 2 kg/m³ (=133) (3.37 lb/yd³), and loaded after 3 and 7 days of age. The results of the mixtures containing SAP are compared with the reference mixtures (indicated by REF) containing no SAP (see also Table 1). The left column of Fig. 9 shows the creep coefficients for specimen loaded after three days of hardening. The column at the right hand side shows the creep coefficients for specimen loaded after seven days of hardening. The results show the creep coefficients for the mixtures containing SAP relative to the reference mixtures without SAP. From the figures it can be observed that, depending on the age at loading and the amount of SAP, adding Super Absorbent Polymers results in a higher creep coefficient. Whenever comparing the results of the creep tests loaded after three days to those loaded after seven days, it can be seen that due to the ongoing hydration of the specimen, the creep coefficient is lower for the specimen loaded after seven days. However, for the specimen loaded after seven days of hardening, the creep coefficient is still relatively high for those specimens containing Super Absorbent Polymers.

CONCLUSIONS

Super Absorbent Polymers (SAP) are added to concrete mixtures to examine the effectiveness of SAP with respect to the ability to reduce the autogenous shrinkage. Besides this, the tensile, compressive strength and elastic modulus of the mixtures are tested on their sensitiveness towards SAP addition. For the tested mixtures (wcr 0.32, 0.39 and 0.5) the amount of SAP added was 1, 1.5, and 2 kg/m³ (1.68, 2.53, and 3.37 lb/yd³). From the limited number of tests conducted within the scope of this research it can be concluded that SAP reduces autogenous shrinkage substantially, i.e. approx. 50 % after 300 hrs of hardening by 1.5 kg/m³ (2.52 lb/yd³). Whether these results are statistically significant can be evaluated by a t-test method but this is not considered in this paper. Besides the reduction of autogenous shrinkage, the addition of Super Absorbent Polymers to concrete mixtures, affects almost all mechanical and viscoelastic properties of the concrete tested. This can either be positive or negative, depending on the water/cement ratio. For the tested mixtures, the results show a reduction up to 10% for the tensile and compressive strength as well as for the elastic modulus. For a water/cement ratio of 0.5, the results are more diffuse. The elastic modulus increased about 7 % and the compressive strength 3 % whereas the tensile strength reduced by about 1 %. In addition to these findings, adding Super Absorbent Polymers to concrete results in higher creep coefficients. To conclude, based on the tests results reported in this paper it turned out that adding SAP to a concrete has a substantial reducing effect on autogenous shrinkage. However, it also affects the mechanical and viscoelastic properties such as tensile and compressive strength and the elastic modules and creep.

ACKNOWLEDGEMENTS

The financial support of the Delft Cluster and the Dutch Ministry of Traffic, Public Works and Water Management and the Applied Research Organization TNO is greatly appreciated.

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Table 1—Mix proportions of reference and SAP-based mixtures

Mix constituent	VM	32REF	39REF	50REF	32A67	32A100	32A133	39A100	50A100	
Water	1000	125.4	156.0	175.0	123.7	123.1	122.5	153.7	172.5	kg/m ³
CEM III/B 42.5 LH HS	3150	237.0	300.0	-	233.7	232.6	231.6	295.5	-	kg/m ³
CEM I 52.5 R	3150	238.0	100.0	-	234.7	233.6	232.6	98.5	-	kg/m ³
CEM I 32.5 R	3150	-	-	350.0	-	-	-	-	345.0	kg/m ³
Sand 0-4 mm	2650	796.5	830.0	1011.5	785.4	781.7	778.3	817.6	996.9	kg/m ³
Aggregate 4-16 mm	2650	973.5	975.0	-	960.0	955.5	951.3	960.4	-	kg/m ³
Aggregate 4-8 mm	2650	-	-	827.6	-	-	-	-	815.7	kg/m ³
Addiment BV1	1000	1.0	1.6	-	1.0	1.0	1.0	1.6	-	kg/m ³
Addiment FM 951	1000	9.5	4.8	-	9.4	9.3	9.3	4.7	-	kg/m ³
Silica fume slurry (50% water)	1000	50.0	-	-	49.3	49.1	48.9	-	-	kg/m ³
Polymer powder	1000	-	-	-	1.0	1.50	2.00	1.50	1.50	kg/m ³
Extra water	1000	-	-	-	8.3	12.50	16.67	12.50	12.50	kg/m ³
Total mass		2430.9	2367.4	2364.1	2406.48	2399.85	2394.16	2345.99	2344.06	kg
Total volume		1.00	0.97	0.98	1.00	1.00	1.00	0.97	0.98	m ³

WCF original		0.32	0.39	0.50	0.32	0.32	0.32	0.39	0.50	-
WCF real		0.32	0.39	0.50	0.33	0.34	0.35	0.42	0.54	-

Table 2—SAP versus amount of extra water added to the mixture

	A67	A100	A133
SAP Polymer (powder)	1.0 kg/m ³	1.5 kg/m ³	2.0 kg/m ³
Extra water	8.3 kg/m ³	12.5 kg/m ³	16.7 kg/m ³

**Figure 1—From left to right two Super Absorbent Polymers, one unsaturated and one saturated (Jensen and Hansen 2001), 25 grams of unsaturated polymers and 630grams of water absorbed by 25 gram polymers.**

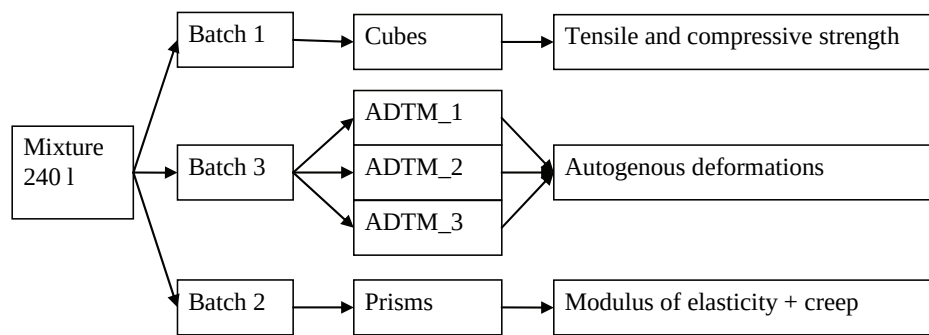


Figure 2—Schematic representation of the testing program.

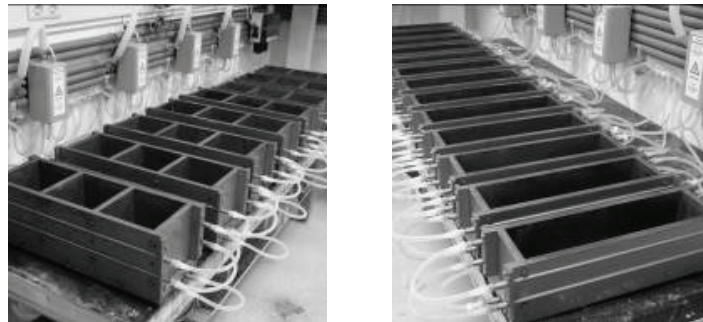
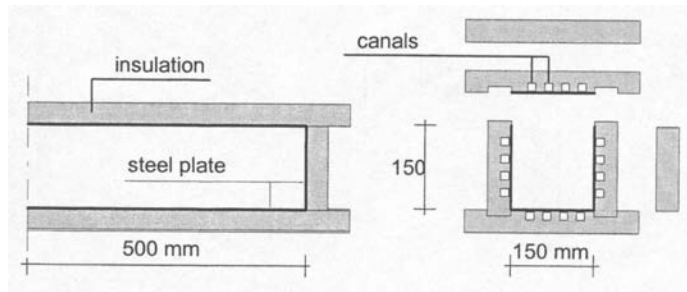


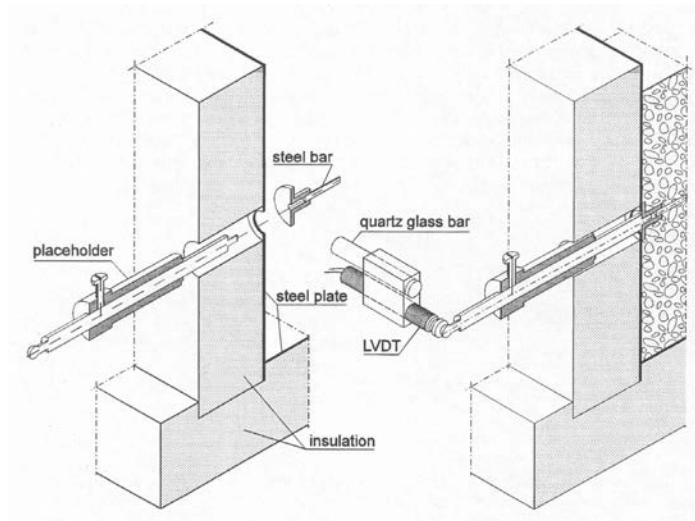
Figure 3—Left: Temperature controlled cube moulds for tensile and compressive strength testing; Right, temperature controlled prism moulds for elastic modulus testing.



4a: ADTM setup for autogenous shrinkage testing.



4b: Schematic drawing of ADTM design.



4c: Schematic drawing of LVDT configuration.

Figure 4—a: ADTM, b: Schematic drawing of ADTM-design, c: Schematic drawing of LVDT configuration.

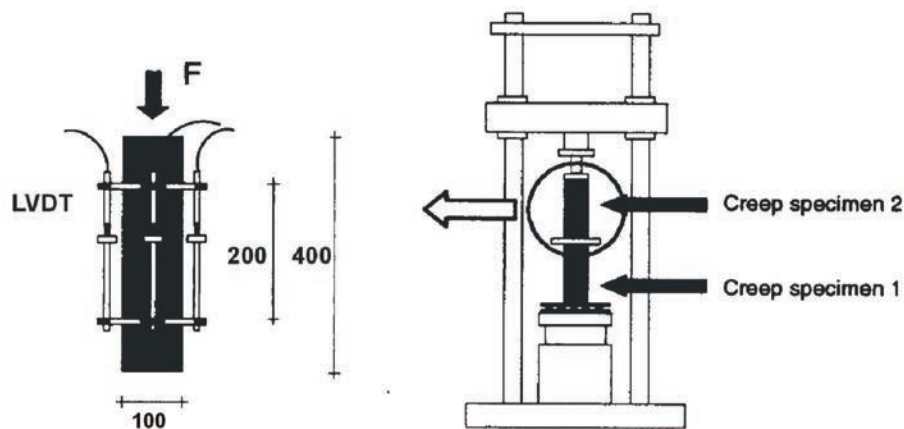


Figure 5—Schematic overview of the test setup for measuring the creep strains. Left: specimen with LVDT configuration, Right: test setup with two specimens placed on top of each other and tested simultaneously.

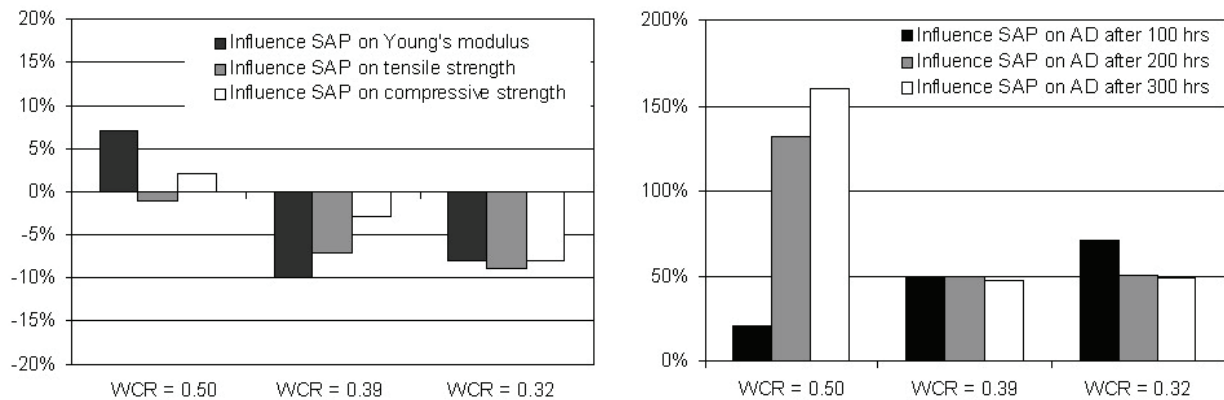


Figure 6—Left: Influence of SAP (1.5 kg/m³) on Elastic modulus, tensile and compressive strength after 28 days of hardening; Right: Influence of SAP (1.5 kg/m³) on autogenous shrinkage at three different ages, 100, 200 and 300 hrs respectively. Note: values larger than 100% means swelling of the specimen (see wcr = 0.50).

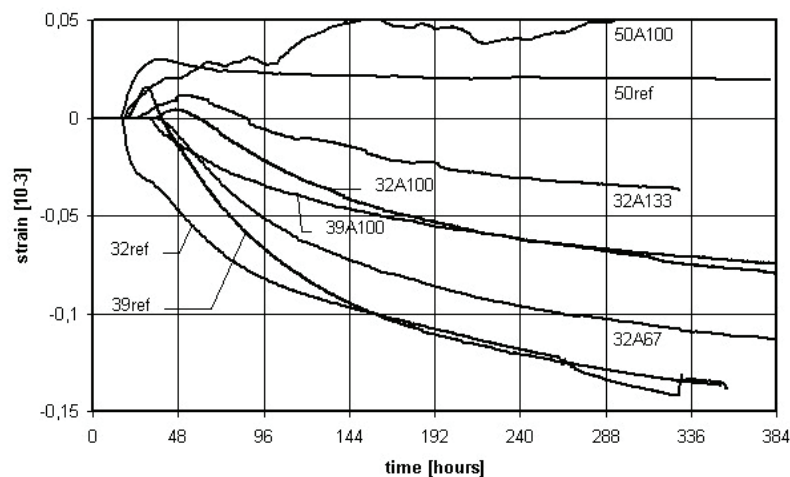


Figure 7—Autogenous shrinkage with and without addition of SAP.

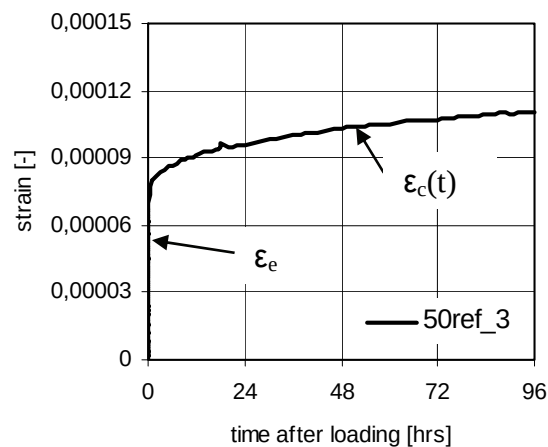
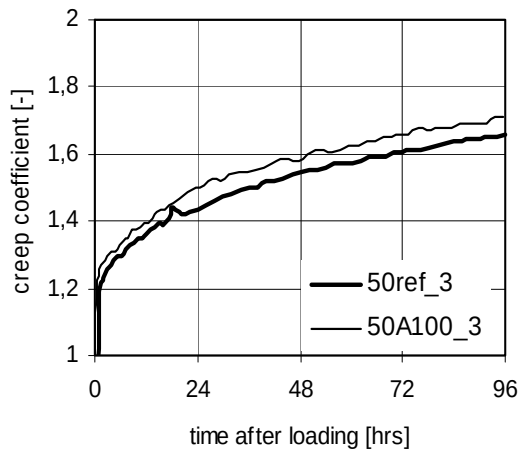


Figure 8—Creep strain measured from a 50REF mixture at 20°C, loaded after 3 days.



Explanatory notes w.r.t. the labeling:

50ref_3 = wcr 0.5, REF mixture, loaded after 3 days

50A100_3 = wcr 0.5, SAP containing mixture, 1.5 kg/m³ SAP added, loaded after 3 days.

32A67_7 = wcr 0.32, SAP containing mixture, 1 kg/m³ SAP added, loaded after 7 days.

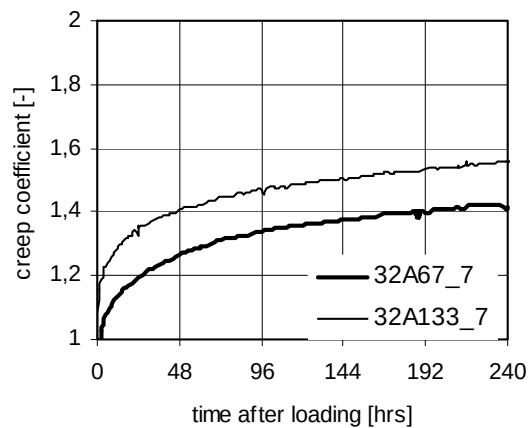
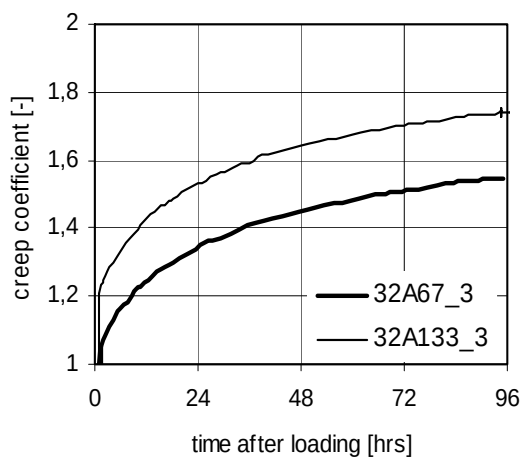
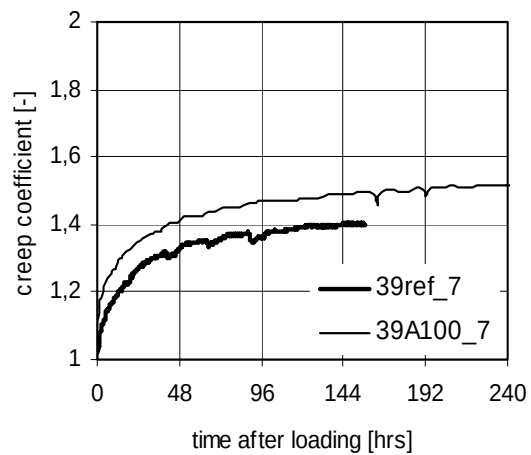
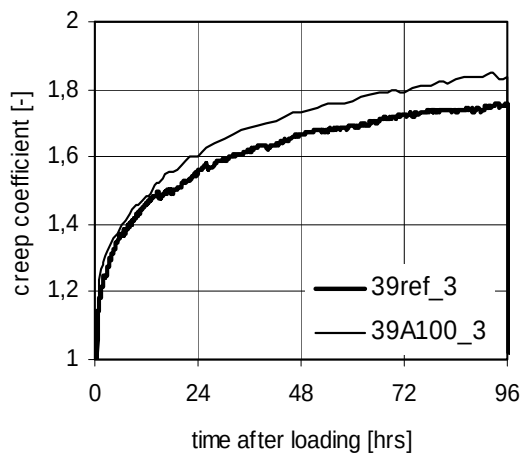


Figure 9—Development of creep coefficients, for different mixtures, loaded after 3 (left-) and 7 days (right column).

Water-Soluble Polymers as Self-Curing Agent in Silica Fume Portland Cement Mixes

by A.S. El-Dieb, T.A. El-Maaddawy and A.A.M. Mahmoud

Synopsis: Maintaining satisfactory moisture content in concrete during its early ages is very important to develop required properties. Retaining free water of the mixture for a longer period will have a beneficial effect similar to that of curing. Self-curing mixtures will be very beneficial especially in regions where water is not adequately available. Polymers in concrete have received considerable attention over the past two decades. This study investigates using laboratory synthesized water-soluble polymers: polyethylene glycol (PEG) and polyacrylamide (PAM) as self-curing agents and its effect on the degree of hydration, water absorption, permeable pores and microstructural characteristics of Portland cement mixtures without and with 8% silica fume replacement. Portland cement mixtures including PEG or PEG+PAM as self-curing agents showed a better quality compared to that of the non-cured mixtures. Mixtures incorporating 8% silica fume including a mixture of PEG and PAM as self-curing agent had a better quality compared to that of the mixture including only PEG especially at later ages.

Keywords: water-soluble polymer, self-curing agent, silica fume, hydration, water absorption, permeable pores, microstructure

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INTRODUCTION

The curing of concrete is an essential step in the concrete construction. According to the ACI 308R-01, Guide to Curing Concrete, the term “curing” is frequently used to describe the process by which hydraulic cement concrete matures and develops hardened properties over time as a result of the continued hydration of the cement in the presence of sufficient water and heat. The necessity of curing lies in the role of reducing water evaporation from concrete and maintaining satisfactory moisture content especially during early stages for the continuation of hydration of the cement, and consequently the development of cement microstructure, which will lead to better quality concrete and develop the desired properties. Nevertheless, good curing is not always practical in many cases. Mather (2001) and Bentz et al. (2005) raised the question whether there will be self-curing concrete. Several studies investigated the development of self-curing concrete (Dhir et al. 1994; Dhir et al. 1995; Dhir et al. 1996; Reinhardt and Weber 1998). In another investigation by Dhir et al. (1998), it was concluded that the concept of self-curing agents is to reduce the water evaporation from concrete, and hence increase the water retention capacity of the concrete compared to conventional concrete. It was found that water-soluble polymers can be used as self-curing agents in concrete (Dhir et al. 1998).

Curing of concrete plays a major role in developing the concrete microstructure and pore structure, and hence improves its durability and performance. The use of self-curing admixtures is very important from the point of view that water resources are getting valuable every day (i.e. each 1 cubic meter of concrete requires about 3 cubic meters of water for construction most of which is for curing). The benefit of self-curing admixtures is more significant in desert areas where water is not adequately available. The use of water-soluble polyethylene glycol as a self-curing agent in concrete mixtures without silica fume and its effect on water retention capacity, and hydration was investigated (El-Dieb 2007).

Previous investigations evaluated the performance of self-curing mixtures made with ordinary portland cement (OPC). The performance of mixtures including silica fume as supplementary cementing materials and self-curing agent has received little attention in previous studies. The aim of this investigation is to evaluate the use of water-soluble polymers as self-curing agent in Portland cement mixtures incorporating silica fume. In this investigation two types of water-soluble polymers, polyethylene glycol (PEG) and polyacrylamide (PAM), were investigated as self-curing agents.

In this study water retention, hydration, water absorption, permeable pores and microstructure of portland cement mixtures with and without silica fume incorporating self-curing agents were investigated. Performance of self-curing mixtures were evaluated and compared to mixtures continuously moist cured and air cured (i.e. no curing). Weight loss measurements with age were carried out in order to evaluate the water retention ability. Non-evaporable water at different ages was measured to evaluate the hydration. Percentage of Water absorption and permeable pores were measured with age as a durability index (Basheer et al. 2001; Türkmen 2003; De Beer 2005; Zhu and Bartos 2003). The development of the microstructure with age was investigated as well.

EXPERIMENTAL WORK

Materials

Ordinary Portland cement and silica fume were used in the study. Table 1 shows the laboratory analysis of the chemical composition for the materials. The main constituent variable parameters in this study were silica fume (8%

replacement) and two types of water-soluble polymers as self-curing agents (polyethylene glycol PEG and polyacrylamide PAM). The polymers were synthesized in the lab. Table 2 gives the main properties for both polymers.

Polyethylene-glycol (PEG) was used alone with a dosage of 0.02% by weight of cement. Polyacrylamide (PAM) was used in conjunction with PEG as a second alternative for self-curing agent. The dosage of PEG and PAM was 0.02% by weight of the cement, PEG dosage was 0.013% and that of PAM was 0.007%.

Specimens and testing

Figure 1 shows the different mixtures, curing regimes and testing used in the study. The mixtures were divided into two groups: one group for OPC mixtures without silica fume and the second group with 8% silica fume replacement. The water-to-cementitious materials (OPC + Silica fume if used) ratio used for all mixtures was 0.4. For the mixtures incorporating 8% silica fume as replacement of the cement, a polycarboxylic ether superplasticizer was used to maintain the same workability of the mixture similar to that of the mixture without silica fume.

For each mixture group, three mixtures were cast: one without self-curing agent (i.e. conventional mixture), the second includes PEG as self-curing agent (SC-1), and the third includes PEG+PAM as self-curing agent (SC-2). For conventional mixtures, not including self-curing agents, two curing regimes were used; continuous moist curing and no curing (i.e. specimens were left in air at an ambient temperature ranging between 25 and 30 °C (77 and 86 °F) and a relative humidity ranging from 55% to 65%). Mixtures without self-curing agents subjected to continuous moist curing and no curing regimes will be called conventional moist-cured and conventional non-cured mixtures, respectively, throughout the paper. Self-curing agents, the solid polymers, were dissolved in almost one-third of the mixing water which was added after first mixing with two-thirds of the mixing water. It should be noted that on dissolving PEG+PAM in the water it becomes slightly gelatinous in appearance. PEG did not change the consistency of the mixtures. For PEG+PAM polymers it was noticed that once the remaining water including polymers were added the mixture consistency was reduced and the mixture became more sticky, due to the very high ability of PAM in absorbing and retaining water. This observation was also reported by Sun and Xu (2008).

Weight loss with age was measured to evaluate the water retention of the mixtures. Cement paste weight loss was carried out by filling polypropylene containers with the mixture. Each container had an internal diameter of 120 mm, a height 90 mm, and a capacity of 1.0 litre. The containers were kept at a constant temperature of about 25 °C (77 °F) and a relative humidity of about 60% (i.e. natural drying conditions). The weight of the containers was measured after casting and at several time intervals up to 28 days of age to determine the weight loss with time.

Non-evaporable water was determined to evaluate the degree of hydration of the mixtures at several age intervals. The non-evaporable water was determined at several time intervals up to 28 days of age. At each age a specimen from each mixture was dried off in a 105 °C oven then weighed. The specimen was then burned in a muffle furnace at 1050 °C. The non-evaporable water was calculated as the sample weight loss relative to its dry weight (g/g).

Percentage of Water absorption and permeable pores tests were conducted according to the ASTM C642-97 at several age intervals up to 28 days. Samples of these tests were in the form of discs, each having a diameter of 100 mm and a thickness of 50 mm. These samples were cut from hardened cylinders at several age intervals up to 28 days.

RESULTS AND DISCUSSIONS

Water retention

Figure 2 (a) and (b) shows the weight loss under natural drying conditions with time due to the moisture evaporation for OPC mixtures without silica fume and OPC mixtures with 8% silica fume replacement, respectively. In both mixture groups, the mixtures without self-curing agents lost more water compared to mixtures including self-curing agents (SC-1 and SC-2). This indicates better water retention for self-curing mixtures.

Mixtures including PEG+PAM as self-curing agent showed better water retention (i.e. lower value in weight loss) compared to mixtures including only PEG as self-curing agent. This may be attributed to the ability of PAM to retain water compared to PEG. Water retention for the self-cured mixtures including silica fume was better than that of similar mixtures but without silica fume; this may be attributed to the fact that silica fume does not consume water at early ages due to its pozzolanic nature, thus more free water is available in the mixture to be held by the water absorbing polymers.

Hydration

The non-evaporable water (W_n) measured for self-curing mixtures was compared with conventional moist-cured and non-cured mixtures. Figure 3 (a) and (b) show the non-evaporable water measured at different ages for OPC mixtures and mixtures of OPC with 8% silica fume replacement, respectively. The degree of hydration is affected by the cementitious materials of the mixture (i.e. OPC or OPC with silica fume). Moist-cured mixtures yielded the highest degree of hydration as expected. Generally, the degree of hydration for the self-curing mixtures was higher than that of the non-cured OPC mixtures. This can be ascribed to the better water retention of the self-curing mixtures, as demonstrated by the lower weight loss.

The OPC mixtures SC-2, including PEG and PAM as self-curing agents, showed better hydration than mixtures SC-1, including only PEG as a self-curing agent, this may be attributed to the higher ability of PEG+PAM to retain water. The OPC mixtures with 8% silica fume replacement showed hydration similar to those of mixtures SC-1 and SC-2 mixtures. The slope of the curve of the SC-2 mixture with 8% silica fume at 28 days of age is higher than that of the SC-1 mixture with 8% silica fume which indicates that hydration and pozzolanic reaction is still progressing due to the availability of higher moisture inside the mixture compared to that of SC-1 mixture.

For OPC mixtures with and without 8% silica fume replacement, the no-curing condition resulted in a very low level of hydration especially at 28 days of age compared to those of the SC-1 and SC-2 mixtures. At early ages (i.e. 3 and 7 days), for OPC mixtures, the non-evaporable water for the non-cured mixture was slightly higher than those of the self-curing mixtures. This may be attributed to the fact that for the self-curing mixtures the water held by the polymers is released and consumed at later ages.

For OPC mixtures with 8% silica fume replacement, conventional non-cured mixtures had a lower level of hydration at all ages compared to SC-1 and SC-2 mixtures. At later ages, this difference increased. The lower level of hydration for conventional non-cured mixtures at all ages compared to self-curing mixtures may be attributed to the self-desiccation normally experienced with silica fume mixtures (McGrath 1989; Mjörnell 1994). This indicates that the self-curing agents are more effective when silica fume is incorporated in the mixture.

Water absorption and permeable pores

Figure 4 (a) and (b) show the percentage of water absorption with age relationships for OPC mixtures with and without 8% silica fume replacement, respectively. Absorption decreased with age for all mixtures except for the non-cured mixture with 8% silica fume replacement. The moist curing condition for both mixtures produced the lowest values especially at 28 days of age. Absorption values for mixtures with silica fume was lower than mixtures without silica fume. For OPC mixtures, both self-curing mixtures, SC-1 and SC-2, showed lower water absorption% compared to the non-cured mixture, also the values are up to 18% higher than that of moist curing regime.

For OPC with 8% silica fume replacement, both self-curing mixtures, SC-1 and SC-2, showed comparable values at all ages and better performance compared to conventional non-cured mixtures. In the conventional non-cured mixtures water absorption values showed slight increase at 14 and 28 days of age. This may be attributed to the increase of connected pores as a result of self desiccation of the mixture (McGrath 1989; Mjörnell 1994); the permeable pores measurement confirmed these results.

Permeable pores versus age for OPC mixtures with and without 8% silica fume replacement are shown in Fig. 5 (a) and (b) respectively. Permeable pores decreased with age for all mixtures, and moist curing for both mixtures produced the lowest values. Similar to water absorption values, permeable pores for mixtures with silica fume are less than those for mixtures without silica fume. For OPC mixtures, both self-curing mixtures, SC-1 and SC-2, showed lower permeable pores compared to conventional non-cured mixtures; also the values are higher within 16% than that of moist curing regime.

The permeable pores for OPC with 8% silica fume replacement and both self-curing mixtures, SC-1 and SC-2, were lower than the permeable pores for the conventional non-cured mixtures. Permeable pores for the conventional non-cured mixtures did not show much reduction with age and as previously explained for the hydration. It may be attributed to the self desiccation of the mixture resulting in increased connected pores (McGrath 1989; Mjörnell 1994). Permeable pores results are consistent with the water absorption% results.

The percentage of water absorption and permeable pores for all self-curing mixtures indicates better development of microstructure compared to those of the conventional non-cured mixtures. This may be attributed to the water retention of the self-curing mixtures and the continuation of hydration compared to the air cured mixtures.

Microstructure

Microstructure investigation of the OPC mixtures showed that moist curing exhibits dense microstructure compared to other curing regimes, owing to the better hydration due to the abundance of moisture. Figure 6 (a) and (b) are scanning electron microscope (SEM) micrographs of fractured conventional moist-cured and non-cured

mixtures at low and high magnification power showing dense microstructure of the conventional moist-cured mixtures compared to that of the conventional non-cured mixtures. For the conventional moist-cured mixtures, the C-S-H cross-links with the crystalline hydration products to form a discrete skeleton network. For the conventional non-cured mixtures, larger voids were observed compared to moist curing mixture. Also, for the conventional non-cured mixtures several microcracks with widths up to 5µm were observed

Figure 7 (a) and (b) show the SEM of OPC specimens self-cured, SC-1 including PEG and SC-2 including PEG+PAM. Can be observed that general microstructure for both mixtures were denser than that of the conventional non-cured mixtures and comparable to that of the conventional moist-cured mixtures. Similar to the observation of Dhir et al. 1996, crystalline hydration products such as $\text{Ca}(\text{OH})_2$ did not have obvious edges and corners. This observation was also noted by Sun and Xu 2008, when they examined polyacrylamide modified concrete. This may be attributed to the dense structure which does not allow $\text{Ca}(\text{OH})_2$ crystals to grow and be well formed. Also, very small microcracks with width ranging between 1µm to 2µm were observed, which are smaller in width compared to those observed in non-cured OPC mixtures.

Microstructural investigation of the OPC mixtures incorporating 8% silica fume as replacement showed that moist curing exhibited denser microstructure compared to other curing regimes and to OPC specimens. Figure 8 (a) and (b) show SEM micrographs of fractured conventional moist-cured and non-cured mixtures. It should be noted that $\text{Ca}(\text{OH})_2$ crystals are less compared to OPC mixtures, and its size is smaller as well. In moist curing dense microstructure and discrete disconnected pores were observed, which confirms the results of water absorption and permeable pores. Hydration products were observed around silica fume particles indicating the continuation of the reactions (i.e. hydration and pozzolanic). On the other hand, the conventional non-cured mixtures exhibited a less dense microstructure and some silica fume particles were observed without any hydration products around it, this is due to the lack of sufficient moisture inside the specimen. Also, the conventional non-cured mixtures, several wide microcracks with width close to 10µm were observed, this is due to self desiccation of the mixture due to the presence of silica fume (McGrath 1989; Mjörnell 1994). These microcracks are responsible for the higher water absorption% and permeable pore% for the non-cured mixtures including silica fume.

Scanning Electron micrographs of self-curing specimens of OPC mixtures with silica fume are shown in Fig. 9 (a) and (b). Self-curing mixtures exhibited microstructure denser than that of the conventional non-cured mixtures. Hydration products were observed around silica fume particles unlike the conventional non-cured mixtures, indicating the continuation of hydration and pozzolanic reaction of silica fume. Few microcracks with widths up to 5µm were observed in self-curing specimens; this may be attributed to the self-desiccation effect of silica fume which is slightly offset by the water retention of self-curing agents.

These observations demonstrate good performance of self-curing agents in OPC mixtures with and without 8% silica fume replacement. Self-curing mixtures exhibits denser microstructure compared to the conventional non-cured mixtures, the existence of fewer microcracks with smaller widths, and a reduction in the size of crystalline hydration products.

CONCLUSIONS

This paper reports on the potential use of laboratory synthesized water-soluble polymers; polyethylene glycol (PEG) and polyacrylamide (PAM) as self-curing agents. Based on test results, the following conclusions could be drawn:

- Effectiveness of the self-curing agents is affected by the cementitious type used (i.e. OPC or OPC+silica fume).
- The use of high molecular weight water-soluble polymers (PAM) together with low molecular weight polymers (PEG) had better performance in retaining water for longer period and releasing it slowly with time than using PEG only.
- The use of high molecular weight polymers (PAM) as a self-curing agent reduced the workability of the mixture.
- Water retention for the self-curing mixtures was higher compared to that of the conventional non-cured mixtures.
- Self-curing mixtures showed better hydration with age compared to conventional non-cured mixtures.
- Better water retention for self-curing mixtures including silica fume showed the tendency of improving hydration at 28 days of age.

- Water absorption and permeable pores for self-curing mixtures were lower than those of the conventional non-cured mixtures.
- Self-curing mixtures exhibited denser microstructure compared to conventional non-cured mixtures.
- Silica fume self-curing mixtures suffered less self-desiccation compared to conventional non-cured mixtures.
- Self-curing using PEG and PAM may be beneficial for mixtures including slow reactive cementitious materials or replacements such as slag due to their high ability in retaining water for longer period.
- Application of PEG and PAM together as self-curing agent in concrete mixtures needs to be evaluated.

ACKNOWLEDGEMENTS

The financial support of the first and the second authors by UAE University is greatly appreciated. Also, the manufacturing of the polymers used in the study at Ain Shams University, Faculty of Engineering is very much appreciated.

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Table 1—Chemical composition of OPC and silica fume used in the study

<i>Compound</i>	<i>Weight %</i>	
	<i>Portland Cement</i>	<i>Silica Fume</i>
<i>CaO</i>	61.5	1.0
<i>SiO₂</i>	21.0	90.0
<i>Al₃O₃</i>	6.1	1.0
<i>MgO</i>	3.8	1.5
<i>Fe₂O₃</i>	3.0	1.5
<i>SO₃</i>	2.5	0.2
<i>Na₂O</i>	0.4	0.5
<i>K₂O</i>	0.3	1.5
<i>Loss on Ignition</i>	1.6	—
<i>Insoluble Residue</i>	0.9	—

Table 2—Properties of polyethylene glycol (PEG) and polyacrylamide (PAM)

<i>Property</i>	<i>PEG</i>	<i>PAM</i>
<i>Molecular Weight</i>	6000	9000000
<i>Appearance</i>	White Flakes	White crystalline powder
<i>Moisture %</i>	0.1% max	0.1% max
<i>Specific Gravity</i>	1.08 – 1.09 (50% aq. Sol.)	0.75 (50% aq. Sol.)
<i>pH value</i>	5 - 7	5 - 7

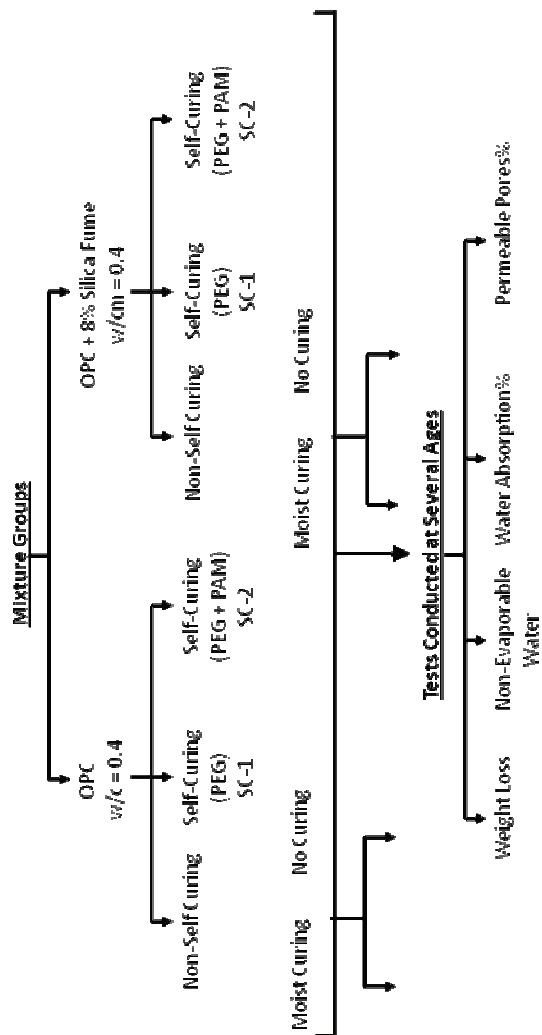
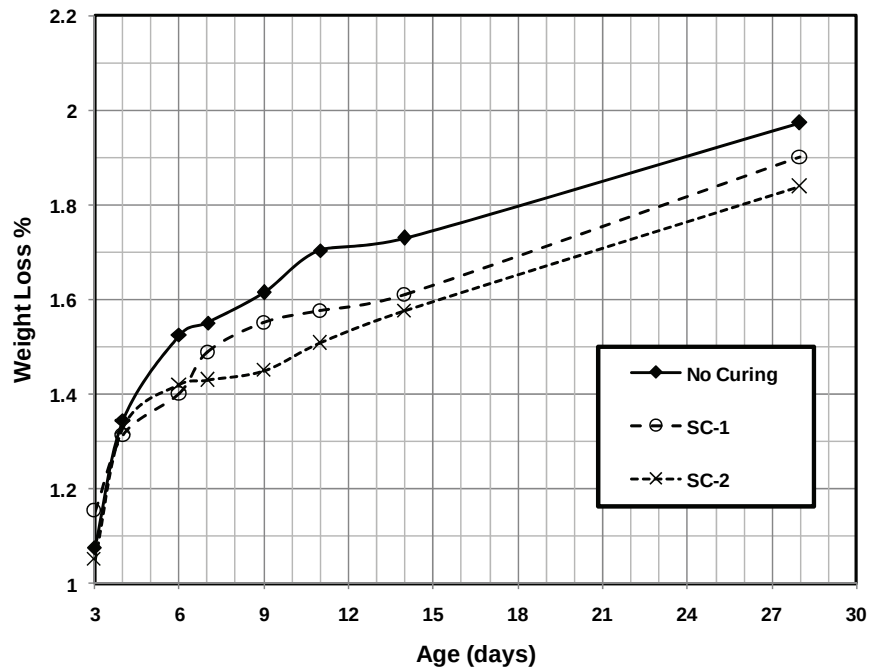
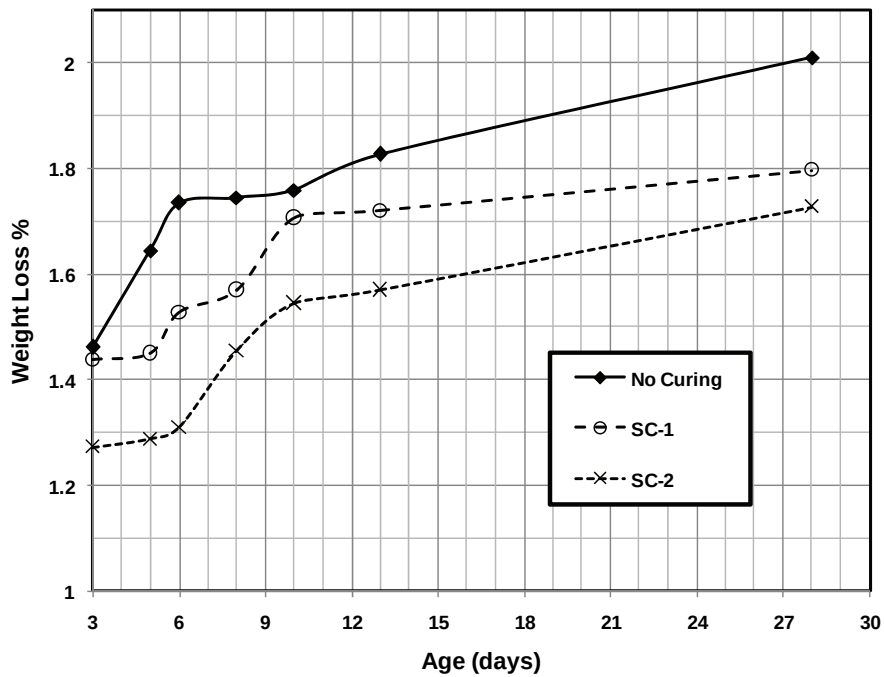


Figure 1—Mixture groups, curing regimes, and tests.

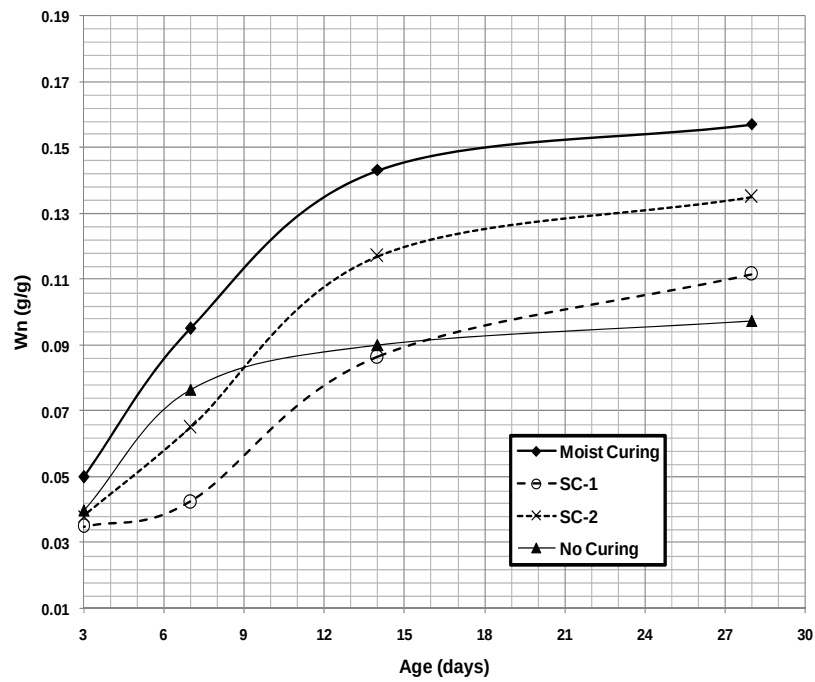


(a) OPC mixtures

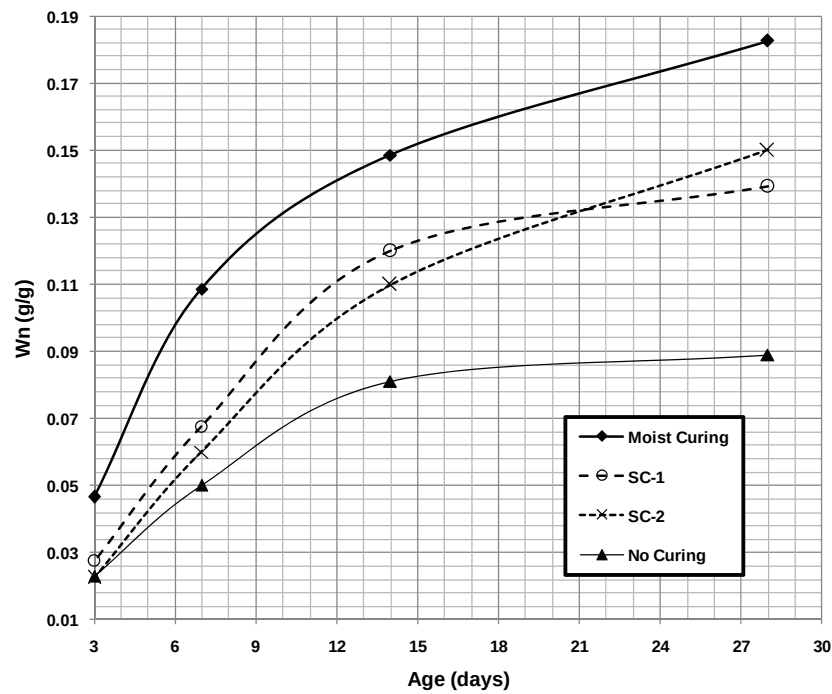


(b) OPC mixtures incorporating 8% Silica fume replacement

Figure 2—Weight loss with age for conventional non-cured mixtures, and self-curing mixtures.

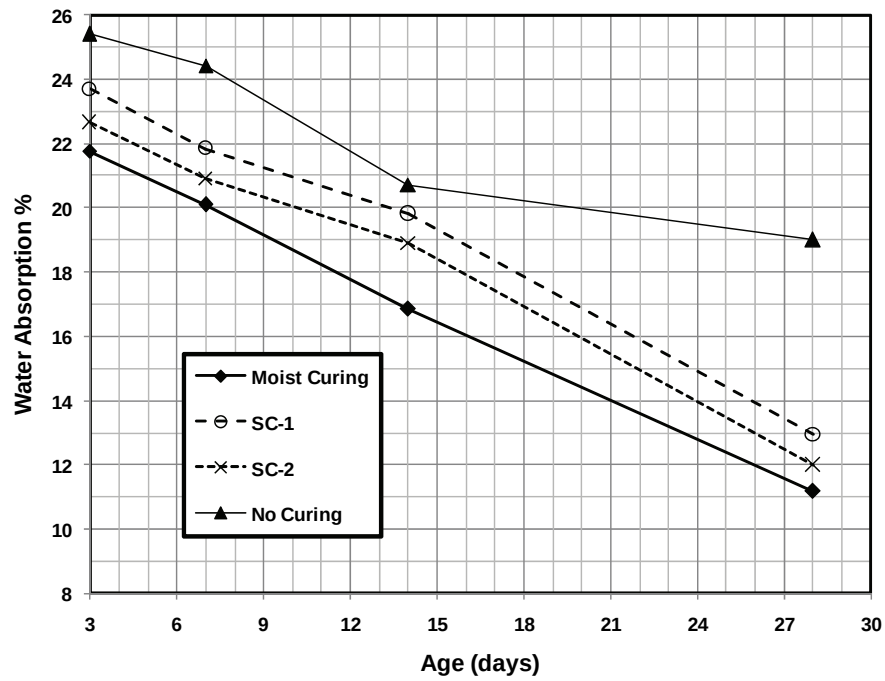


(a) OPC mixtures

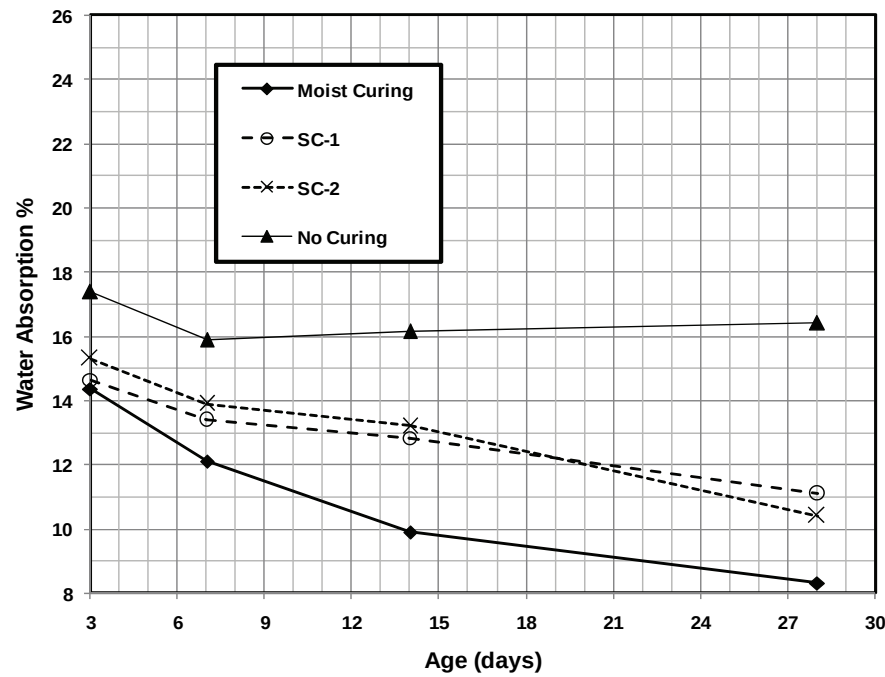


(b) OPC mixtures incorporating 8% Silica fume replacement

Figure 3—Non-evaporable water with age for moist-cured, non-cured, and self-curing mixtures.

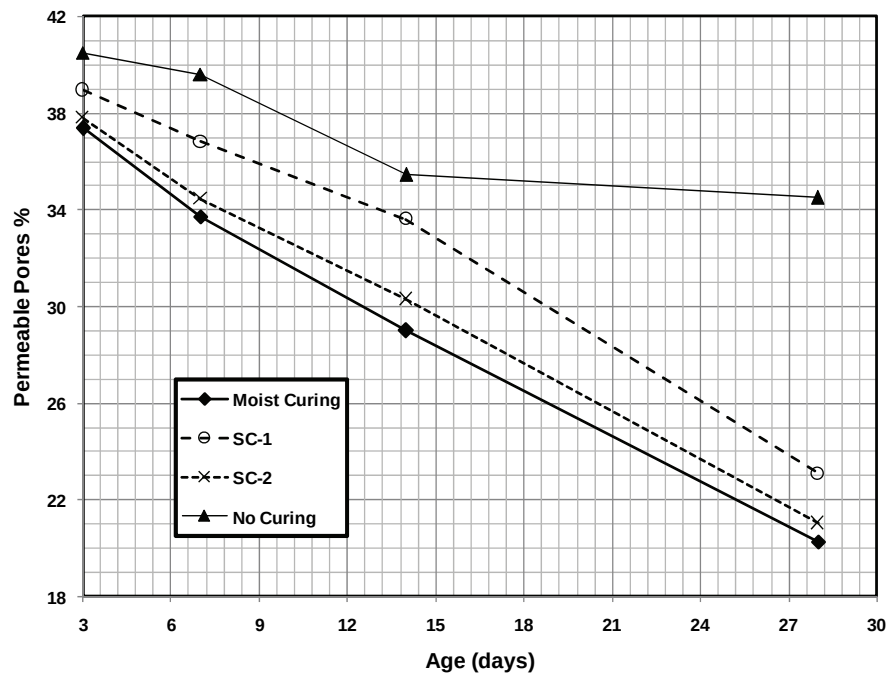


(a) OPC mixtures

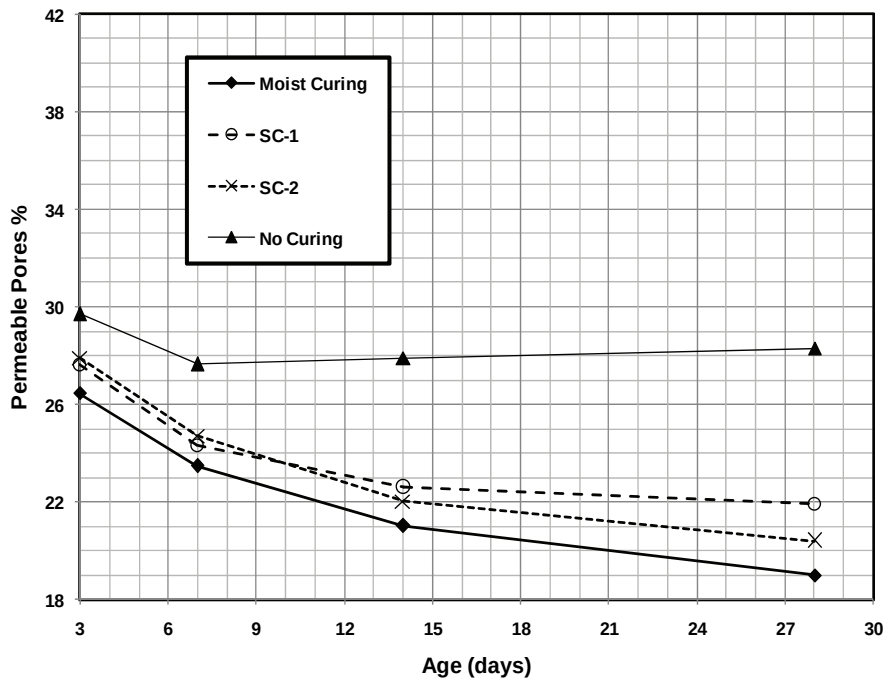


(b) OPC mixtures incorporating 8% Silica fume replacement

Figure 4—Water absorption versus age for moist-cured, non-cured, and self-curing mixtures.

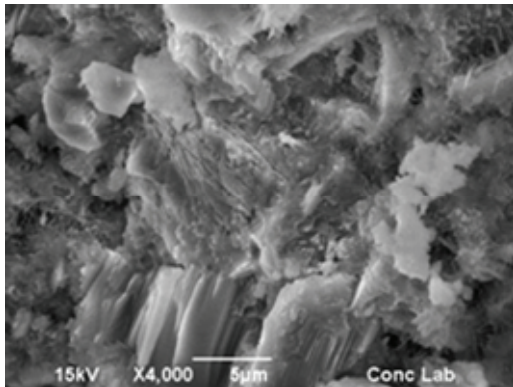
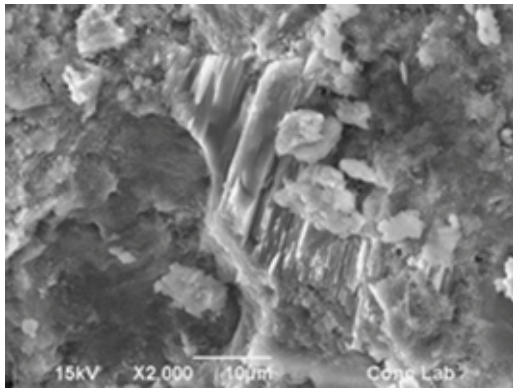
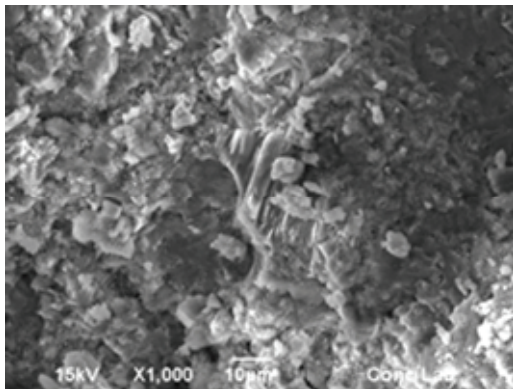


(a) OPC mixtures

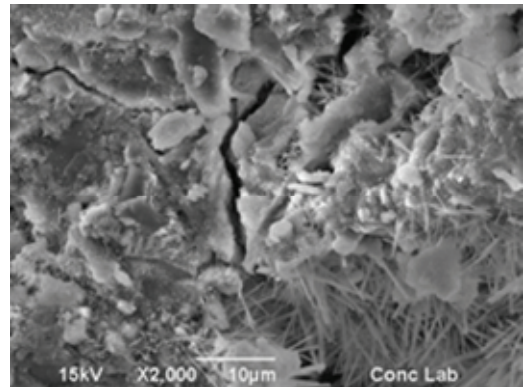
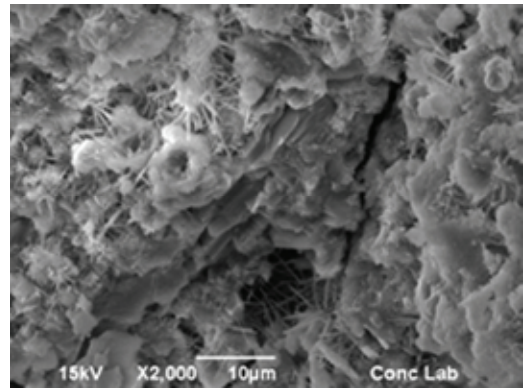
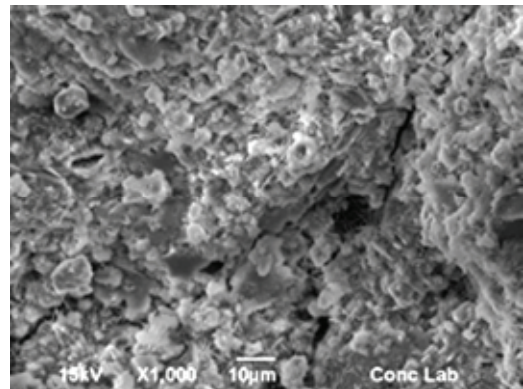


(b) OPC mixtures incorporating 8% Silica fume replacement

Figure 5—Permeable pores versus age for moist-cured, non-cured, and self-curing mixtures.

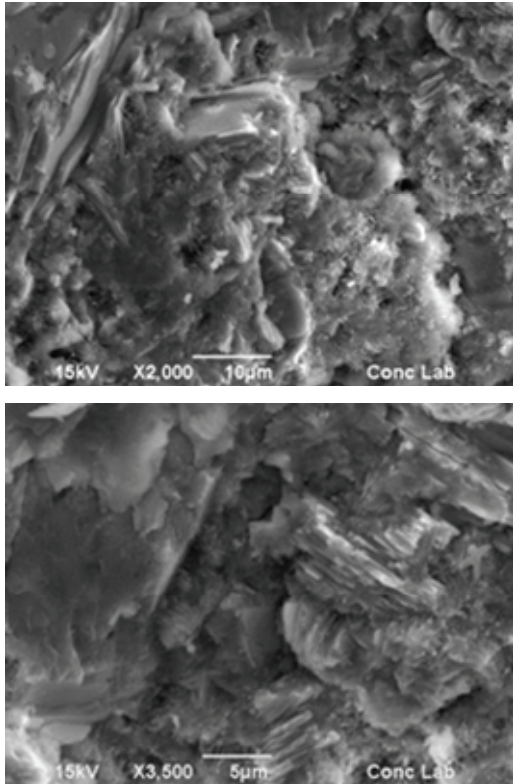


(a) OPC mixture moist curing

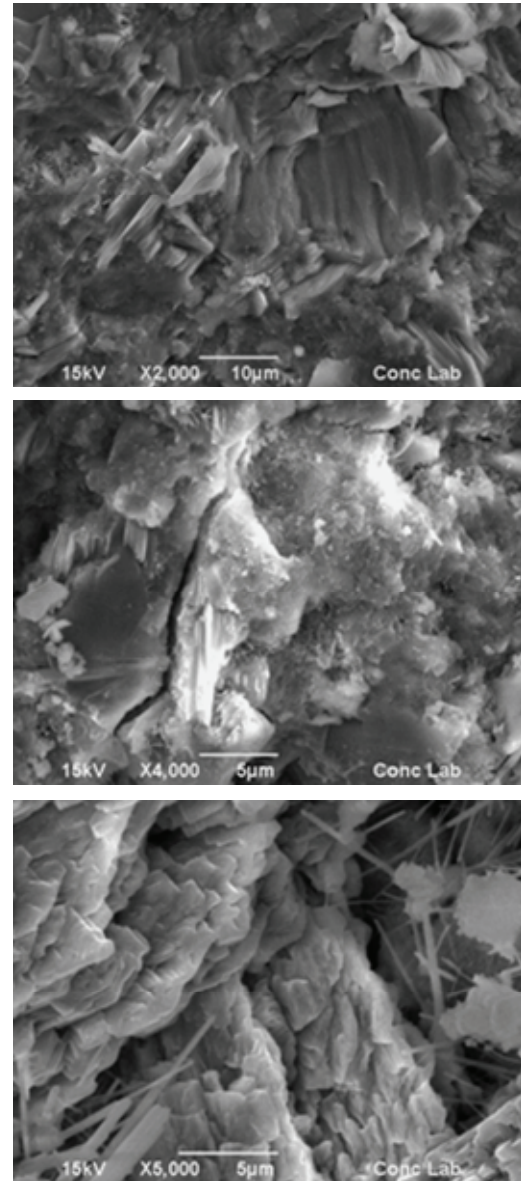


(b) OPC mixture no curing

Figure 6—Microstructure of conventional moist-cured and non-cured OPC mixtures.

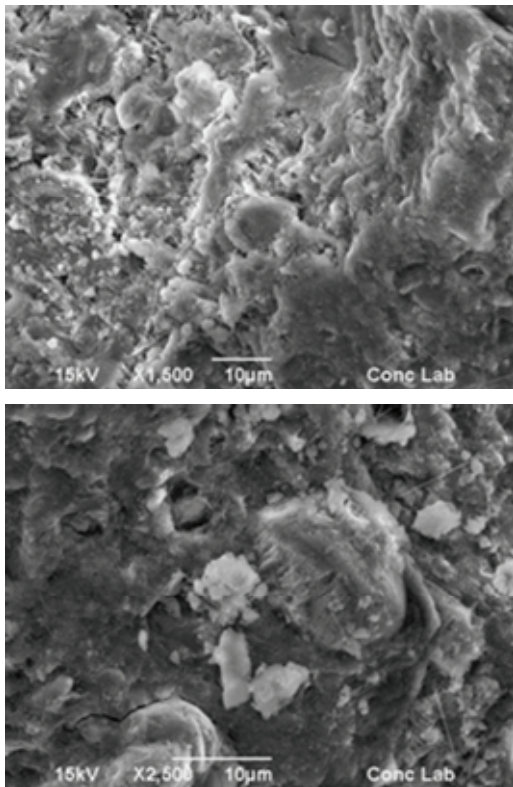


(a) OPC mixture self-curing (SC-1)

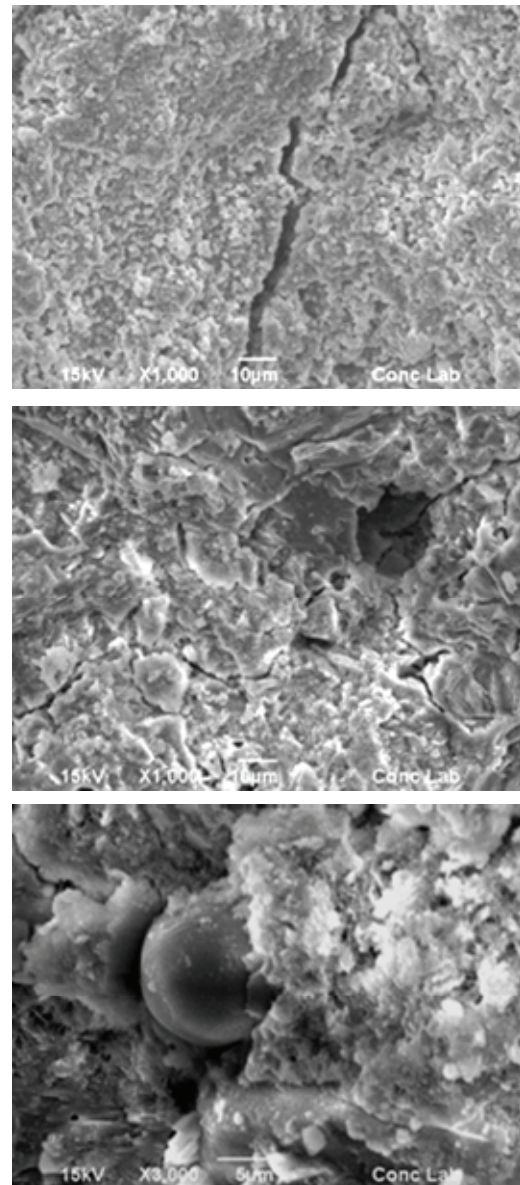


(b) OPC mixture self-curing (SC-2)

Figure 7—Microstructure of self-cured OPC mixtures, SC-1 (PEG), and SC-2 (PEG+PAM).

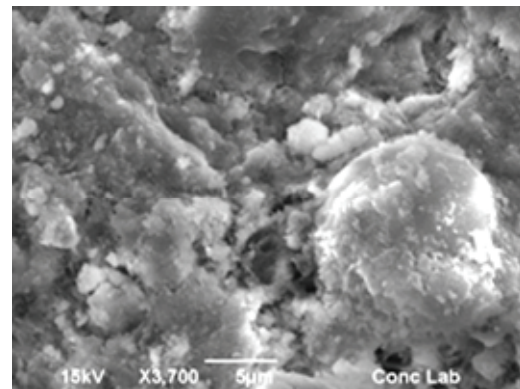
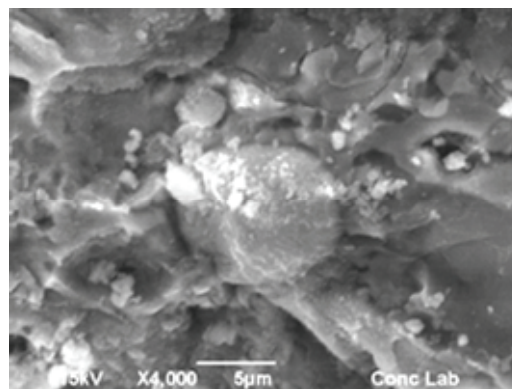
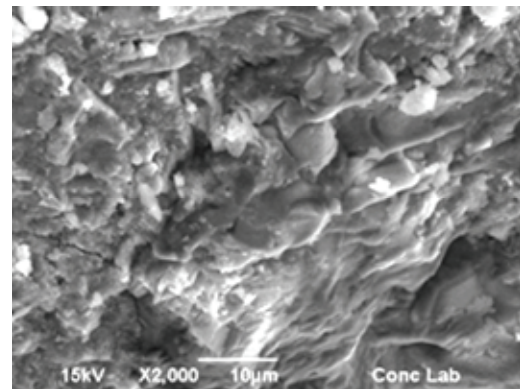
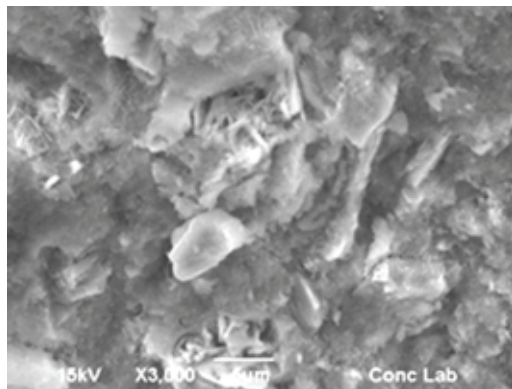
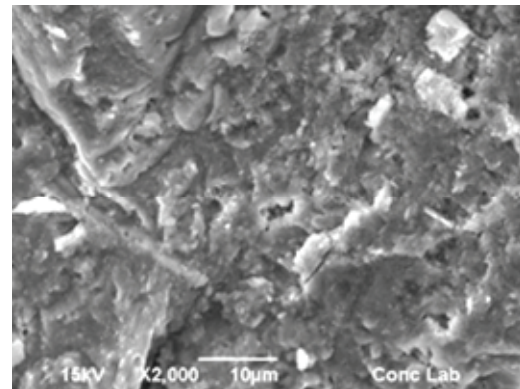
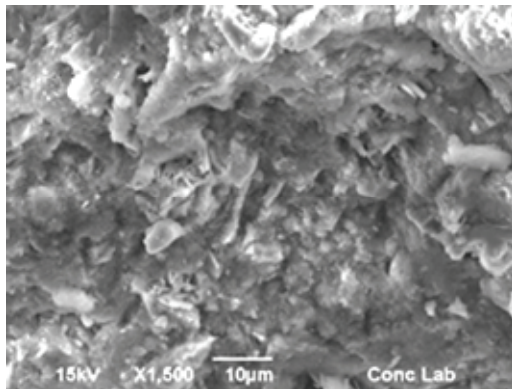


(a) Silica fume mixture moist curing



(b) Silica fume mixture no curing

Figure 8—Microstructure of conventional moist-cured and non-cured OPC mixtures incorporating 8% silica fume.



(a) Silica fume mixture self-curing (SC-1)

(b) Silica fume mixture self-curing (SC-2)

Figure 9—Microstructure of self-cured OPC mixtures incorporating 8% silica fume, SC-1 (PEG), and SC-2 (PEG+PAM).

Economical Bridge Overlays Using Waste Latex Paint

by O.I. Quiroz and A.M. Said

Synopsis: Polymer modified concrete (PMC) was introduced to address some of the disadvantages of normal concrete such as low tensile strength and vulnerability to chloride penetrability. Latex-modified concrete (LMC), a type of PMC where latex-based polymers are used, is usually utilized in special applications that require some of PMC's advantageous properties. Approximately 10% of all latex paint purchased in the United States becomes unused. This waste latex paint (WLP) contains volatile organic compounds (VOC), which makes it difficult and expensive to recycle. Using WLP in concrete as a replacement for styrene-butadiene rubber (SBR) has been found to produce a PMC comparable to LMC. WLP could produce a cost effective PMC as it can replicate the improved properties of LMC. Bridge overlays use LMC due to its durability under environmental conditions and traffic loads. Bridge overlays are subjected to chloride ion ingress, which may result in corrosion of the reinforcement and surface scaling of concrete. In this study, four concrete mixtures were evaluated. These mixtures consisted of a control mixture of normal concrete, one with SBR, and two with WLP. The experimental program included fresh properties as well as hardened properties. Results showed that a WLP mixture can meet the requirements for LMC bridge overlays. The success of the proposed technique can result in a total of one to two million cubic yards of inexpensive LMC produced in the United States yearly, with a substantial recycling of WLP.

Keywords: abrasion, bridge overlays, latex paint, recycling, SBR, sustainability

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INTRODUCTION

Portland cement concrete has been a popular construction material for the past 180 years. Concrete has several disadvantages such as low tensile strength and ductility. Using polymers in concrete is an established solution for some of these disadvantages. The first patents that used polymers in concrete were issued in the 1920s. One of the first polymers used in the concrete mixture was natural rubber. In the 1930s, the first patent for a synthetic polymer was issued. Beside their availability, synthetic polymers offered further advantages as their properties can be engineered to suit specific applications. In the 1960s, synthetically-produced polymers like styrene-butadiene rubber (SBR) and polyacrylic ester-modified mortars and concrete were widely accepted in special construction applications (Ramakrishnan 1992; Ohama 1995).

Latex-modified concrete (LMC) is a type of polymer modified concrete (PMC) where latex-based polymers are used. The improved properties of LMC make it suitable for bridge overlays (Ramakrishnan 1992). Bridge deck overlays are usually exposed to repeated loading and abrasion from traffic as well as ingress of chloride ions from de-icing salts. Chloride ions penetration through bridge overlays into concrete superstructure accelerates corrosion of steel reinforcement. In a Federal Highway Report, the chloride-induced corrosion and deterioration in bridge deck was referred to as “one of the most severe problems facing the highway industry” (Clear and Chollar 1978). Accordingly, LMC has provided a viable solution to enhance bridge durability through its application in bridge overlays. Styrene-butadiene concrete bridge overlays became more commonly used in the 1970s after a study by the Dow Chemical Company and the Michigan Highway Department. The study found that styrene-butadiene concrete had considerably lower chloride permeability than ordinary concrete used for bridge overlays (Clear and Chollar 1978; Ramakrishnan 1992).

When latex paint remains unused, it becomes a hazardous waste due to the volatile organic compounds (VOC) it contains. The VOC make the latex paint difficult to recycle despite that many valuable components remain in WLP. The cost of recycling or disposing of leftover paint is approximately \$8 per gallon, with an estimated 16 to 35 million gallons of paint remaining unused in the United States every year (Product Stewardship Institute 2004). Different solutions exist to reuse and recycle waste latex paint (WLP) such as paint swaps, paint consolidation, landfill spraying, and using it as an additive in concrete. Paint swaps are organized exchanges of unused paint in communities. Paint consolidation consists of collecting unused paint and combining paints with similar characteristics into larger batches. Hernando County, Florida requires a daily cover over any landfill to protect from disease, odor, and wind gusts. The landfill uses collected latex paint mixed with water as a cover (Greiner et al. 2004). Segala (2003) discussed different techniques to recycle paint including a technique known as processed latex pigment (PLP), which is a patented method for recycling industrial leftover latex paint among other wastes. PLP is shipped to portland cement plants and used as an additive for special cements or used as raw material for the kiln feedstock (Segala, 2003). One of the methods for disposal of paints involve solidification of paint which is then disposed in a landfill. This is considered the last resort for disposal of waste paint. Due to decreasing budgets many areas are increasingly relying on solidification as a disposal method. Additionally, combustion or incineration chambers are also used to dispose of paint. The chambers use the paint as fuel to create energy and are able to decrease the weight and volume of paint by 75% and 90% respectively. This is not an effective use of the valuable components in paint due to the low fuel value of paint.

Nehdi and Sumner (2003) studied the effects of using WLP in concrete. Their research included testing the ability of WLP to replace virgin latex and the benefits using of WLP for sidewalks. Five mixtures were investigated including a control one of normal concrete, one with virgin latex, one with WLP and two with a 25-75% virgin latex and WLP interchangeably. It was reported that the increase of the WLP percentage in the mixture resulted in a decrease in compressive and flexural strength. These findings suggest that WLP ingredients, other than latex, may have an adverse effect on some mechanical properties of hardened concrete. For the sidewalk evaluation project, six additional mixtures were investigated including one normal concrete mixture and five WLP mixtures in varying percentages (10-60% at 10% increments, except at 50%) to replace mixing water. The concrete mixtures containing

WLP generally exhibited improvements in compressive strength, flexural strength, and chloride penetrability. In addition, the field demonstration displayed enhancements in concrete workability and finishing when WLP was added.

Mohammed et al. (2008) investigated the use of WLP in concrete. Different proportions of WLP addition to concrete were compared to virgin latex. Results showed that WLP was able to improve the properties of ordinary concrete and produce concrete comparable to regular LMC. In their study, WLP had comparable compressive strength, rapid chloride penetrability, and air content to LMC. Furthermore, the WLP had improved properties over the control mixture in compressive strength, flexural strength, and chloride penetrability. The study focused on general-purpose concrete used for applications like sidewalks and non-structural elements. General-purpose applications usually do not employ LMC, they rather use normal concrete. Accordingly, limited economical benefits are achieved, mostly through the reduction of admixture dosage. However, in special applications that require LMC use, WLP can provide an economical substitute. The current study explores the potential use of WLP in bridge overlays to produce an economic LMC.

A solution to the high cost of recycling WLP and of the high cost of using LMC would be to use WLP in concrete instead of SBR. If concrete incorporating WLP is able to meet the requirements of special applications and show similar characteristics found in LMC, it can then provide a durable alternative at a reduced cost. PMC is used in bridge overlays because of its increased bonding, increased compressive strength, increased tensile strength, resistance to acid, resistance to chemicals, and natural imperviousness. In addition, PMC is used because of its rapid cure time. In one project, repair on a bridge began at night, and the bridge was opened by morning (Miller 2005). In overlay construction practice, concrete must have superior abrasive characteristics to handle traffic loads. Concrete also must have a high early strength for the roadway to be open to traffic as soon as possible. Furthermore, concrete should be workable for easy placement. Finally, concrete needs to have very low permeability. In the current study, the aforementioned performance aspects were tested on a control mixture of normal concrete, and SBR mixture, and two WLP mixtures. The present study aims at identifying a concrete mixture incorporating WLP for the use in bridge overlays, while achieving a performance similar to existing practices.

METHODOLOGY

Materials

Materials used in the study include locally available type II/V portland cement, coarse aggregate with size number 8 grading, well rounded fine aggregate sand (fineness modulus of 3.00, specific gravity of 2.78, absorption of 0.80%, and water content of 0.13%), and commercially available high-range water-reducing admixture (HRWR). The number 8 coarse aggregate consists of aggregates between sieves with square openings of 3/8 in. to No. 8 (0.374 to 0.093 in.) (9.5 to 2.36 mm). The SBR is commercially available with 48% solid content and a density of 8.4 lbs/gal (1 kg/L). The SBR's recommended applications include toppings, stucco, latex-modified overlays, bridge decks, highways, and parking decks. The SBR's data sheet cautions the use of air entrained cements or the use of admixtures due to a significant increase in the total entrained air content (Euclid Chemical, 2009). Two types of paints were used in this study. The first paint, WLP1, was eggshell white with a density of 83.1 lbs/ft³ (1246 kg/m³) and a tested solid content of 58%. The second, WLP2, was interior eggshell enamel latex paint with a density of 77.8 lbs/ft³ (1331 kg/m³) tested solid content of 50%. The first paint was from a known source in a sealed unopened container whereas the second paint was from an unknown source with an open container, with potential drying.

Experimental procedures

In order for the latex paint to be a potential substitute to LMC, it must meet the same acceptance criteria for regular LMC used in overlays. ACI 548.4 (1993) standards were used to verify the ability of WLP mixtures to meet the same requirements as LMC. ACI 548.4 identifies three tests: air content, slump, and compressive strength.

The air content was tested for the four mixtures since ACI 548.4 recommends air content less than 6.5%. The volumetric method was used for testing the air content of the fresh concrete according to ASTM C173. According to ACI 548.4 (1993) the slump should be kept between 3 to 8 in. (75-200 mm) measured according to ASTM C143. In order for the roadway to be opened for traffic, a compressive strength of 3000 psi (20.7 MPa) should be reached (ACI 548.4, 1993). The compressive strength of the four mixtures was evaluated to compare their rate of strength gain, ultimate compressive strength and to identify the time each mixture reaches the 3000 psi (20.7 MPa) mark. The test used 4 × 8 in. (100 × 200 mm) cylinders that were covered for the first 24 hours and then air cured at room temperature according to ASTM C39. The cylinders were tested at 1, 3, 7, and 28 day according to the standard test procedure (ASTM C 39/C 39M-03).

Due to the nature of overlays exposure to vehicular traffic, they must be capable of resisting abrasion. To simulate the abrasive characteristics of concrete under traffic conditions, an abrasion test by sandblasting was performed according to standards (ASTM C 418-98). This test used small circular slab specimens, which were sandblasted for 1 minute at 100 psi (690 kPa). The procedure was repeated eight times per mixture. To calculate the volume of the cavity resulting from sandblasting, clay with a density (D) of 0.98 oz/in.³ (1.7 g/cm³) was used. The initial mass (M_1) of clay was measured and then used to fill the cavity in the specimen. The mass (M_2) of the remaining clay was measured after filling the cavity. The volume (V) was calculated using Eq. (1):

$$V = \frac{(M_1 - M_2)}{D} \quad (1)$$

Next, the area of surface abraded (A) was measured and then the abrasion coefficient (A_c) was calculated using the following equation as per ASTM C 418-98:

$$A_c = \frac{V}{A} \quad (2)$$

A significant concern for bridge overlays is the ingress of chloride ions, which causes corrosion of steel leading to deterioration of concrete. For concrete incorporating WLP to be a successful substitute to regular LMC in bridge overlays, it must have a low permeability that is comparable to LMC. The rapid chloride penetrability test was used to assess the permeability of concrete. The test uses a 2 in. (50 mm) thick 4 in. (100 mm) diameter disc cut from a concrete cylinder at 28 days. The disc specimen is placed in water for 18 ± 2 hours and conditioned according to ASTM C1202-97. The specimen is then connected to 60 V for 6 hours. The charge passing through the specimen during testing is a measure of the conductance of concrete, which in turn relates to its permeability. The chloride ion penetrability of the concrete is determined by the current that passes the specimen which is then translated into a penetrability rating of the specimen. The rapid chloride penetrability test (RCPT) setup is shown in Fig. 1. The physical chloride ion penetration depth is measured after the test through spraying the specimen with silver nitrate solution which forms a white precipitate of silver chloride within approximately 15 minutes. The average depth of five points in a sample is then calculated from the top of the disc to the chloride penetration line (Bassuoni et al. 2006). In the present study, for each concrete mixture, two samples from different concrete cylinders were tested for their chloride penetrability.

The temperature of concrete while curing was monitored to evaluate its reactivity. The test was completed using a freshly mixed concrete sample cast in a 4 × 8 in. (100 × 200 mm) cylinder. A thermocouple was placed in the center of the cylinder, a cover was placed, and then the container was sealed. The thermocouple was then connected to a data logger, which then recorded the temperature of concrete every minute for three days per ASTM standard (ASTM C 1064/C 1064M-99). The sealed cylinder and the data logger can be seen in Fig. 2.

Initially, the water content published in the paint data sheets were used to calculate their contribution to mixing water. During mixing WLP2 showed a significant deficit of water. As a result, the paints and the latex were tested to determine the actual water content. To find the water and solid content of the paint, samples were placed in containers inside a desiccator. The initial weights of the containers and of the paint were measured. These samples were then left to air dry at room temperature and their weights were measured periodically. The actual water content (w_c) was then calculated by subtracting the initial water content by the final water content and dividing the result by the initial water content. The result was then converted to a percentage. Finally, the solid content was calculated by subtracting the actual water content from 100%.

Mixture proportions

ACI 548.4 (1993) guidelines were used to create a WLP and an SBR mixture with comparable workability. The document specifies a minimum cement content at 658 lb/yd³ (390 kg/m³), a minimum amount of latex required as 24.5 gal/yd³ (121 L/m³), a maximum water of 18.9 gal/yd³ (94 L/m³), and a cement to fine to coarse aggregate ratio of 1.0:2.8:1.7 by weight. Consequently, the mixture contains more fine aggregate than coarse aggregate.

A series of trial batches were performed to target a WLP concrete mixture that meets the slump and air content requirements. Table 1 shows the concrete mixtures used for the study. The mixtures in the table are equal in volume in but the proper ratio was maintained. The concrete mixture proportions achieved using WLP1 had a water-cement ratio (w/c) of 0.38. Subsequently, a control mixture with similar amount of cement, coarse aggregate, fine aggregate

and total water was batched. Table 1 shows that the control mixture required 12 oz of HRWR/100 lbs of cement (780 mL/100 kg of cement) instead of the 5 oz/100 lbs of cement (325.99 mL/100 kg of cement) used by the WLP1 mixture. Generally, polymer dispersion has a considerable water reducing effect on a concrete mixture (Concrete Society 1994). However, WLP did not have the same water reducing effect as the SBR at similar slump. The SBR mixture had a w/c of 0.3, which is lower than the 0.38 w/c of the control or WLP1. This is due to the SBR having a slump larger than 8 in. when the w/c is more than 0.35 compared to the WLP1, which requires a w/c of 0.38 to reach the 3 in. (75 mm) slump.

RESULTS AND DISCUSSIONS

Air content

As shown in Table 1, the four mixtures had air content less than the maximum allowable content of 6.5%. The largest air content was 4% with the SBR mixture. Both WLP1 and WLP2 mixtures had an air content of 1%, whereas the control mixture had an air-content of 2%. The WLP in the concrete mixture resulted in a reduction in air content. However, the air content can be modified if needed accordingly.

Slump

The recommended slump for LMC overlays is 3 to 8 in. (75 and 300 mm). All of the mixtures met the slump specification. The control had the same w/c as the WLP1 but higher HRWR. Therefore, the addition of the latex from the paint increased the slump. Although, the SBR mixture only had 0.5 oz/100 lbs of cement (32.6 mL/100 kg of cement) of the HRWR admixture it had a slump larger than the WLP1 which used 5 oz/100 lbs of cement (325.99 mL/100 kg of cement). The increase in admixtures dosage will increase the final cost of concrete and may need to be considered.

Compressive strength

As stated in the standard specification for latex-modified concrete overlays, the overlay must reach a compressive strength of 3000 psi (20.7 MPa) in order for the road to be open for traffic (ACI 548.4, 1993). WLP1 had a 1 day compressive strength of 2300 psi (16 MPa) which is closer to the requirement than WLP2's 747 psi (5 MPa) and SBR's 1200 psi (8.3 MPa). The data in Table 2 shows that the control mixture had a slightly higher strength than WLP1. On day 3, the control, SBR, and WLP1 mixtures all had a compressive strength greater than 3000 psi (20.7 MPa). WLP2 did not achieve the required compressive strength by day 7 and did not reach the required strength of 3000 psi until 28 days. The excess water in WLP2 lowered concrete compressive strength. At 28 days, WLP1 surpassed the control mixture as the highest compressive concrete mixture. Figure 3 illustrates that WLP1 and the control reached the 3000 psi mark after an estimated 1.5 days. This would be the estimated opening time of the roadway. In addition, the figure shows that WLP1 surpassed the control in strength after an estimated 8 days.

Abrasion

WLP1 and SBR mixtures had the same abrasion coefficient, as shown in Table 3. These results suggest that WLP1 and the SBR mixtures have similar resistance to surface abrasion due to traffic. The SBR mixture had an abraded volume and an area of surface abraded nearly half the size of WLP1. The control mixture had an abraded volume 3% larger than WLP1. Table 3 and Fig. 4 show that WLP2 had a larger abrasion coefficient than the three other mixtures. WLP2 had a high abrasion volume greater than 0.17 in.³ (2.8 cm³). The higher w/c of WLP2 mixture compared with WLP1 may be the cause for the larger abrasion coefficient.

WLP1 had a higher resistance to abrasion than WLP2 and the control mixture. WLP1 had a large abraded area with very shallow cuts into the specimen. The only difference between WLP1 and the control in terms of mixture proportions was the addition of the WLP. Accordingly, the increase in abrasion resistance of WLP1 can be attributed to the addition of WLP.

The abrasion test results showed that generally a decrease in w/c increases the abrasion resistance in a concrete sample and an increase in the polymer-cement ratio (*p/c*) will increase the abrasion resistance of concrete. Accordingly, to create a WLP mixture with higher abrasion resistance the mixture needs an increase *p/c* coupled with a decrease in w/c.

Rapid chloride penetrability

The RCPT showed positive results for SBR, WLP1, and WLP2. The test was completed to compare the vulnerability of the mixtures to chloride ions because overlays are susceptible to chloride attack from salts. Table 4

shows the SBR mixture having the lowest current passing through the specimen with only 703.5 coulombs. The WLP1 mixture had the second lowest passing current with 738.5 coulombs followed by the WLP2 mixture having 745.5 coulombs passing. The three latex mixtures were evaluated as having very low penetrability. The control had 1751 coulombs passing which is a low penetrability rating. The WLP lowered the chloride penetrability in a comparable level to the SBR. The specimens can be seen with precipitate of silver chloride in Fig. 5. The distance from the top of the specimen to the silver chloride is the recorded penetration depth shown in Table 4.

Adiabatic temperature

Figure 6 shows the control mixture reached its highest temperature of 80 °F (26.6 °C) at approximately 12 hours. The latex mixtures reached their peak temperature between 15 and 18 hours. WLP1 had the highest temperature of the three latex mixtures. The adiabatic temperature change test was completed to compare the reactivity of the concrete because the higher temperature is an indicator of higher reactivity. The three latex-modified concrete mixtures had a lower reactivity than the control mixture. After 24 hours all four mixtures began to reach a constant temperature.

Solid content of paint and styrene-butadiene rubber

In order to properly proportion the mixtures the water content of WLP1, WLP2, and SBR needed to be found so the solid content was first found which allowed the water content to be calculated. The majority of mass loss for the three latex-containing products, WLP1, WLP2, and SBR, was recorded during the first two days yet continued for another 35 days as recorded and shown in Fig. 7. Specimens were dried at room temperature in a desiccator. The largest discrepancy from the manufacturer provided product solid content to the test results were observed in the SBR and WLP2. Both products had a difference greater than 10% at 35 days. WLP2 had a greater discrepancy than WLP1, most likely due to WLP2 being acquired from an unknown source. The amount of open exposure that WLP2 received before testing is unknown. For the mixture proportioning, a different approach was taken for both WLP1 and WLP2's solid content than for the SBR solid content. For the SBR mixture, the published value (48%) was used in mixture design as SBR is intended for concrete. A manufacture recommended mixture was used and no additional water was required. As for WLP, the solid content used in mixture design was derived from the data plotted in Fig. 7. WLP1 and WLP2 had a solid content of approximately 58% and 50%, respectively for the majority of the first 35 days. Table 5 shows that the SBR latex had a published solid content of 48% but had a tested solid content of 41.7% during day 2. The solid content of the SBR continued to decrease into 36% by day 35. The difference in the published value and the SBR tested value continued to decrease with time. The difference for both WLP1 and WLP2 decreased with time. The data in Table 5 shows that WLP1 had a difference of 1.9% in the published and tested solid content. With WLP2 having a 31.5% difference in the tested and published value the need for testing of unknown paint has to be implemented.

CONCLUSIONS

LMC is a superior material compared with normal portland cement concrete. LMC is able to address some of normal concrete disadvantages. WLP was added to concrete to try and reproduce the properties of LMC at a reduced cost. Tests performed on concrete specimens included fresh and hardened properties and compared to LMC within the context of LMC overlays standard (ACI 548.4). The abrasion and chloride penetrability were also tested to evaluate durability aspects of WLP performance as bridge overlays. The following conclusions can be drawn:

- WLP1 mixture showed a rate of strength gain that is slightly higher than SBR mixture and had a greater ultimate strength. Rate of strength gain is essential for introduction into traffic service.
- The abrasion performance of WLP1 was comparable to SBR in terms of abrasion coefficient despite its higher area of surface abraded. However, WLP2 had a significantly higher abrasion coefficient, which may be attributed to its high w/c.
- Both WLP1 and WLP2 mixtures had a permeability that is comparable to the SBR mixtures based on the rapid chloride penetrability test.
- WLP1 met the overall requirements to be used as an overlay. However, WLP2 underperformed in terms of abrasion, strength gain, and ultimate strength.
- A protocol needs to be established for evaluation of a specific type of paint before its use in construction. The variation in the properties of the two WLP concrete mixtures implies a significant variation in contents based on manufacturer, type and source.

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial support of the University of Nevada, Las Vegas, through the Urban Sustainability Initiative. The help from the Nevada Department of Transportation is greatly appreciated. The authors would like to thank the manufacturers that contributed materials used in this investigation.

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Table 1—Details of mixtures and their proportions

	Control	SBR	WLP1	WLP2
Cement lb/yd ³ (kg/m ³)	200 (120)	200 (120)	200 (120)	200 (120)
Water lb/yd ³ (kg/m ³)	60 (40)	60 (40)	60 (40)	60 (40)
Styrene-butadiene rubber lb/yd ³ (kg/m ³)	-	60 (40)	-	-
Waste latex paint 1 lb/yd ³ (kg/m ³)	-	-	80 (50)	-
Waste latex paint 2 lb/yd ³ (kg/m ³)	-	-	-	80 (50)
Coarse aggregate lb/yd ³ (kg/m ³)	170 (100)	180 (110)	170 (100)	180 (110)
Fine aggregate lb/yd ³ (kg/m ³)	170 (100)	170 (100)	170 (100)	170 (100)
High-range water-reducing- admixture, oz/100 lb cement (mL/100 kg of cement)	12	0.5	5	4
Air Content, %	2	4	1	1
Water-cement ratio (<i>w/c</i>)	0.38	0.30	0.38	0.47
Polymer-cement ratio (<i>p/c</i>)	-	0.30	0.26	0.30
Solid content	-	48%	58%	50%
Slump in. (mm)	7 (180)	4.5 (110)	3 (80)	4.75 (120)

SSD Conditions

HRWRA Volume < 0.1 ft³

Table 2—Average compressive strength for the tested mixtures

Mixture	Compressive strength			
	1 Day, psi (MPa)	3 Day, psi (MPa)	7 Day, psi (MPa)	28 Day, psi (MPa)
Control	2441 (17)	4950 (34)	6099 (42)	7004 (48)
SBR	1248 (9)	3103 (21)	3912 (27)	6268 (43)
WLP1	2371 (16)	4580 (32)	5873 (40)	7613 (52)
WLP2	747 (5)	1874 (13)	2815 (19)	4673 (32)

Table 3—Average abrasion coefficient for the tested mixtures

Mixture	Volume abraded in ³ (cm ³)	Area of surface abraded in ² (cm ²)	Abrasion coefficient in ³ /in ² (cm ³ /cm ²)
Control	0.15 (2.51)	3.31 (21.34)	0.05 (0.12)
SBR	0.08 (1.26)	1.89 (12.22)	0.04 (0.10)
WLP1	0.15 (2.43)	3.71 (23.91)	0.04 (0.10)
WLP2	0.17 (2.82)	1.63 (10.53)	0.11 (0.27)

Table 4—Summary of the rapid chloride penetration test results

Mixture	Passed charge, coulombs	Penetrability evaluation, ASTM C1202	Penetration depth in. (mm)
Control	1751	Low	0.50 (12.8)
SBR	703.5	Very Low	0.08 (2.1)
WLP1	738.5	Very Low	0.19 (4.7)
WLP2	745.5	Very Low	0.15 (3.9)

Table 5—Solid content by weight for the investigated latexes

Mixture	Published solid content	Experimental solid content			
		2 Days	% Difference	35 Days	% Difference
SBR	48%	41.7%	13.1%	33.0%	36.0%
WLP1	54%	59.0%	9.3%	55.1%	1.9%
WLP2	33%	55.4%	67.9%	50.5%	31.5%



Figure 1—The rapid chloride permeability test setup.



Figure 2—The adiabatic temperature test setup.

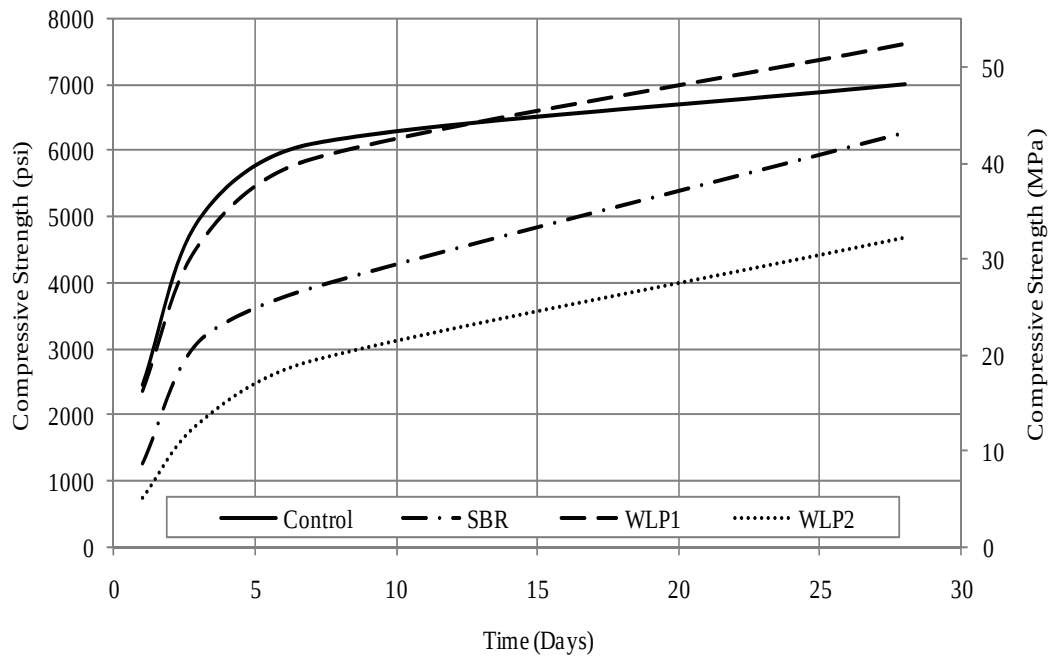


Figure 3—Relation between curing age and compressive strength.

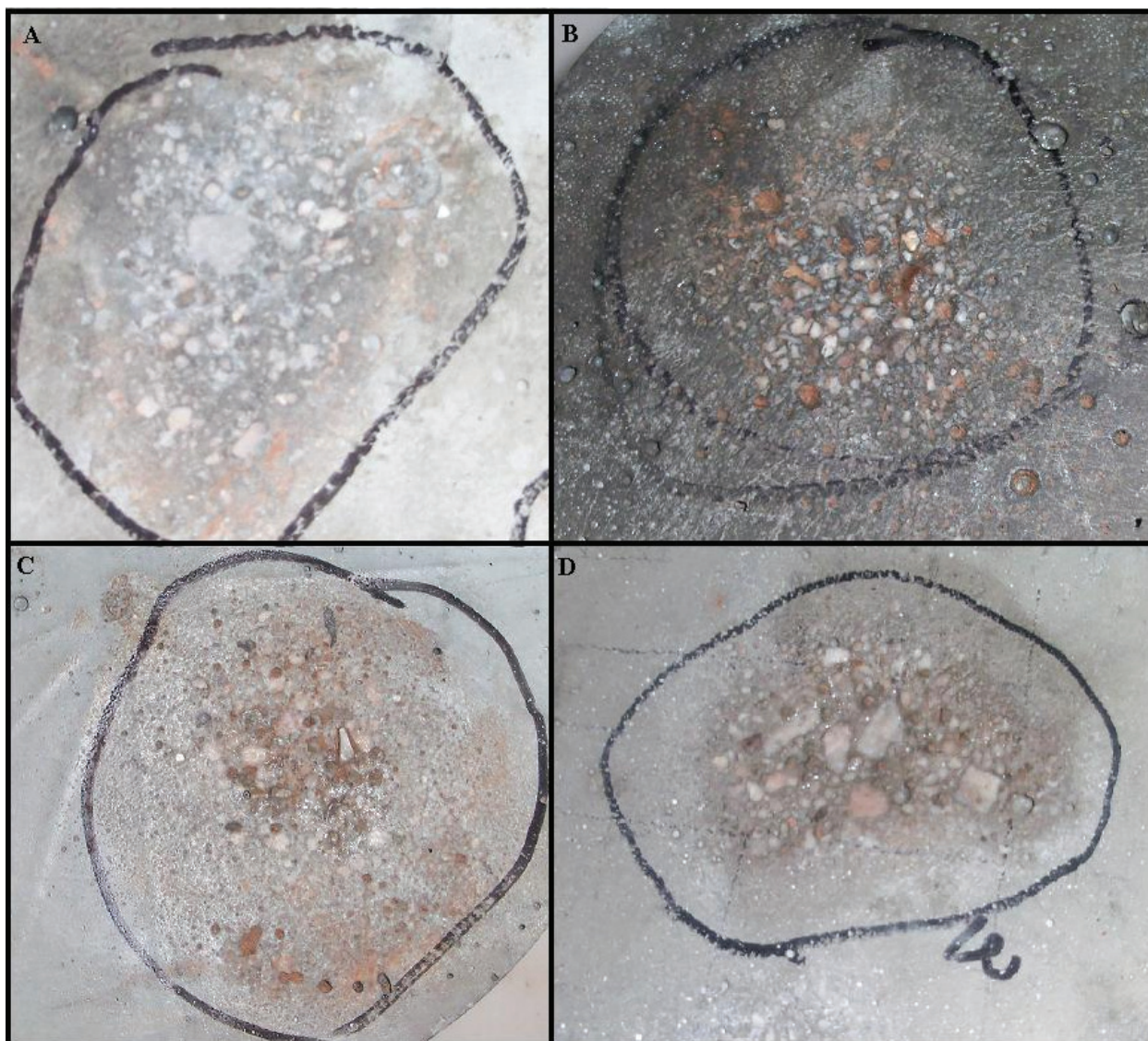


Figure 4—Abrasion by sandblasting results: (A)control, (B) SBR, (C) WLP2 and (D) WLP1.

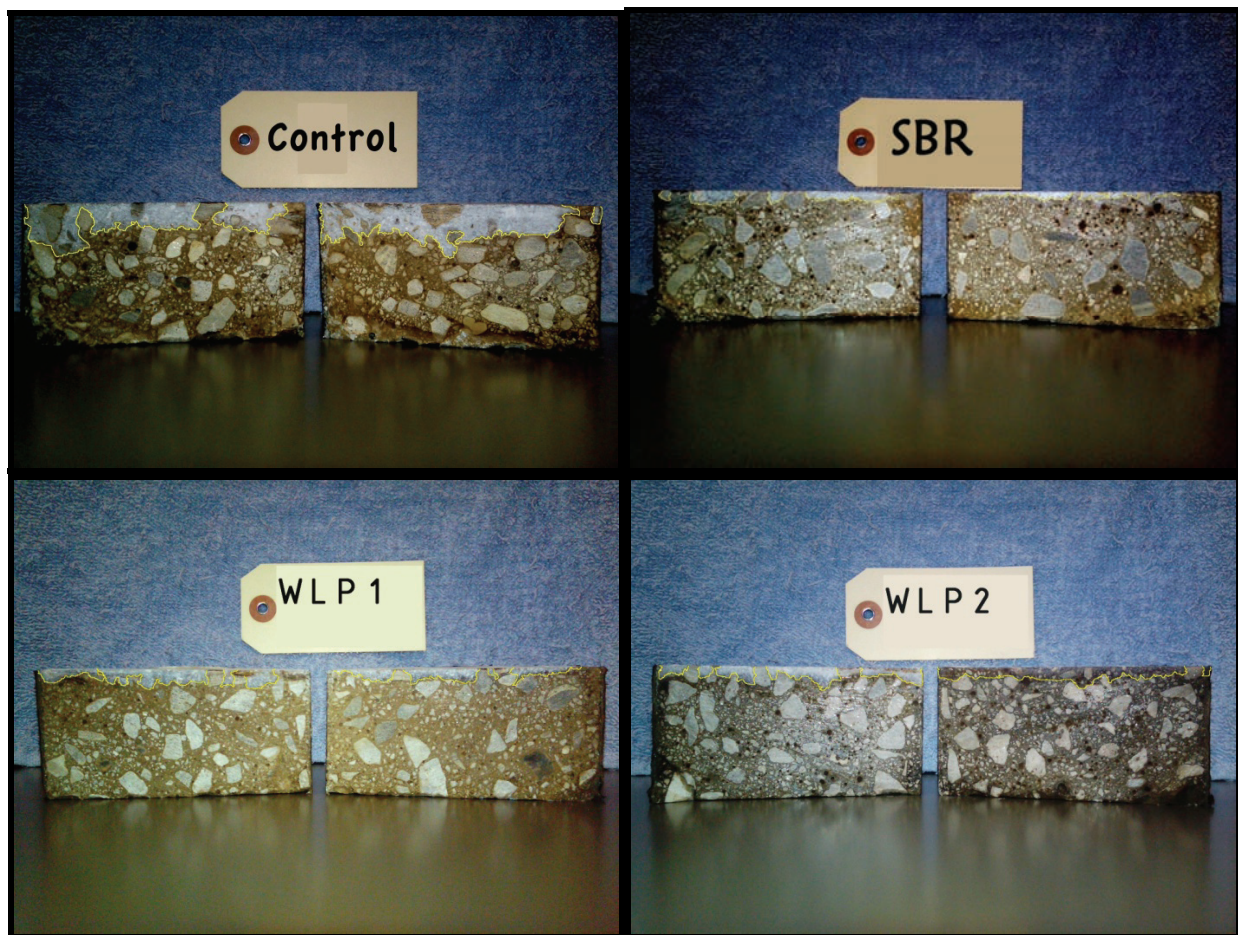


Figure 5—Physical Chloride Penetration for specimens SBR, Control, WLP1, WLP2.

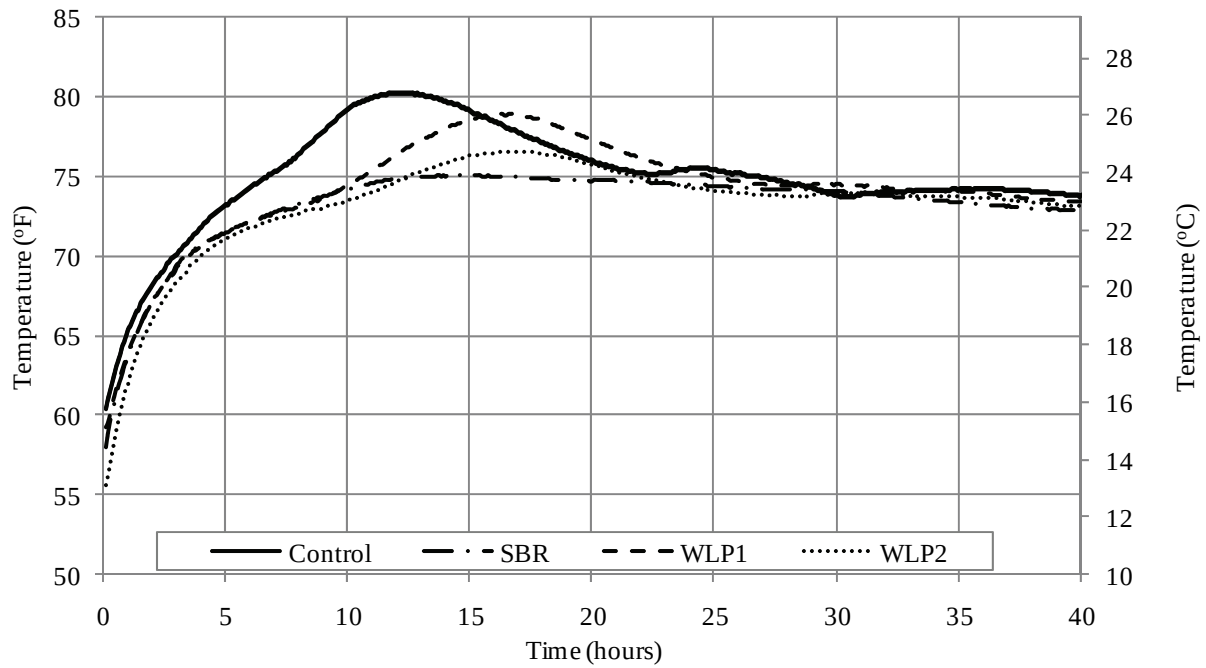


Figure 6—Change in adiabatic temperature for the different mixtures.

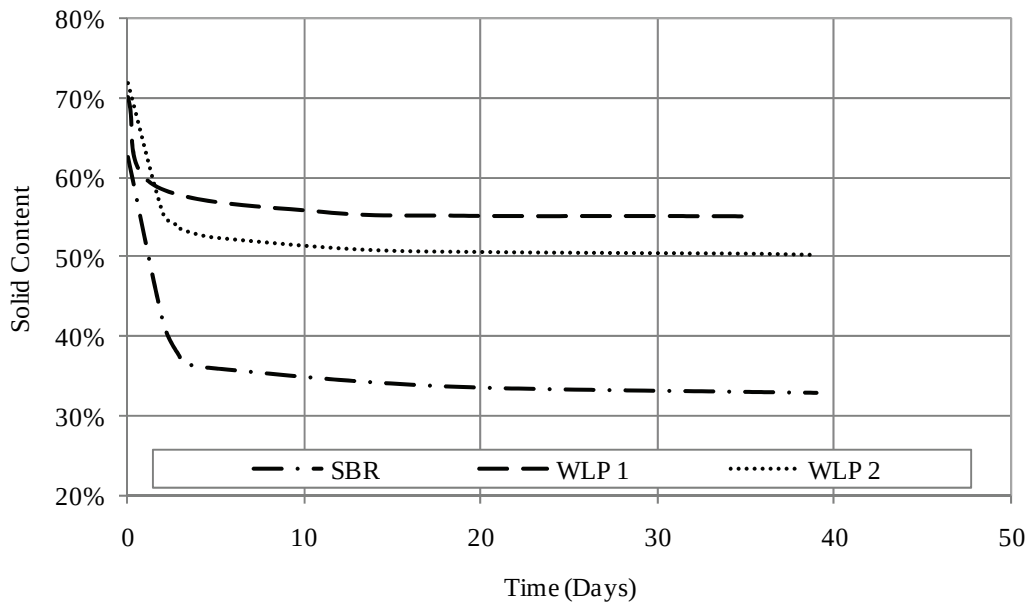


Figure 7—Relation between solid content and time for WLP1, WLP2, and SBR.

A Preliminary Investigation of Polymer Modified Hydrated Cement Paste Prisms and the Fracture Analysis of Tested Specimens

by J. Belkowitz, M. Best, M. Nilsen, F. Fisher and D. Armentrout

Synopsis: The following paper documents the preliminary experimentation and analysis of a polymer fortified hydrated cement sample. Concrete is a brittle construction material. When compared to other construction materials, concrete can offer competitive structural resistance under compressive loads. But due to the brittle nature of the hydrated cement matrix, C-S-H network, concrete is poor when resisting flexural loads. The brittle C-S-H structures cannot absorb the flexural energy like a ductile material. The properties of concrete fracture are analyzed at the microscopic level to understand the method of failure. By including the acrylic polymer into the hydrated specimens it was the belief of the authors that the acrylic polymer would enhance the fracture behaviour of the concrete in flexure. The C-S-H hydrates precipitate from a saturated solution. The acrylic polymer, after being mixed into the cement paste while still fresh, becomes secured in the C-S-H structure as said structure hardens. Samples were cast, cured, and tested in order to determine if the acrylic polymer cause the C-S-H structure to behave in a ductile manner. The testing included compressive and flexural stress tests with microstructure observation via Scanning Electron Microscope (SEM). The compressive and flexural tests were used to discern a measured value of gain when using an acrylic polymer compared to a control mix. The SEM images were used to determine crack origin, type of failure, and acrylic polymer benefit. The tests and SEM images revealed that there was a negative reaction between the admixtures to cause an excessive air generation. Despite the setback, the SEM images revealed evidence of energy absorbing of the acrylic polymer mix.

Keywords: acrylic polymer; compressive and flexural strengths; hydrated cement; scanning electron microscopy