SELECTION OF CLOSURE POUR MATERIALS FOR CIP CONNECTION OF THE PRECAST BRIDGE DECK SYSTEMS

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ABSTRACT

With the public's demands for reduced construction time and traveling delays, full-depth precast bridge decks or decked concrete girders should be more widely used and become a standard construction method for bridges. For the precast bridge deck system with CIP connection, precast elements are brought to the construction site ready to be set in place and quickly joined together, and a concrete closure pour completes the deck connection and ties the individual units together in a manner that is intended to emulate monolithic behavior. The selection of closure pour materials is critical. The performance criteria are being developed to select closure pour materials in this paper.

The procedure and methods used in the NCHRP Project 10-71 for selecting durable bridge joint materials are discussed to demonstrate guidelines for selecting bridge joint materials. The performance criteria are determined, and two categories, overnight cure and 7-day cure, are developed for rapid construction. Candidate materials are collected accordingly. The short-term tests, including compressive strength and flow and workability, were performed to select closure pour materials and test results are discussed.

Keywords: Closure Pour Material, Performance Criteria, Accelerated Construction, Grout, HPC, Compressive Strength, Flow, Workability

FORWARDS

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INTRODUCTION

The use of prefabricated bridge systems can minimize traffic disruption, improve work-zone safety, minimize impact to the environment, and improve constructability, increase quality, and lower life-cycle costs. This technology is applicable and needed for both existing and new bridge construction. For the precast bridge deck system with CIP connection, precast elements are brought to the construction site ready to be set in place and quickly joined together. A concrete closure pour completes the deck connection and ties the individual units together in a manner that is intended to emulate monolithic behavior. Depending on the system, the connections are either transverse (across the width of the bridge) or longitudinal (along the length of the bridge), as shown in Fig.1 (reinforcement not shown for clarity).

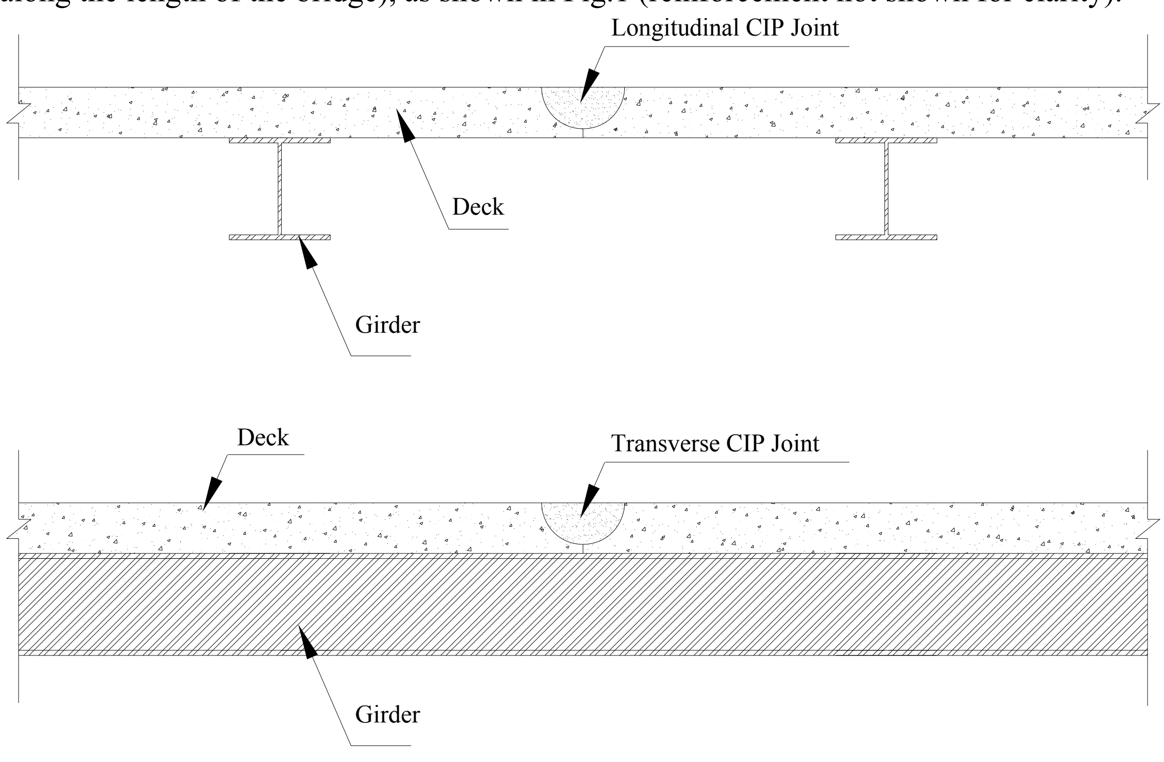


Fig. 1 Sketches with Longitudinal and Transverse Joint Examples

Traditionally, different grouts as closure pour materials for the precast bridge deck system with CIP connection have been tried and summarized below. Mrinmay (1986) documented a wide variety of materials used after 1973 to avoid joint failure/distress in closure pours (i.e., longitudinal and transverse joints), grout pockets and keyways of precast deck panel bridges.

These materials include sand-epoxy mortars, latex modified concrete, cement-based grout, non-shrink cement grout, epoxy mortar grout, calcium aluminate cement mortar and concrete, methylmethacrylate polymer concrete and mortar, and polymer mortar. Cementitious grouts have been used more in precast construction than epoxy or polymer-modified grouts (Matsumoto, E., et al 2001). Epoxy or polymer modified grouts can have significant advantages, such as a high strength in a shorter time (e.g., 6 ksi in 6 hours), better bond, reduced chloride permeability, improved freeze thaw durability, and lower creep. However, they are often significantly more expensive and less compatible with surrounding concrete. In addition, if the resin is used in too large a volume, the heat of reaction may cause it to boil, and thereby develop less strength and loose bond. A primary disadvantage of cementitious grouts is the shrinkage and cracking that result from the use of hydraulic cement. Non-shrink grout compensates for the shrinkage by incorporating expansive agents into the mix. With non-shrink grout, the effects of shrinkage cracks or entrapped air on the transfer of forces and bond are minimized, though not eliminated. ASTM C 1107 establishes strength, consistency, and expansion criteria for prepackaged, hydraulic-cement, non-shrink grout.

Dennis Nottingham (1996) reported that the very nature of portland cement grouts virtually assures some shrinkage cracks in grout joints, regardless of quality control. Prepackaged magnesium ammonium phosphate based grout often extended with pea gravel can meet requirements, like high quality, low shrinkage, impermeable, high bond, high early strength, user friendly and low temperature curing ability. Set 45 pockets and joints showed complete bond after two years in a heavily used arctic bridge. Gulyas et al (1995) undertook a laboratory study to compare composite grouted keyway specimens using two different grouting materials: non-shrink grouts and magnesium ammonium phosphate (MAP) mortars, in which Mg-NH4-PO4 materials perform better than non-shrink grouts. Gulyas and Champa (1997) further examined inadequacies in the selection of a traditional non-shrink grout for use in shear key ways. The MAP grout outperformed the non-shrink in all areas tested, including direct vertical shear, direct tension, longitudinal shear, bond, shrinkage, etc. Badie and Tadros (2006) considered several commercial grout materials for use in the proposed systems. Issa et al. (2003) evaluated the behavior of a female-to-female joint detail using Set 45, Set 45HW, Set Grout and EMACO 2020 (polymer concrete). The shear, tensile and flexural strength of joints made with EMACO 2020 were the highest among all 4 types of grouting materials, and EMACO 2020 was significantly less permeable and showed lower shrinkage deformation compared to other grout materials. Menkulasi and Roberts-Wollmann (2005) presented a study of the horizontal shear resistance of the connection between full-depth precast concrete bridge deck panels and prestressed concrete girders. Two types of grout were evaluated: a latex modified grout and a magnesium phosphate grout (Set 45 hot weather formulation). For both types of grout, an angular pea gravel filler was added. The Set 45 formulation developed slightly higher peak shear stresses than the latex modified grout.

Grout without coarse aggregate extension is usually referred to as neat grout, while grout with coarse aggregate extension, typically 1/2 –in. or 3/8 in. coarse aggregate, is extended grout. Comparing with neat grout, extended grout has the following potential benefits: (1) more compatible with concrete; (2) better interlock between connection components; (3) denser, less permeable; (4) less drying shrinkage and creep; and (5) larger grout volume per bag, hence less expensive.

Based on the research performed in Texas (Matsumoto et al, 2001), however, the following conclusions were made regarding the use of extended grouts. (1) The excessive surface area of mixes with 50 lbs of pea gravel required more cement paste than available in prepackaged bags, leading to lower strengths and poor workability. (2) Using coarse aggregate larger than 3/8-in. would reduce segregation and improve workability, compared to extended grouts with 3/8-in. pea gravel. Use of extended grouts or concrete with small aggregate should be used with caution. And (3) Neat grouts are preferable from a constructability and economic perspective. Ralls (2004) reports that for grouts, concretes and sealants for joints, non-shrink grouts are typically specified for the smaller closure joints, and standard or special concrete mixtures for larger joints. It was indicated that alternate materials such as magnesium ammonium phosphate mortars and polymer modified concretes exhibit superior bond strength, compressive strength and lower permeability. More information on the long-term durability and ease of construction is needed to implement these materials. More concerns are related to the interface between the precast deck and the cast-in-place closure, since cracks can develop due to shrinkage or poor bonding from the outset.

Varieties of materials are available for the joint materials. And the selection of joint materials for precast deck systems in this paper is based on the performance specification. Performance-based specifications focus on properties such as consistency, strength, durability, and aesthetics, rewarding quality, innovation, and technical knowledge, in addition to promoting better use of materials, and thus present an immense opportunity to optimize the design of materials. The industry is evolving specifications from prescriptive requirements to performance-based concepts.

In this paper, for rapid construction purpose, two categories of materials (overnight cure and 7-day cure) are studied. For the overnight cure, published performance data from different grout materials were collected through contacts with material suppliers and users. For the 7-day cure, standard or special concrete mixtures and their performance data were collected through contacts with HPC showcase states as well as with material suppliers. Four grouts were firstly selected as candidate overnight cure materials, and five special concrete mixes as candidate 7-day cure materials. The preliminary selection was based on some strength tests of selected materials or prediction model to narrow the choices down to two different materials in each of the two joint material classifications. Then long-term tests will be performed on the four final selected materials, including freeze thaw, shrinkage, bond, and permeability tests. This paper is focused on the preliminary selection.

SIGNIFICANCE

Joints between adjacent precast decks or flanges are filled with joint materials to bond the two precast members, thus making the joints structural elements of the bridge. As such, longitudinal and transverse joints must be able to resist shear and moment induced by vehicular loads. Shrinkage of joint materials and transverse shorting of precast members further subject the joints to direct tension. Freeze thaw resistance and low permeability of joints are also important. The joints are important because the whole bridge performance is manifested in the behavior of its joint. The best joints should provide high flexural and shear resistance, full bond and complete tightness. However, there have been cases of unsatisfactory performances of such joints as evidenced by cracking in asphalt surfacing directly over the joints and moisture leakage. Issa et. al. (1995) concluded that material quality, construction procedures and maintenance are the main reasons for the problems associated with joints. The closure pour/precast unit interface is of concern in the area of durability. The focus must be on minimizing cracking in this location to reduce intrusion of water that may result in corrosion. An ideal connection detail emulates monolithic behavior and results in a more durable and longer lasting structure. When selecting bonding materials, performance based specifications for durability in the form of performance criteria need to be developed to be able to proportion concrete mixtures or other grouting materials that are capable of protecting structures against a given degradation for a specified service life in given environmental conditions. The selection of joint materials is critical.

PERFORMANCE CRITERIA

Performance characteristics, compressive strength, shrinkage, chloride penetration, freezing-and-thawing durability and bond strength, are investigated as performance criteria. As mentioned, for the closure pour/precast unit interface the focus must be on minimizing cracking in this location to reduce intrusion of water that may result in corrosion. And thus, shrinkage, chloride penetration, freezing-and-thawing durability and bond strength need be investigated to control cracking and corrosion. For accelerated construction, two classifications of materials, overnight cure and 7-day cure, are studied. An extensive literature review has been performed to develop performance criteria of overnight and 7-day cure materials.

The FHWA produced a definition of HPC that identified a set of concrete performance characteristics for long-term concrete durability and strength of highway structures. The four performance characteristics related to durability are freezing-and-thawing durability, scaling resistance, abrasion resistance, and chloride ion penetration. The four structural design characteristics are compressive strength, modulus of elasticity, shrinkage, and creep. Standard laboratory tests, specimen preparation procedures, and grades of performance were suggested for each characteristic. Because standard test methods sometimes offer different options, Russell and Ozyildirim (2006) modified the FHWA definition and the modified performance characteristic grades for high-performance structural concrete are shown in Table 1. Only compressive strength, shrinkage, chloride penetration and freezing-and-thawing durability, performance characteristics investigated in the research, are listed here.

Tepke and Tikalsky (2007) provided a working guide to the design and construction of concrete structures using attainable high standards rather than common practice. An engineering design tool for the development of performance specifications for reinforced concrete highway structures was developed and performance characteristic grades for HPC are shown in Table 2, where only compressive strength, shrinkage, chloride penetration and freezing-and-thawing durability, performance characteristics investigated in the research, are listed.

Table 1 Proposed Performance Characteristic Grades (FHWA)

Performance characteristic	Test Method	Grade 1	Grade 2	Grade 3
Compressive Strength (CS) (ksi)	AASHTO T22 ASTM C 39	8≤CS<10	10≤CS<14	14≤CS
Shrinkage (S) (micro-strain)	AASHTO T160 ASTM C157	800>S≥600	600>S≥400	400>S
Chloride Penetration (CP) (coulombs)	AASHTO T277 ASTM C1202	2500≥CP>1500	1500≥CP>500	500≥CP
Freezing-and-thawing durability (F/T) relative dynamic modulus of elasticity after 300 cycles	AASHTO T161 ASTM C666 Procedure A	70%≤ F/T <80%	80%≤ F/T<90%	90%≤ F/T

*All tests to be performed on concrete samples moist- or submersion-cured for 56 days until otherwise specified.
**The 56-day strength is recommended.
*** Shrinkage measurements are to start 28 days after moist curing and be taken for a drying period of 180 days.

Table 2 Performance Characteristic Grades (PENNDOT)

Performance Characteristic	Test Method	Grade 1	Grade 2	Grade 3
Compressive Strength (CS), ksi	AASHTO T22	3.5≤CS<8.0 @ 28 days	8.0≤CS @ 28 days	3.5≤CS @ early ages
Shrinkage (S) micro-strain	ASTM C157	600≥S @ 56 days	400≥S @ 56 days	200≥S @ 56 days
Chloride Penetration (CP) coulombs	AASHTO T277*	4000≥CP @ 56 days**	1500≥CP @ 56 days	800≥CP @ 56 days
Freezing-and-thawing durability (F/T) relative modulus after 300 cycles	AASHTO T161 Proc. A after 28 days moist curing and 7 days air drying	60%≤F/T	80%≤F/T	90%≤F/T

*Mixtures containing permeability reducing admixtures or corrosion inhibiting admixtures must be evaluated using alternative procedures.
** Alternatively, the samples can be tested at 28 days after 7 days of curing at 73 ^{0}F and an additional 21 days at 100 ^{0}F.

As shown in Tables 1 and 2, the same or similar standard laboratory tests were recommended. Also three grades were suggested in both criteria. PENNDOT performance criteria have lower requirements for compressive strength and chloride penetration, and higher requirements for shrinkage than the FHWA criteria in all three grades. They have similar grade limits for freezing-and-thawing durability.

The problem for these two criteria is that they are exactly “Lab crete” and not “Real crete”. The materials should be cured in the same way as in the real project, and then tested. In this research, EUCO-SPEED MP and SET 45 HW will be air cured for 8 hours, as overnight cure materials, while HPC will be cured for 7 days, as 7-day cure materials, by both the membrane-forming compound method and the water method with burlap (a specific curing method for bridge decks required by some state DOT). If time and labor are of no consequence to the research, different curing condition can be considered, a worst case scenario (no cure), best case scenario (100% humidity cure) and something in between (curing compound).

The test methods need also be modified. For the shrinkage, when shrinkage occurs after initial moist curing, concrete starts to develop stiffness as measured by the Modulus of Elasticity. High Performance concretes often have Low W/CM ratios and high stiffness as a result. If the shrinkage strains are high enough, they simply crack due to the restraint, the stiffness, and the drying shrinkage. For joint materials, the restraint is developed due to the internal reinforcing steel, especially the steel that runs through the construction joint in existing concrete member into the next cast adjacent concrete member or section. This is tremendous "racking restraint" that does not allow the second adjacent slab to shorten during cooling from hydration heat and also due to later developing drying shrinkage--especially if there is considerable time allowed between the two adjacent placement. The ASTM C1581 Restrain Shrinkage Ring Test can test the crack potential, and should be used instead of ASTM C157 test. There are also issues with the ASTM C1202 RCP test. The RCP test has some interference problems with materials such nitrate corrosion inhibitors and even Set-45. Part of the problem is the epoxy coating that must be bonded to the exterior side walls of the core. The coating must block the chloride from runing through the specimen. To avoid that issue, ASTM C1543 ponding test should be used to determine the Chloride gradient.

Table 3 was proposed as the draft performance criteria of closure pour materials before the tests. As ASTM C1543 ponding test is newly developed and not used widely, the criterion value for this test is not decided here and will be developed after evaluation tests.

Table 3 Performance Criteria

Performance Characteristic	Test Method	Draft Performance Criteria
Compressive Strength (CS) ksi	ASTM C39	6.0≤CS @ 8 hours (overnight cure) @ 7 days (7-day cure)
Shrinkage (S) Crack age, day	ASTM C1581	S≤5
Bond Strength	After evaluation tests	
Chloride Penetration (CP) Percent Chloride by mass of mortar or concrete after 90-day ponding	ASTM C1543	After evaluation tests
Freezing-and-thawing durability (F/T) relative modulus after 300 cycles	ASTM C666 Procedure. A Modified	90%≤F/T

Based on the above proposed performance criteria, a preliminary selection was made to narrow the choices down from the candidate materials to two different materials in each of the two joint material classifications. Further long-term tests, including freeze thaw, shrinkage, bond, and permeability tests, will be performed to evaluate these selected four joint materials (two for each cure) in order to validate the proposed performance criteria.

CANDIDATE MATERIALS

OVERNIGHT CURE MATERIALS

For the overnight cure, different grout materials were considered as the candidate materials. Published performance data from different grout materials were collected through contacts with material suppliers and users. Based on their potentials to meet the proposed performance criteria, candidate grouts were selected. The mixing information is shown in Table 4. Five Star® Patch is cement-based, while EUCO-Speed MP, Set® 45 and Set® 45 Hot Weather are all magnesium-phosphate based. Water and aggregate extension amounts used were based on manufacturer recommendations. 3/8-in. pea gravel is used as aggregate. And the aggregate should be tested for fizzing with 10% HCL to avoid calcareous aggregate made from soft limestone.

Table 4 Candidate Grouts and Mixing Information

ID No. and Product Name		Mixing Quantities per 50-lb, Bag				
		Initial Water, pints	Additional Water, pints	Aggregate Extension, % by weight	Aggregate Extension, lb	Yield Volume, cu. ft.
Neat Grout	EUCO-SPEED MP	3.1	0.5	0	0	0.42
	Five Star Patch	5.00	1.00	0	0	0.40
	SET 45	3.25	0.50	0	0	0.39
	SET 45 HW	3.25	0.50	0	0	0.39
Extended Grout	EUCO-SPEED MP	3.1	0.5	60	30	0.57
	Five Star Patch	5.00	1.00	80	40	0.66
	SET 45	3.25	0.50	60	30	0.58
	SET 45 HW	3.25	0.50	60	30	0.58

7-DAY CURE MATERIALS

For the 7-day cure, different HPC mixes were considered as the candidate materials through contacts with HPC showcase states. The candidate HPC mix designs are listed in Table 5. Mixes 1 to 4 were selected from Russell, Miller, Ozyildirim, and Tadros (2006), and Mix 5 was developed by working with River Region Cement Division of Lafarge.

Table 5 Candidate HPC Mix Proportions

MIX NUMBER	MIX 1	MIX 2	MIX 3	MIX 4	MIX 5	
Source Reference	"Compilation and Evaluation of Results from HPC Bridge Projects, Volume 1: Final Report"				Lafarge	
W/CM Ratio	0.31	0.39	0.35	0.31	0.32	
Cement Type	IP	II	I	II	I / II	
Cement Quantity, lb/yd^3	750	511	474	490	563	
Fly Ash Type	C		C	C	C	
Fly Ash Type Quantity, lb/yd^3	75	118	221	210	75	
Slag Quantity, lb/yd^3					113	
Silica Fume, lb/yd^3		55			39.4*	
Fine Aggregate, lb/yd^3	1400	1100	1303	1365	1161	
Coarse Aggregate Maximum Size (inches) OR #	0.5		1	1.25	#57	#8
Coarse Aggregate Quantity, lb/yd^3	1400	1725	1811	1900	1530	270
Water, lb/yd^3	255	264	244	219	234	
Air Entrainment, fl oz/yd^3	5			3.1	3	
Water reducer, fl oz/yd^3	30	41			60	
Retarder, fl oz/yd^3			22	28		
High-Range Water Reducer, fl oz/yd^3	135		122	156		
Shrinkage Reducing Admixture, fl oz/yd^3					32	

* 7% of silica fume in blended cement.

SELECTION OF TWO OVERNIGHT CURE MATERIALS

The preliminary selection is based on some strength tests of selected materials to narrow the choices down to two different materials in the overnight cure material classification. Then long-term tests will be performed on the two final selected materials, including freeze thaw, shrinkage, bond, and permeability tests. It has been found that a certain high compressive strength is needed to develop headed bars and/or U-bars within a short overlap length. Therefore, compressive strength tests were used to select two overnight cure materials.

MIXING

Each candidate grout was mixed according to manufacturer recommendations. For all neat grout, first an initial amount of water is placed in the mixer, and then the grout powder is added while the mixer turns. When approximately 80% of the powder is added, an additional specified amount of water is supplied to the mix, which significantly improves its workability. And 2-min mixing was used for EUCO-Speed MP, 3-min mixing for Five Star® Patch, and 1.5-min mixing for Set® 45 and Set® 45 Hot Weather. For Five Star® Patch, Set® 45 and Set® 45 Hot Weather batches with a pea gravel aggregate extension, all of the aggregate for each batch is placed in the mixing container with the initial water before any powder is added. And the mixing time is the same as used for the neat grout. For EUCO-Speed MP extended, the pea gravel was added after the neat grout had mixed, and then was mixed for an additional 1 minute.

COMPRESSIVE STRENGTH TEST METHODS

For neat grouts, the compressive strength is tested per ASTM C109 (2005). Both ASTM C109 (2005) and ASTM C39 (2005) were used to obtain the compressive strength for extended grouts to get both the cube strength and the cylinder strength.

CURING METHODS

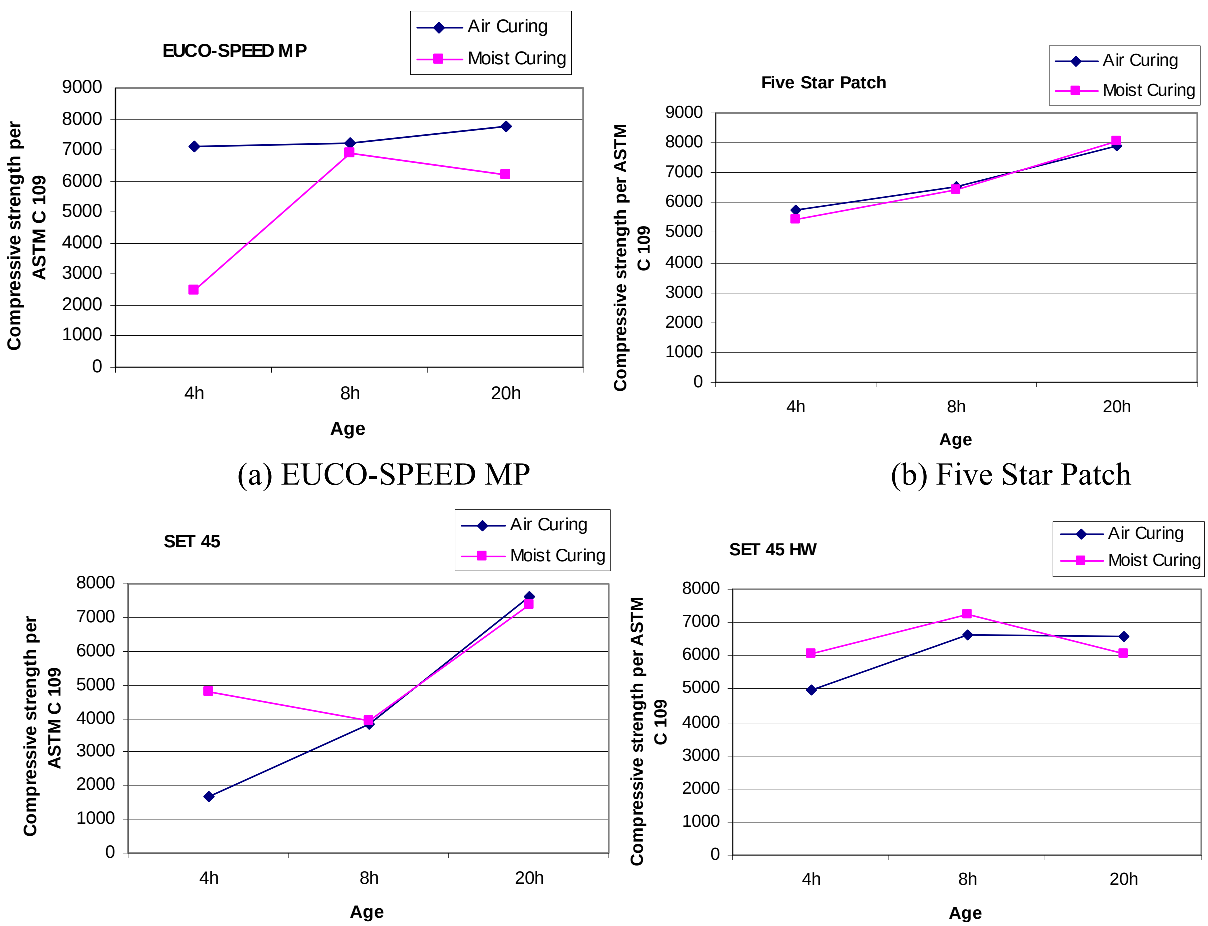
Both ASTM C109 and ASTM C39 require moist curing. However, the manufacturers for Euco-Speed MP, Set45 and Set45 HW do not recommend wet curing their products. And thus two normally used curing methods, air curing and moist curing, are investigated. The test results for different grouts using these two curing methods are summarized in Table 6 for neat grouts and Table 7 for extended grouts. The compressive strengths are compared in Figure 2 for neat grouts and Figure 3 for extended grouts. And it is found that the curing methods do not make a big difference for the strength.

Table 6 Compressive strengths of the neat grouts per ASTM C 109

	4h		8h		20h	
	Air Curing	Moist Curing	Air Curing	Moist Curing	Air Curing	Moist Curing
EUCO-SPEED MP	7091.9	2474.5	7201.4	6898.8	7746.0	6194.0
Five Star Patch	5776.9	5436.7	6558.2	6452.7	7887.2	8051.5
SET 45	1696.6	4767.3	3849.8	3940.7	7598.7	7381.7
SET 45 HW	4991.7	6042.3	6614.3	7235.5	6584.6	6045.4

Table 7 Compressive strengths of the extended grouts per ASTM C 39

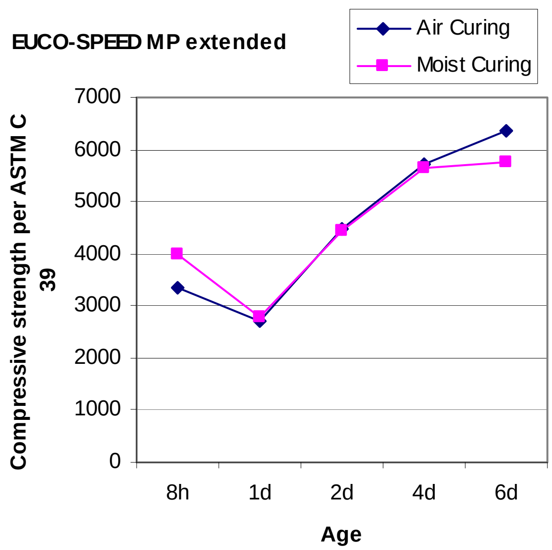
	8h		1d		2d		4d		6d	
	Air Curing	Moist Curing	Air Curing	Moist Curing	Air Curing	Moist Curing	Air Curing	Moist Curing	Air Curing	Moist Curing
EUCO-SPEED MP extended	3357.0	3989.2	2691.6	2766.7	4474.9	4436.6	5726.4	5650.2	6347.2	5745.7
Five Star Patch extended	1283.4	473.1	2824.0	2721.2	722.0	1362.1	NA	NA	NA	NA
SET 45 extended	2099.6	1967.9	3143.4	3673.0	6373.7	6386.5	NA	NA	NA	NA
SET 45 HW extended	3444.9	2903.8	4102.3	3425.4	5684.2	5514.7	6749.0	6416.9	6286.0	6217.7



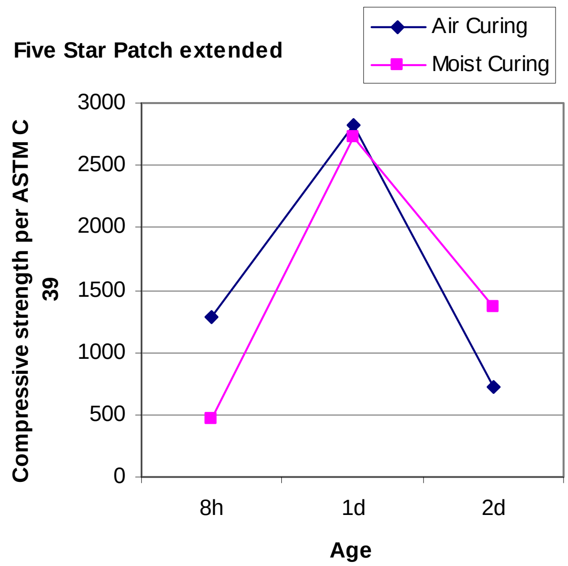
(a) EUCO-SPEED MP (b) Five Star Patch

(c) SET 45 (d) SET 45 HW

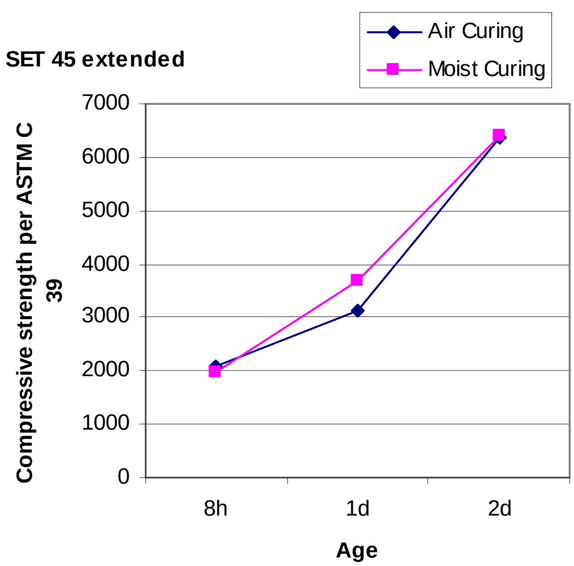
Fig. 2 Compressive Strength Development of Neat Grouts



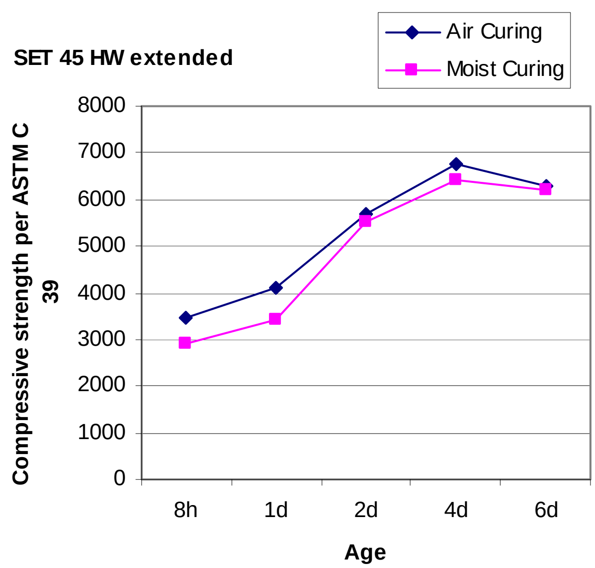
(a) EUCO-SPEED MP extended



(b) Five Star Patch extended



(c) SET 45 extended

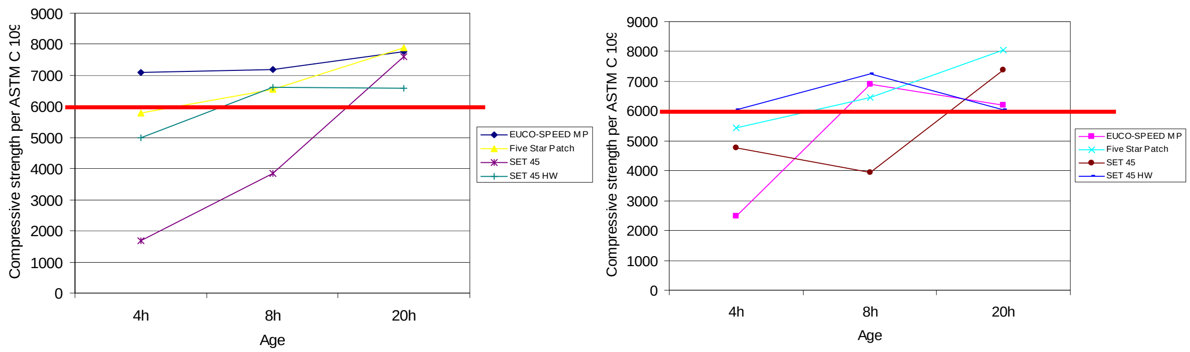


(d) SET 45 HW extended

Fig. 3 Compressive Strength Development of Extended Grouts

GROUT APPLICATION

To reach the same strength, different grouts need different curing periods, curing methods, etc. For the 6000-psi strength, all the curing and test information is listed in Table 8 for neat grouts based on the results in Figure 4. And for extended grouts, based on Figure 5 and 6, the curing and test information is presented in Table 9 and 10. Also, more test data for SET 45 HW extended (air curing) is shown in Figure 7.

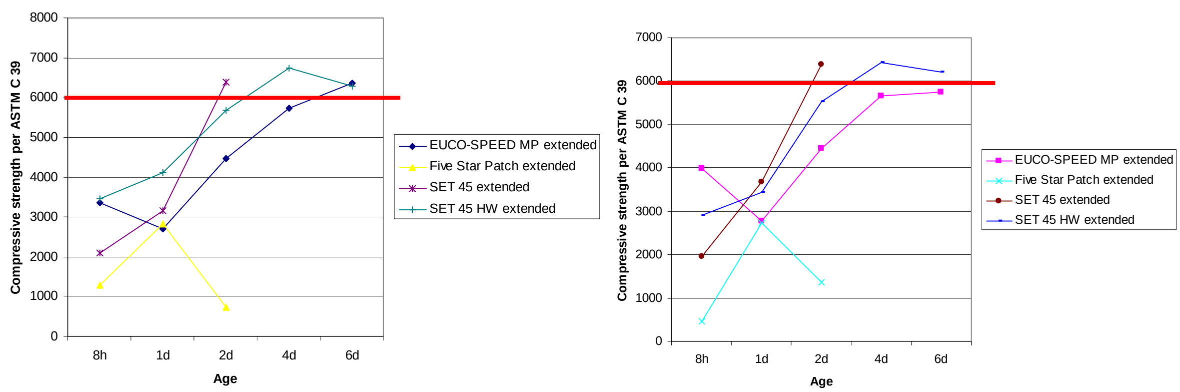


(a) Air Curing (b) Moist Curing

Fig. 4 Compressive Strength Development of the Neat Grouts Per ASTM C109

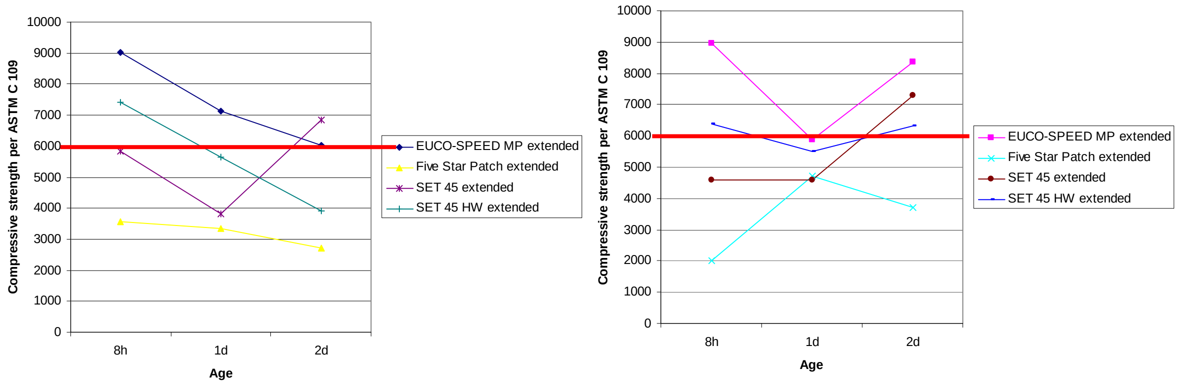
Table 8 Curing conditions for compressive strength of 6000 psi for neat grouts

	Age	Curing Method	Specimen Size
EUCO-SPEED MP	4 hour	Air curing	2-in. Cube
Five Star Patch	8 hour	Air/Moist curing	2-in. Cube
SET 45	20 hour	Air/Moist curing	2-in. Cube
SET 45 HW	4 hour	Moist curing	2-in. Cube



(a) Air Curing (b) Moist Curing

Fig. 5 Compressive Strength Development of the Extended Grouts Per ASTM C39



(a) Air Curing (b) Moist Curing

Fig. 6 Compressive Strength Development of the Extended Grouts Per ASTM C109

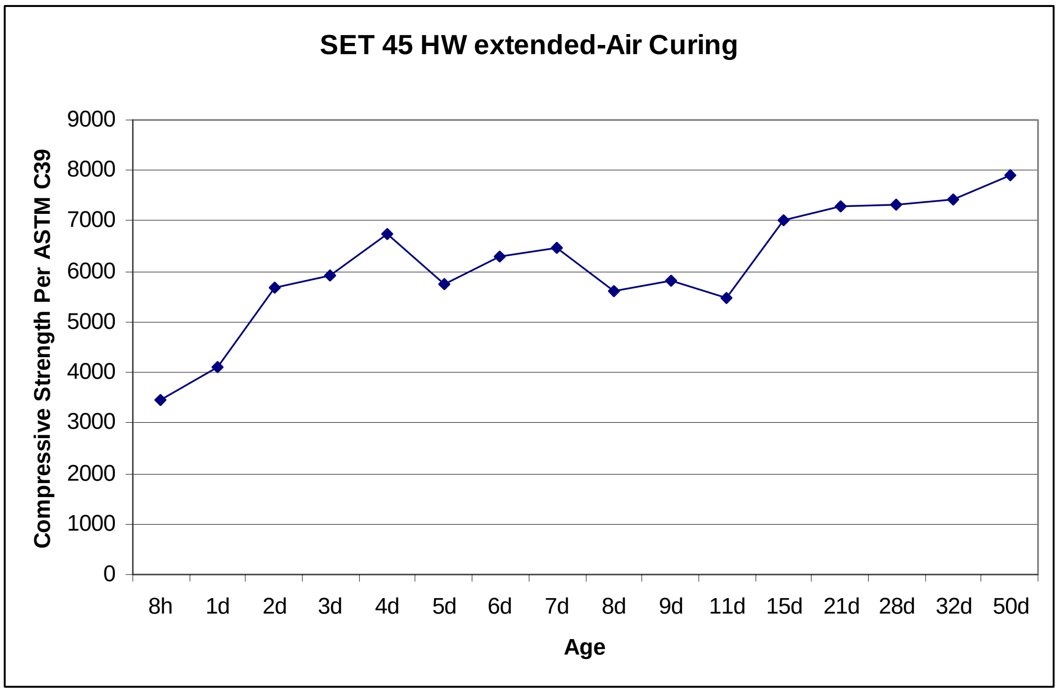


Fig. 7 Compressive Strength Development of SET 45 HW extended Per ASTM C39 (Air Curing)

Table 9 Curing conditions for compressive strength of 6000 psi for extended grouts per ASTM C39

	Age	Curing Method	Specimen Size
EUCO-SPEED MP extended	6 day	Air curing	4-by-8 Cylinder
Five Star Patch extended	N.A.	N.A.	4-by-8 Cylinder
SET 45 extended	2 day	Air/Moist curing	4-by-8 Cylinder
SET 45 HW extended	4 day	Air/Moist curing	4-by-8 Cylinder

Table 10 Curing conditions for compressive strength of 6000 psi for extended grouts per ASTM C109

	Age	Curing Method	Specimen Size
EUCO-SPEED MP extended	8 hour	Air/Moist curing	2-in. Cube
Five Star Patch extended	N.A.	N.A.	2-in. Cube
SET 45 extended	2 day	Air/Moist curing	2-in. Cube
SET 45 HW extended	8 hour	Air curing	2-in. Cube

FLOW AND WORKABILITY

Flow

Flow characteristics for each grout were measured in accordance with ASTM C 1437 (2001) [21]: Standard Test Method for Flow of Hydraulic Cement Mortar (modified). Specifications for the flow table and truncated flow cone were found in ASTM C 230 (2003) [22]: Standard Specification for Flow Table for Use in Tests of Hydraulic Cement.

In the tests, the table was dropped 10 times within 15 seconds instead of 25 drops within 15 seconds according to the standard test method. The modification was needed to consider the fact that these particular types of grouts tend to flow better than the average mortars for which this test method is intended. Twenty-five drops would result in the grout spreading across the entire 10 in. diameter of the table and the purpose of the test would be lost. Flow results from the ASTM C 1437 (2001) truncated flow cone tests are presented in Table 11 and Figure 8 for neat gouts and Table 12 and Figure 9 for extended gouts.

Table 11. Truncated Flow Cone Spread Values per ASTM C 1437 for neat gouts

Grout name	Initial		After 10 Drops		Total Diameter Increase, %
	Average Spread, in.	Diameter Increase, %	Average Spread, in.	Additional Diameter Increase, %	
EUCO-SPEED MP	9.6	140	10.0	4	150
Five Star Patch	4.8	20	5.6	17	40
SET 45	4.4	10	5.5	25	37.5
SET 45 HW	8.8	120	9.3	6	132.5

Initial Flow Cone Diameter = 4 in.

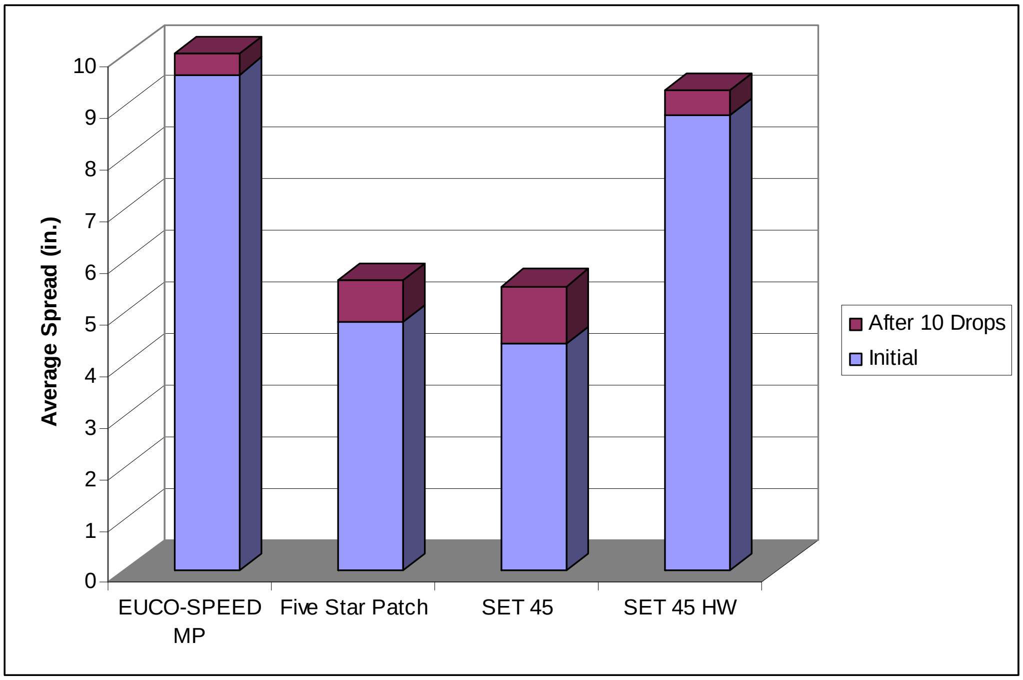


Fig. 8 Truncated Flow Cone Spread Values per ASTM C 1437 for neat gouts

Table 12. Truncated Flow Cone Spread Values per ASTM C 1437 for extended gouts

Grout	Initial		After 10 Drops		Total Diameter Increase, %
	Average Spread, in.	Diameter Increase, %	Average Spread, in.	Additional Diameter Increase, %	
EUCO-SPEED MP extended	4.0	0	4.1	2	2.5
Five Star Patch extended	4.0	0	4.0	0	0
SET 45 extended	4.0	0	4.0	0	0
SET 45 HW extended	3.9	-3	4.0	3	0

Initial Flow Cone Diameter = 4 in.

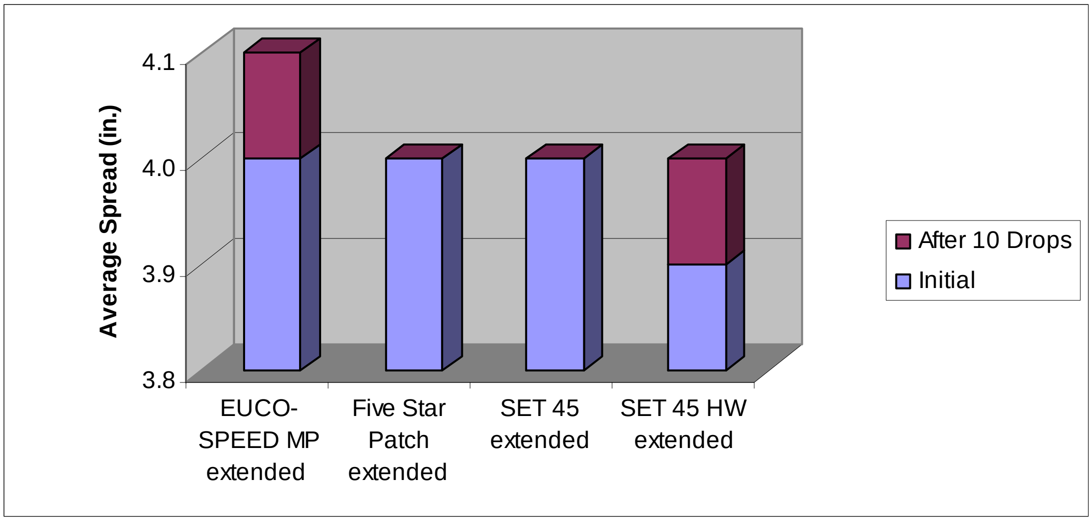


Fig. 9 Truncated Flow Cone Spread Values per ASTM C 1437 for extended gouts

Workability

Observations were made regarding the workability of each grout based on the degree of effort required to mix each product as well as their work time and initial set time. Work time was measured from the start of mixing until workability began to decrease. Decreased workability is defined by the inability to move the grout with vibration, or easily finish a surface. Initial set time was measured from the start of mixing until the product showed resistance to the penetration of a thin rod or trowel edge. The product had attained its initial hardened state at this time. This information, along with observations regarding each product's consistency is presented in Table 13 for neat gouts and Table 14 for extended gouts.

Table 13. Candidate Grout Workability Observations for neat gouts

Grout	Work Time, min.	Initial Set Time, min.	Consistency
EUCO-SPEED MP	8	14	medium
Five Star Patch	18	32	medium
SET 45	6	10	medium
SET 45 HW	32	47	runny

Table 14. Candidate Grout Workability Observations for extended gouts

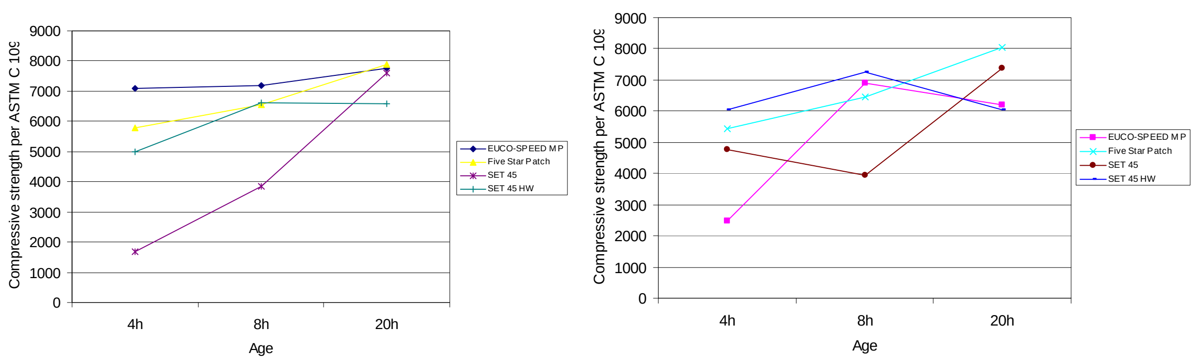
Grout	Work Time, min.	Initial Set Time, min.	Consistency
EUCO-SPEED MP extended	16	21	thick
Five Star Patch extended	13	27	thick
SET 45 extended	10	18	thick
SET 45 HW extended	30	45	thick

Among the neat grout candidates, EUCO-SPEED MP and SET 45 HW perform better than the remaining two based on the flow and workability performance.
Among the extended grout candidates, EUCO-SPEED MP extended and SET 45 HW extended perform better than the remaining two based on the flow and workability performance.

All the extended grouts didn't perform well in the flow cone spread testing. And for the workability, only SET 45 HW extended has favorable workability results. And Five Star Patch extended 80% and SET 45 extended 60% were almost impossible to mix with such a high recommended aggregate extension. Their flow suffered because of this. The Five Star Patch extended 80% exhibits lower strength than the neat grout, while SET 45 extended 60% gains higher strength than the neat grout for 8-hour period. A lower aggregate extension ratio would be more suitable for use in a precast deck panel system.

GROUT SELECTION

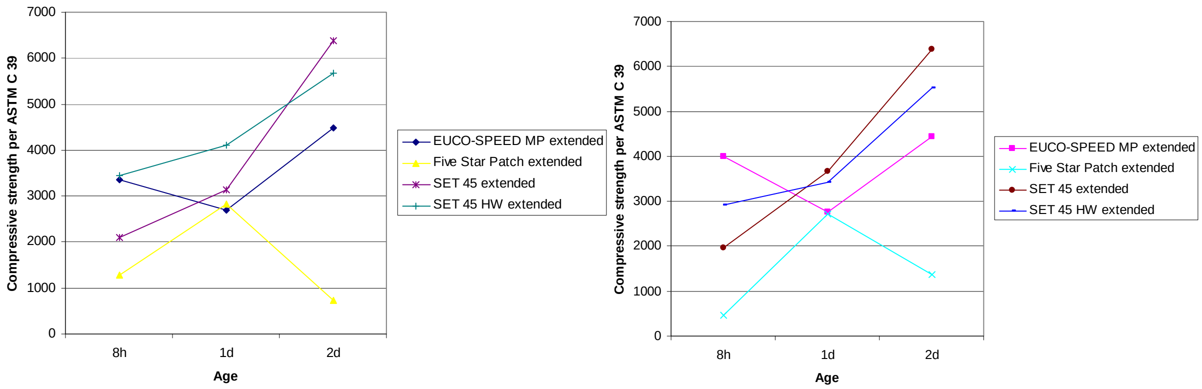
The compressive strengths of the neat grouts are compared in Figure 10. EUCO-SPEED MP (air curing) and SET 45 HW (moist curing) perform better than the remaining two. These two grouts also exhibited good flow and workability performance among the four neat grouts, as is shown in Table 11, 13 and Figure 8.



(a) Air Curing (b) Moist Curing

Fig. 10 Compressive Strength Development of the Neat Grouts

The compressive strength development of the extended grouts is presented in Figures 11. Comparing the strength development in Figure 11, SET 45 extended and SET 45 HW extended perform better than the remaining two. However, SET 45 extended didn't show good workability performance, which is listed in Table 14. EUCO-SPEED MP extended exhibited good compressive strength and also flow and workability performance. And thus EUCO-SPEED MP extended and SET 45 HW extended are selected among the extended grouts.



(a) Air Curing (b) Moist Curing

Fig. 11 Compressive Strength Development of the Extended Grouts

Furthermore, comparing the compressive strength and flow and workability performance of both neat and extended grouts, EUCO-SPEED MP and SET 45 HW are much better and selected.

SELECTION OF TWO 7-DAY CURE MATERIALS

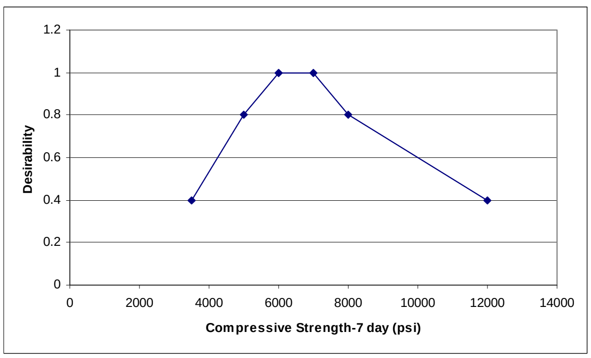
For HPC, the mixing procedure is based on ASTM C192, Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. Prior to starting rotation of the mixer add the coarse aggregate, some of the mixing water, and the solution of admixture, when required. When feasible, disperse the admixture in the mixing water before addition. Start the mixer, then add the fine aggregate, cement, and water with the mixer running. Mix the concrete, after all ingredients are in the mixer, for 3 min followed by a 3-min rest, followed by a 2-min final mixing.

In the test, it was found this procedure is too long to be applicable for the HPC materials due to their quick setting. And thus 3-min mixing, then 0.5-min rest followed by 2-min final mixing was used.

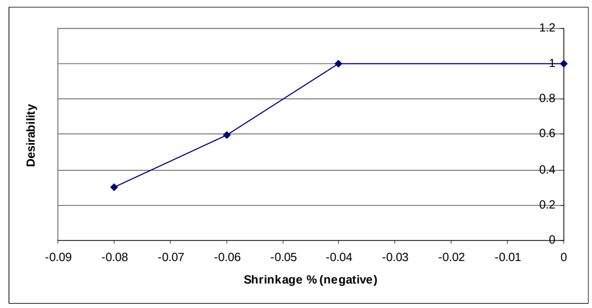
The candidate HPC mix designs are listed in Table 5. Due to the incomplete information for Mix 2, it is not considered. Two best mix proportions is selected from these four mixes (Mix 1, Mix 3, Mix 4 and Mix 5), as discussed in details below.

The approach developed by NCHRP project 18-08A (Lawler et al, 2007) was used to predict and compare the performance of the four selected candidate mixes. In the NCHRP project 18-08A, researchers developed a statistically based experimental methodology that can be used to identify the optimum concrete mixture proportions for a specific set of conditions. The test program for the case study was conducted by the researchers, and based on the test data collected, a completed worksheet was developed, which can be used to predict performances of hydraulic cement concrete mixtures incorporating supplementary cementitious materials. Some terms used in this research are defined below.

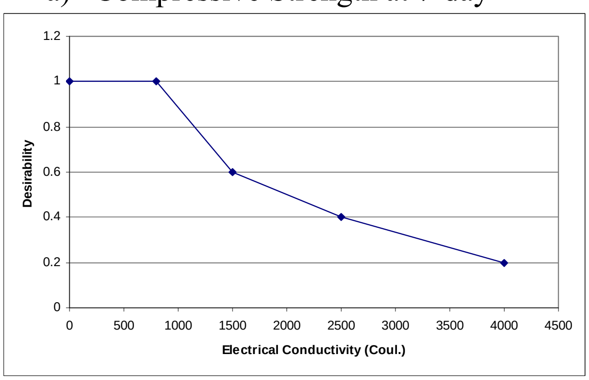
Desirability was defined in the NCHRP project 18-08A. Desirability function is a function that converts any test result into a value between 0 and 1, where 0 means the result is unacceptable, and 1 means the result needs no improvement. Intermediate values show the level of acceptability (desirability) of the result. The overall desirability for each mixture is the geometric mean of the individual desirability for that mixture for each test. For example, if the desirability functions for four different tests are represented by d_1, d_2, d_3 and d_4, the overall desirability, D, will be defined as $\sqrt[4]{d_1 \times d_2 \times d_3 \times d_4}$. Response is the measured value from a performance test. This value is the dependent, or y-variable, used in an experiment. According to our criteria, the four responses are compressive strength at 7 day, shrinkage, chloride penetration and freezing-and-thawing durability. The corresponding desirability functions of the four responses were selected, as shown in Figures 12.



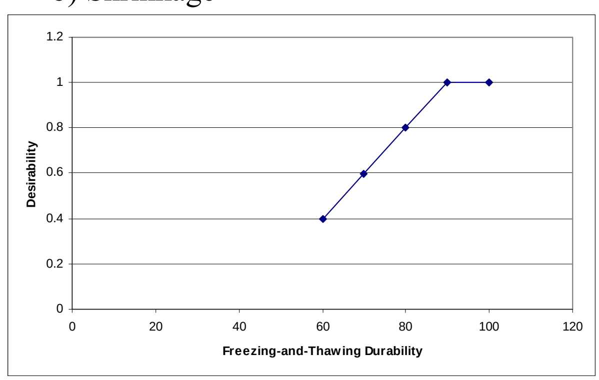
a) Compressive Strength at 7-day



b) Shrinkage



c) Chloride Penetration



d) Freezing-and-Thawing Durability

Fig. 12 Desirability Function for a) Compressive Strength at 7-day, b) Shrinkage, c) Chloride Penetration and d) Freezing-and-Thawing Durability

Factors are the independent variables, or x-variables, that are intentionally varied in an experiment. In the test program provided by NCHRP project 18-08A, four factors of the mix design were investigated, including type of supplementary cementitious materials (SCM), amount of SCM, amount of silica fume, and w/cm ratio. Factor level is a level associated with a specific factor. For example for the type of SCM, three levels were considered in NCHRP project 18-08A: class C fly ash, class F fly ash and slag.

Using the standard linear regression analysis to obtain the response of a given mix that best fits the testing data, a model was developed in NCHRP project 18-08A (NCHRP18-08A Model). The NCHR18-08A Model can be used to predict the desirability functions of an untested mixture from a combination of the levels of the factors and materials of the mixture. And using this model, the predicted overall desirability for all the four mixes in our project is listed in Table 15.

Table 15 Predicted Overall Desirability for the Four Mixes

	MIX 1	MIX 3	MIX 4	MIX 5	
Predicted Overall Desirability	0.80	0.66	0.75	0.98[1]	0.90[2]

1. Based on the quantity of Fly ash Type C
2. Based on the quantity of Slag

In the NCHRP18-08A Model, only one type of SCM (Fly ash Type C, Fly ash Type F or Slag) was considered. However, there exist two types of SCM (Fly ash Type C and Slag) in Mix 5. By considering the two types of SCM separately in the Model, two overall desirability values were predicted, as shown in Table 15. The combined overall desirability of Mix 5 can be taken as $(0.98 \times 0.90)^{0.5} = 0.94$.

Better performance is expected for the mix with the greater predicted overall desirability. In summary, Mix 1 and Mix 5 are selected as the 7-day cure materials for the long-term tests in the second phase.

CONCLUSIONS

Based on extensive literature reviews and experimental investigation carried out in this paper, the following conclusions were made.

1. The selection of joint materials is critical. For rapid construction, two categories of materials, overnight cure and 7-day cure, are studied. Performance based specifications in the form of performance criteria are developed, and a preliminary selection protocol is developed.
2. For the candidate grouts, the curing method, air curing or moist curing, didn't make a big difference for the compressive strength. [From a field performance stand point, air curing is easier at the job site.
3. Among the neat grout candidates, SET 45 HW and EUCO-SPEED MP perform better than the rest two based on the compressive strength, considering flow and workability performance.

4. Among the extended grout candidates, EUCO-SPEED MP extended and SET 45 HW extended perform better than the rest two based on the compressive strength, considering flow and workability performance.
5. Comparing the compressive strength and flow and workability performance of both neat and extended grouts, SET 45 HW and EUCO-SPEED MP are much better than the extended ones and selected.
6. For the Five Star Patch extended and SET 45 extended, a lower aggregate extension ratio would be more suitable for use in a precast deck panel system.
7. The completed worksheet developed by NCHRP project 18-08A (Lawler et al, 2007) can be used to predict performances of hydraulic cement concrete mixtures incorporating supplementary cementitious materials.

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