CHARACTERIZATION OF MATERIALS USED IN PRECAST BRIDGE ELEMENT CONNECTIONS

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ABSTRACT

Accelerated construction of bridges with precast components requires the rapid placement of connections. Many of these connections between precast components include fast curing materials designed for implementation within days or even hours. Previous case studies have shown that some materials currently used in precast construction connections may have shrinkage and durability shortcomings leading to substandard performance.

This investigation consisted of characterizing seven different unique materials that may be used in the construction of precast bridge element connections. Some of these materials have been used on previous projects but others have had limited testing on bridge applications. The tested materials include: high early strength, low shrinkage grouts; magnesium phosphate grout; ultra-high performance concrete; epoxy grout; post-tensioning cable grout; and a standard concrete bridge deck mix. Various material characteristics were documented during the first few months after casting. Some of the materials reached in service strengths (3000 psi) days before the control concrete mix, however in many cases early age shrinkage was also substantially larger. Additionally, the long term shrinkage results demonstrate that some materials exhibit reduced early shrinkage then increased long term shrinkage as compared to a standard concrete mix. Each material had unique setting characteristics that could impact its workability and proper placement. The results provide a set of direct comparisons among all the materials including compressive strength gain, short and long term shrinkage, tensile strength, workability, and relative cost.

Keywords: Accelerated Construction, Bridge, Concrete, Connections, Grout, UHPC

INTRODUCTION

Initiatives such as the Federal Highway Administration's "Every Day Counts" program encourage the use of accelerated construction methods on bridges (FHWA 2010). The superstructure is one part of a bridge that can take a significant amount of time to construct or reconstruct. One popular method to reduce construction times is to use precast components. Their use has been documented for many years in a variety of situations. One of the most labor intensive parts of the construction process is placing the connections. Connections tend to deteriorate quicker than the rest of the bridge and have generally had varying levels of long-term performance (Biswas 1986, Issa, et al. 1995). One of the reasons for substandard performance may be the field-cast materials often used in these connections.

The materials within the connections have had limited research for bridge superstructure connections. Some researchers have tested a few types of grouts such as magnesium phosphate grout or non-shrink grouts. (Gulyas, Wirthlin and Champa 1995, Zhu and Ma 2010, Issa, et al. 2003, Badie and Tadros 2008). Many designers continue to specify low shrinkage, high early strength grouts even though these grouts have exhibited substandard performance at times in the past. Controlled laboratory testing of these grouts has demonstrated that shrinkage cracking and durability issues are of significant concern (Swenty 2009, Markowski 2005). There are renewed efforts that recognize the need to investigate a greater variety of materials in context of prefabricated component connections (French, et al. 2011).

A definitive set of guidelines or a comprehensive set of material results for precast connections has not been developed. Most research has focused on a particular grout or type of connection, not on direct comparisons between various connections and grouts. In addition, some newer materials, such as ultra-high performance concrete and cable grout, have not been as thoroughly investigated. The question remains whether there is a better material than standard cementitious grouts for field-cast connections between precast bridge components. A set of tests have been performed that compare multiple materials to a base line, standard bridge deck mix in order to characterize the numerous possible materials for use in precast bridge construction.

TESTING PROGRAM

A program was developed to investigate materials that have the potential for use in precast bridge component connections. The program was designed to characterize seven different unique materials that are readily available as prebagged mixes or standard concrete mixes. The materials included ultra high performance concrete (UHPC), magnesium phosphate grout, high strength-low shrinkage grouts (grout 1 and grout 2), epoxy grout, a bridge deck concrete, and post-tensioning cable grout. These generic names are listed in Table 1. Both materials traditionally referred to as grouts and materials traditionally referred to as concretes were engaged within this study to assess the performance of a range of materials which might be used in these field-cast connections between prefabricated bridge elements. Although field-cast materials placed into small volume connection spaces between prefabricated elements are traditionally referred to as grouts, some of these same materials could be referred to as concretes in other contexts.

Table 1 – Material names

Materials Tested
Grout 1
Grout 2
Cable Grout
Magnesium Phosphate Grout
Epoxy Grout
UHPC
Deck Concrete

Materials were chosen based on past performance, applicability to onsite construction processes, and suitable published properties. Some of the desirable properties include early compressive strength gain, high tensile strength, dimensional stability, and sufficient work time. Grout 1 and grout 2 are standard grouts with low shrinkage, good workability, and high early strength. The magnesium-phosphate grout has low shrinkage and high early strength. These types of grout have had previous use on precast bridges with varied success. The Virginia bridge deck concrete is a standard mix that would be used on a bridge deck and serves as the control within the study. The mix is designed to have a 0.45 water to cement ratio, 1 in. (2.5 cm) aggregate, and a 28 day strength of 4,000 psi (27.6 MPa). The cable grout is pumpable, easy to use, and has reasonable strength gain. The ultra-high performance concrete exhibits exceptional mechanical and durability characteristics (Graybeal 2006). All of the chosen materials had typical properties for their particular material category. It is important to note that, with the possible exception of the UHPC, other similar commercially available products exist within these categories in the North American market. Also note that the UHPC tested herein represented a standard setting formulation, not the accelerated setting formulation which has recently become available in the North American market.

Each material was cast independent of the other materials. The objective was to compare the materials based on construction issues, early age properties, and long term properties. The early age properties helped determine the applicability to accelerated construction while the long term behavior provided information for comparisons to standard materials. The construction issues included workability, work time, economics, and flow.

EXPERIMENTAL METHOD

All specimens were produced under the same conditions at the Turner-Fairbank Highway Research Center concrete laboratory in a series of pours that spanned ten weeks. The laboratory mixing conditions, mixer, curing conditions, molds, and testing protocols were the same. Five of the seven materials were mixed in one pour under the manufacturer's recommendations for a fluid mix suitable for pouring tight joints. The UHPC required two pours due to volume and mixing power limitations of the laboratory mixer. The magnesium phosphate grout required a large number of mixes because of the short workability time and number of specimens required. Immediately after mixing, the materials were placed into the appropriate molds. Aside from the magnesium phosphate grout, a high velocity pan mixer was used to mix the materials. The magnesium phosphate grout was mixed with a paddle mixer inside a 5 gallon plastic bucket. The unrestrained shrinkage bars (ASTM C157) and all of the shrinkage rings (ASTM C1581) were cast in an environmental chamber. The remaining specimens were cast inside a standard concrete laboratory, cured for 24 hours in that laboratory, demolded, and then immediately placed in the environmental chamber. The specimens were all covered in moist burlap and plastic for the first 24 hours regardless of their curing location. The magnesium phosphate grout was the exception as it did not require a moist burlap layer according to the manufacturer. Each specimen remained in the environmental chamber until the conclusion of the appropriate test. The chamber was held at a humidity of 45% ± 5% and a temperature of 74 ^{o}F ± 4^{o}F.

The tests included ASTM standards for compressive strength (ASTM C39 and C109), tensile strength (ASTM C496), flow or slump (ASTM C1437 and C143), modulus of elasticity (ASTM C469), restrained shrinkage (ASTM C1581) and unrestrained shrinkage (ASTM C157). All tests were run in the concrete laboratory where the specimens were poured. Data was taken on the schedule shown in Table 2. Testing began immediately after the materials were cast, and continued for a minimum of two months. The measurements at 24 hours were used for accelerated construction comparisons while the longer term measurements were used for standard construction schedule comparisons.

Table 2 – Testing schedule and number of specimens for each test

Tests	**2 Hr***	**6 Hrs***	**24 Hrs***	**2 Days**	**4 Days**	**7 Days**	**14 Days**	**28 Days**	**56 Days**
Compressive Strength (ASTM C39 & C109)	3	3	3			3		3	
Shrinkage (ASTM C157)			3	3	3	3	3	3	3
Modulus of Elasticity (ASTM C469)								3	
Split Cylinder (ASTM C496)								3	
Restrained Shrinkage (ASTM C1581)	1 Specimen – Data taken every 5 minutes for 56 days								
Early Age Shrinkage (VWG† & ASTM C157)	2 Specimens – Data taken every 5 minutes for 56 days								

**Where applicable - Some materials had not set.*
†Vibrating Wire Gage

In precast bridge component field installation, the early-age shrinkage values are of interest as the construction may be accelerated and put into use soon thereafter. A non-standardized method was employed to measure early age unrestrained shrinkage during the first 24 hours. Unrestrained shrinkage specimens were made with the same procedures as ASTM C157 shrinkage bars with a few exceptions. A 6 in. (15.1 cm) long vibrating wire gauge (VWG) was placed directly in the middle of the standard 3 in. by 3 in. by 11 in. (76.2 mm by 76.2 mm by 279.4 mm) ASTM C157 mold (Figure 1). No gage studs were embedded into the ends of the specimens. VWGs provided the axial strain in the material into which they were cast. The forms were heavily oiled with a form release agent immediately prior to casting the specimens to ensure very little friction developed between the material and form. As such, the specimens are considered to have been unrestrained from casting, through demolding at 24 hours, and to cessation of data collection after a minimum of two months. The gauges provided shrinkage measurements to the nearest microstrain every five minutes.

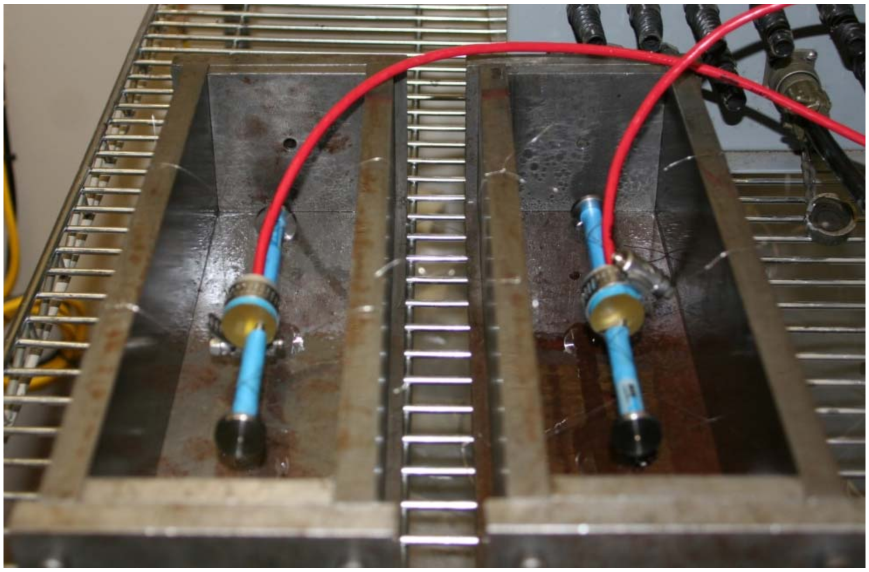

Figure 1 – ASTM C157 molds embedded with vibrating wire gages to measure shrinkage

RESULTS

Construction

Workability

Immediately after mixing, the spread was measured for every material except the deck concrete (Table 3). A standard slump was taken for the deck concrete. The spreads were first measured for the grouts immediately after releasing the grout to flow and prior to dropping the table. After this measurement the table was dropped either 25 times (according to ASTM C1437) or until the grout flowed off the table (indicating a spread greater than 10 in. (25.4 cm)).

The two standard grouts and the cable grout had full spreads using less than the 25 table drops. These materials were very fluid and easy to pour. The magnesium phosphate grout, epoxy grout, and UHPC, had spreads between 6.6 in. (16.8 cm) and 7.1 in. (18.0 cm) without dropping the spread table. When the table was dropped 25 times the spread increased by approximately 1.0 inch (2.5 cm) on average for each material. These materials are considered to have exhibited flowable characteristics. All of the grouts were easy to use when pouring them into the specimen molds. All materials were rodded during the placement operations according to their respective ASTM specifications.

The deck concrete had coarse aggregate and was not flowable but was very workable. Over the course of using this mix, the average slump was 5.3 in. (13.5 cm). It was easy to place in all specimens except for placement in the shrinkage rings. These rings were narrow with an opening of only 1.5 in. (3.8 cm) and required extensive rodding to consolidate the deck concrete. This exemplified why a fluid grout is desirable in very narrow connections or connections with congested rebar.

Table 3 - Spread measurements using ASTM C1437 methods

Material	Initial Spread With No Table Drops, in. (cm)	Final Spread (Number of Table Drops Noted)	
		Table Drops	Spread (in. (cm))
Grout 1	4.8 (12.2)	17	10.0 (25.4)
Grout 2	4.0 (10.2)	9	10.0 (25.4)
Cable Grout	10.0 (25.4)	---	---
Magnesium Phosphate	6.6 (16.8)	25	7.6 (19.2)
Epoxy Grout	6.8 (17.3)	25	7.2 (18.2)
UHPC	7.1 (18.0)	25	8.5 (21.7)

Table 4 presents notes on the mixing and placing procedures for each material. Aside from the magnesium phosphate grout, all of the materials were workable for at least 30 minutes, the time needed to fabricate all the specimens. The magnesium phosphate grout was only workable for about 10 minutes on average. The number of smaller batches mixed was substantially greater in order to cast all of the specimens within the shortened working time.

Cleaning tools and mixers was easy with grout 1, grout 2, and the deck concrete, but more challenging with other materials. The cable grout and epoxy grout were very sticky and required abrasion to clean the tools. The magnesium phosphate grout reached a setting point so quickly that tools had to be cleaned between every mix. The UHPC was not hard to clean, but the steel fiber reinforcement contained therein did necessitate modified casting and cleaning procedures.

All the materials were easy to demold except for the magnesium phosphate and epoxy grouts. Both of these materials bonded to the steel forms even though form oil was added prior to casting. Note that these grouts did not bond as well to plastic forms, therefore plastic formwork should be considered when engaging these grouts.

Table 4 - Mixing notes

Material	Work Time*	Number of Pours†	Cleanup Issues	Demolding Notes
Grout 1	Sufficient	1	Easy	Easy to demold
Grout 2	Sufficient	1	Easy	Easy to demold
Cable Grout	Sufficient	1	Sticky, Easy cleanup	Easy to demold
Magnesium Phosphate	Average of 10 Minutes	13	Hard to clean tools, Clean every pour	Expansive, Bonds well to steel
Epoxy Grout	Sufficient	1	Very sticky, Hard to clean tools	Bonds very well to steel
UHPC	Sufficient	2	Bonds to tools, Needle-like fibers	Not set at 24 hours, Easy to demold
Deck Concrete	Sufficient	1	Easy	Easy to demold

"Sufficient" is listed if there were no problems pouring the specimens (approximately 30 minutes).

†Number of batches used to make all the test specimens.

Cost Comparison

All of the materials except the UHPC used in this study were obtained from local suppliers in the Washington DC metropolitan region. Approximately 15 bags of each type of grout were acquired through a single purchase in the August through September of 2010 timeframe. The constituent materials for the deck concrete were purchased individually. The UHPC was purchased directly from the manufacturer. It is recognized that cost differences may occur if larger quantities of materials are purchased or if the materials are purchased from a ready mixed concrete company. Transportation costs were not included. The costs are seen in Table 5.

The least expensive material was the deck concrete. The cost of the deck concrete was \$178/yd^3 (\$233/m^3) for the material. The cable grout, the second least expensive material, was \$995/yd^3 (\$1300/m^3). The standard grout prices ranged from \$1566/yd^3 (\$2047/m^3) to \$1881/yd^3 (\$2458/m^3). UHPC and magnesium phosphate grout were both around \$2000/yd^3 (\$2614/m^3). The most expensive was the epoxy grout with a cost of \$4577/yd^3 (\$5982/m^3).

Table 5 – Bulk material unit cost

Material	Unit Cost, $/yd^3	($/m^3)
Grout 1	1566	(2047)
Grout 2	1881	(2458)
Cable Grout	995	(1300)
Magnesium Phosphate	2077	(2715)
Epoxy Grout	4577	(5982)
UHPC	2000	(2614)
Deck Concrete†	178	(233)

†Constituent materials only

Material Properties

Density

The density of the different materials varied from 105.6 pcf (1692 kg/m^3) for the cable grout to 159 pcf (2547 kg/m^3) for UHPC. The density was calculated based on the weight and volume of compression specimens just before the completion of the 28-day compression tests. The full results are presented in Table 6.

Table 6 - Density

Material	Density, pcf	(kg/m^3)
Grout 1	119.0	(1906)
Grout 2	143.1	(2292)
Cable Grout	105.6	(1692)
Magnesium Phosphate	125.9	(2017)
Epoxy Grout	133.7	(2142)
UHPC	159.0	(2547)
Deck Concrete	150.3	(2408)

Compressive Strength

The compressive strength results are listed in Table 7. The deck concrete was measured with 4 in. by 8 in. (10.2 cm by 20.3 cm) cylinders according to ASTM C39 while all other materials were measured with 2 in. by 2 in. (5.1 cm by 5.1 cm) cubes according to ASTM C109. The first strength reading was attempted within the first 6 hours of testing if the material could be demolded. As seen in the table, the magnesium phosphate grout and the epoxy grout both had significant strength within 6 hours of casting. The magnesium phosphate grout exhibited 5.49 ksi (37.9 MPa) of strength at 2 hours. The epoxy grout exhibited a strength of 3.28 ksi (22.6 MPa) within 6 hours. Both the epoxy grout and magnesium phosphate grout could likely meet accelerated construction project timelines.

The two standard grouts exhibited strengths of 3.45 ksi (23.8 MPa) and 5.07 ksi (35.0 MPa) at 24 hours. Both of these grouts may provide sufficient strength for applications that needed usable strength within one day.

The deck concrete, cable grout, and UHPC had very little compressive strength at 24 hours but did have 4.52 ksi (31.2 MPa), 5.25 ksi (36.2 MPa), and 15.7 ksi (108 MPa) strength at 7 days, respectively. Additional strength tests were not performed prior to 7 days, therefore the strength gain for these materials between 24 hours and 7 days was not assessed. These materials gained compressive strength slower but still had sufficient strength for structural applications by one week.

Table 7 – Material compressive strengths

	Average Compressive Strength, ksi (MPa)				
Material	**2 Hours**	**6 Hours**	**24 Hours**	**7 Days**	**28 Days**
Grout 1	*	*	3.45 (23.8)	6.22 (42.9)	6.70 (46.2)
Grout 2	*	*	5.07 (35.0)	7.90 (54.5)	8.94 (61.6)
Cable Grout[†]	*	*	*	5.25 (36.2)	8.47 (58.4)
Magnesium Phosphate	5.49 (37.9)	Not Tested	8.40 (57.9)	8.10 (55.8)	9.91 (68.3)
Epoxy Grout	*	3.28 (22.6)	10.1 (69.6)	14.1 (97.2)	14.4 (99.3)
UHPC	*	*	*	15.7 (108)	18.3 (126)
Deck Concrete	*	*	1.51 (10.4)	4.52 (31.2)	5.55 (38.3)

**Material had not yet set.*

[†]Significant shrinkage cracking occurred prior to testing the cubes.

Modulus of Elasticity

The modulus of elasticity tests were completed according to ASTM C469 on 4 in. (101.6 mm) diameter cylinders. The measured modulus of elasticity values are shown in Table 8. The standard grouts and the epoxy grout were all within the typical 1000-4000 ksi (6,900 – 27,600 MPa) range for cementitious pastes (Mindess, Young and Darwin 2003). This is reasonable, given that these grouts have little or no coarse aggregate. The deck concrete, UHPC, and magnesium phosphate grout had values within a 20% range of the value which would be predicted by a simple, compressive strength based design specification equation, such as AASHTO LRFD Bridge Design Specification Equation 5.4.2.4-1. Significant shrinkage cracking was evident in the cable grout specimens prior to the start of the test, thus the ASTM C469 modulus of elasticity test could not be completed on this material.

Table 8 – Average modulus of elasticity

Material	**Average 28 Day Modulus of Elasticity, ksi (GPa)**
Grout 1	2300 (15.9)
Grout 2	3100 (21.4)
Magnesium Phosphate	4770 (32.9)
Epoxy Grout	3390 (23.3)
UHPC	7550 (52.0)
Deck Concrete	3940 (27.1)

Splitting Tensile Strength

The splitting tensile strength tests were completed according to ASTM C496 on 4 in. (101.6 mm) diameter cylinders. The results are presented in Table 9. The epoxy grout exhibited the highest splitting tensile values. Its strength was about four times stronger than grout 1 and grout 2, the magnesium phosphate grout, and deck concrete. The standard grouts, deck concrete, and magnesium phosphate grout had similar splitting tensile values, ranging from 525 psi to 665 psi (3.6 to 4.6 MPa) at 28 days. Results pertaining to UHPC are not presented. The splitting tensile strength as reported by the ASTM C496 test method is not indicative of the cementitious matrix tensile cracking strength of UHPC due to the presence of a high concentration of fiber reinforcement. Additionally note that, as with the modulus of elasticity testing, the significant shrinkage in the cable grout specimens impacted the test method and precludes the presentation of the cable grout splitting tensile results here.

Table 9 - Splitting tensile strengths

	Average Splitting Tensile Strength, psi (MPa)	
Material	**1 Day**	**28 Days**
Grout 1	385 (2.65)	525 (3.62)
Grout 2	435 (3.00)	665 (4.59)
Magnesium Phosphate	330 (2.28)	650 (4.48)
Epoxy Grout	1940 (13.4)	2125 (14.7)
Deck Concrete	210 (1.45)	570 (3.93)

Shrinkage

Shrinkage was measured with two different methods for every material. The first method was the ASTM C157 3 in. (76.2 mm) square shrinkage bars. Per the specification, the first reading for these tests was obtained at 24 hours after casting. The second method used the same geometry ASTM C157 shrinkage bar with an embedded vibrating wire gage (VWG). The VWG method captured unrestrained length change beginning immediately after casting, thus capturing behaviors during the first 24 hours which are not captured in the standard ASTM C157 method. A typical shrinkage versus time graph for the deck concrete is shown in Figure 2. Note that the shrinkage values are plotted and reported as positive, while the expansion values are shown as negative.

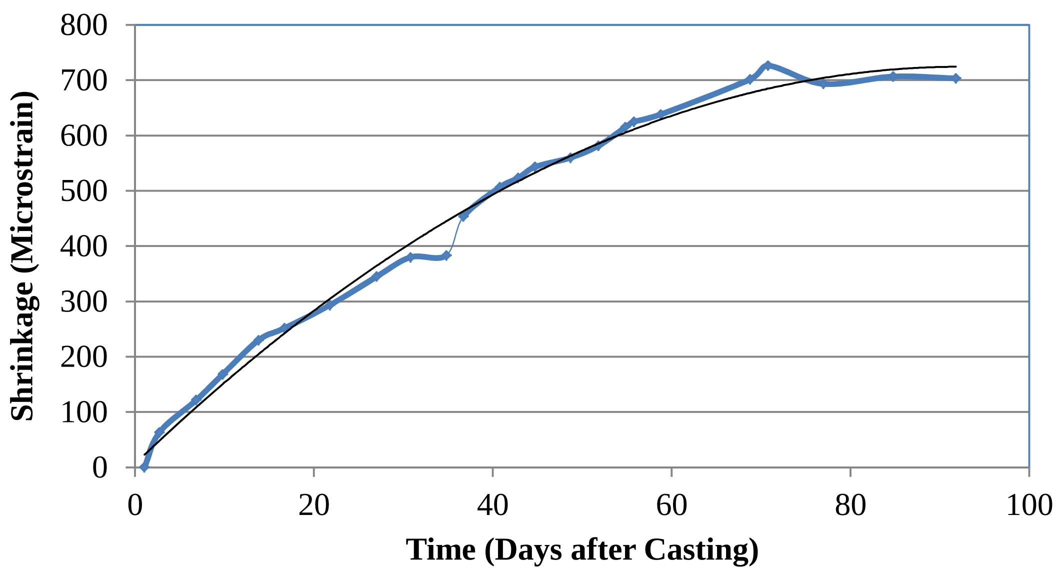

Figure 2- Deck concrete shrinkage beginning at 1 day after casting via ASTM C157

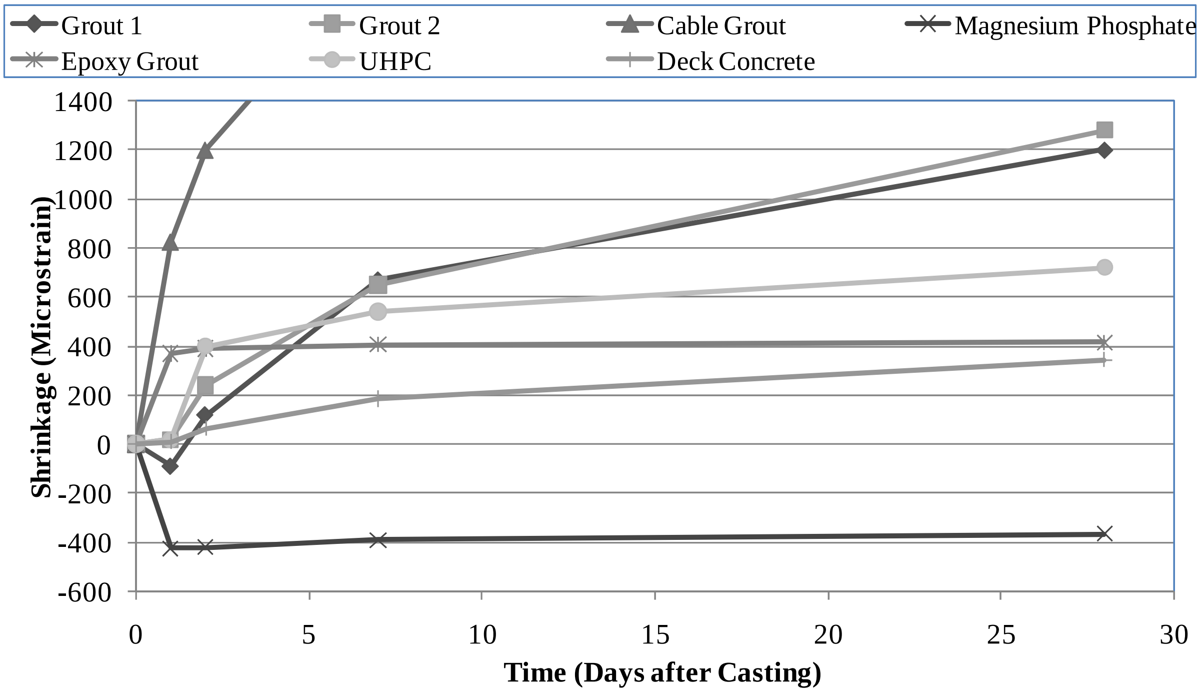

Figure 3 – Unrestrained length change beginning at casting as measured with a vibrating wire gage

Figure 3 shows four key shrinkage values for the seven different materials from the time of casting through 28 days. After 1 day the magnesium phosphate grout had expanded about 400 $\mu\varepsilon$ and epoxy grout had shrunk about 400 $\mu\varepsilon$. These values did not change significantly after the initial 24 hours. Thus, after the first day, the magnesium phosphate and epoxy grouts proved the most dimensionally stable of all the materials.

The cable grout shrank over 800 $\mu\varepsilon$ at 24 hours and over 4000 $\mu\varepsilon$ at 28 days. The standard grout, deck concrete, and UHPC concrete had insignificant length changes at 24 hours. The two standard grouts peaked at about 1200 $\mu\varepsilon$ in 28 days while the UHPC had about 700 $\mu\varepsilon$ in 28 days. The deck concrete had shrinkage values less than 400 $\mu\varepsilon$ in 28 days.

The length change values captured via the ASTM C157 test and presented in Figure 4, as compared to the results presented in Figure 3, demonstrate the important role that early age behaviors play in the overall dimensional stability of some materials. The magnesium phosphate grout and epoxy grout showed approximately 100 $\mu\varepsilon$ of shrinkage past the 48 hour point. For both of these materials the bulk of their length change occurred soon after casting. Shrinkage for grout 1 was not captured for this test. Grout 2 had total shrinkage values about 10 percent less with ASTM C157 than were measured with the vibrating wire method. The UHPC had approximately 400 $\mu\varepsilon$ of initial shrinkage that occurred prior to the first reading

with the standard ASTM C157 test. The reading for deck concrete in this figure at 48 hours saw little change because its set time was much longer and little length change occurred in the first 24 hours (
Figure 3). The cable grout had very high shrinkage values throughout the entire process.

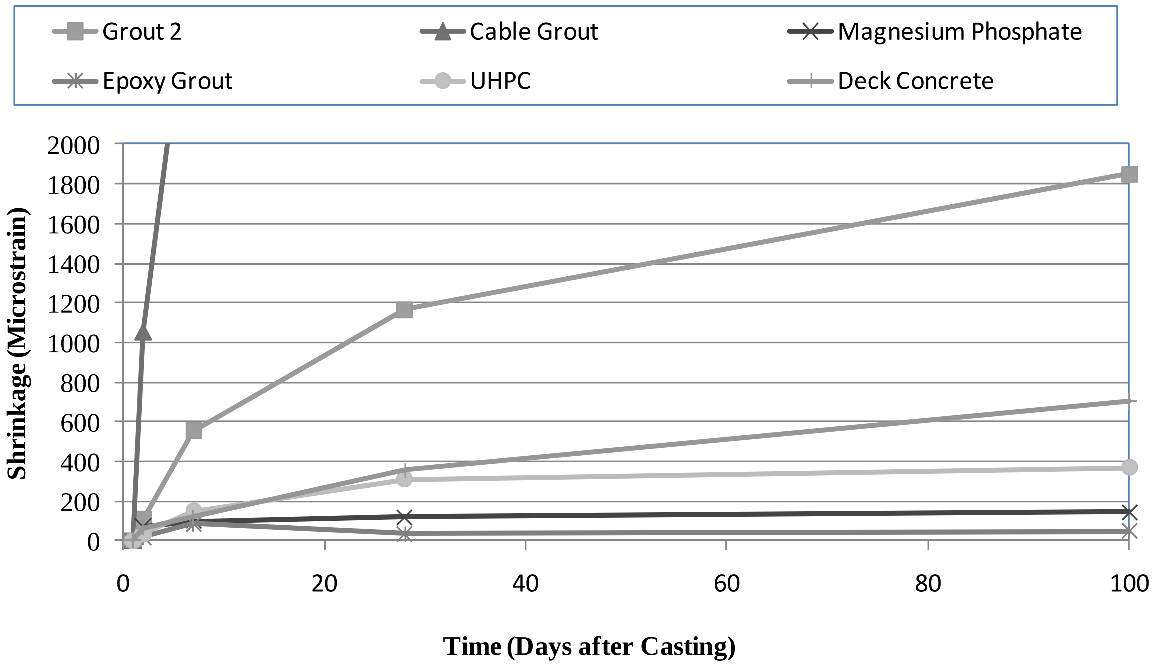

Figure 4 – Unrestrained length change measured via the ASTM C157 test method.

Shrinkage Rings

ASTM C1581 was used to compare the propensity of the materials to crack under restrained shrinkage. Each material was cast inside a controlled environment with a temperature between 75 +/- 4 degrees Fahrenheit and 45% +/- 5% humidity. The rings were demolded 24 hours after casting and cracking was monitored visually and with four strain gages on the inner ring (Figure 5).

Figure 5 – Typical Shrinkage Ring

A typical strain development plot of the inner steel ring is shown in Figure 6. Four gages were used on all rings although on some specimens one of the gages was damaged and only three strain measurements were captured. Cracking was indicated by the rapid drop in strain as seen around 3 days in Figure 6 and confirmed visually. The strain rate factor was found by plotting the square root of time versus strain in the inner ring. Four measurements were made and then averaged. The slope of this line as determined in the following equation is the strain rate factor (α):

$$\varepsilon_{net} = \alpha\sqrt{t} + k \quad (1)$$

with:

ε_{net} = Net Strain – The difference in strain in the steel rings from demolding through time *t*.

α = Strain rate factor – Strain rate for each gage on the inner, steel ring (in./in/day$^{1/2}$)

t = Elapsed time starting from demolding the ring through the period of interest (days)

k = Regression constant – Used when fitting a line to the data.

The stress rate (q) in each test at cracking was measured using the strain rate factor. The following equation from ASTM C1581 was used to find q, the stress rate in each specimen (psi/day):

$$q = \frac{G\ |\alpha_{avg}\ |}{2\sqrt{t_r}} \tag{2}$$

with:

G= 10,470,000 psi

α_{avg} = Absolute value of the average strain rate factor ((in./in)/day$^{1/2}$)

t_r = Elapsed time at cracking or the end of the test, whichever occurs first (days)

Table 10 – Shrinkage Ring Results

Material	**Age at First Cracking – Visual, days**	**Age at First Cracking - Strain Gages, days**	**Strain Rate Factor, (in/in)/day$^{1/2}$**	**Stress Rate, psi/day, (MPa / day)**
Grout 1	2.9	2.9	0.0000974	302 (2.1)
Grout 2	2.8	2.5	0.0000769	254 (1.8)
Cable Grout*	0.9	0.9	---	---
Magnesium Phosphate	**	**	0.0000026	1.22 (0.01)
Epoxy Grout	†	†	0.0000001	0.03 (0.00)
UHPC	71.4	16.4	0.0000491	63.4 (0.44)
Deck Concrete	23.6	23.1	0.0000134	14.6 (0.10)

** Cracked before demolding.*
***Test stopped at 121.5 days without any cracking.*
†Test stopped at 114.6 days without any cracking.

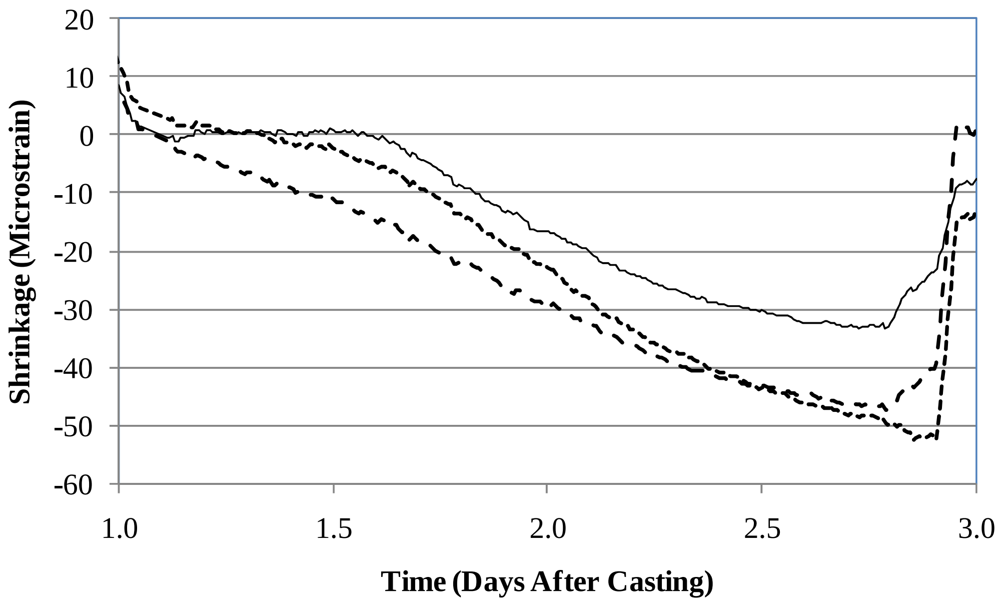

Figure 6 – Strain development in the inner ring over time for grout 1

The standard grouts all cracked within 3 days of their casting (Table 10). The strain rate factors ranged between 0.000097 and 0.000077 (in./in.)/day$^{1/2}$. Aside from the cable grout, these strain rates were the highest of the materials tested and resulted in the largest stress rates. The stresses ranged between 254 and 302 psi (1.8 and 2.1 MPa) per day.

The deck concrete performed better than grouts 1 and 2. The first cracks were detected on day 23 after casting both visually and with the strain gages on the inner ring. The strain rate factor was 0.0000134 (in./in.)/day$^{1/2}$ and the stress rate was 14.6 psi/day (0.10 MPa/day) up until cracking. The stress and strain rates were both smaller than the standard grouts and cracking in the deck concrete commenced three weeks later than the standard grouts.

The UHPC behaved very differently than typical grouts or deck concrete. Figure 7 shows the strain in the shrinkage ring versus time. The ring had small drops in strain but never a large reduction as typically seen with other materials (such as shown in Figure 6). The largest drop across all of the gages occurred on day 16 after pouring. However, because the cracking was so small the cracks were not apparent visually until day 71. Because UHPC has steel fibers embedded in the cementitious matrix, after cracking began, the fibers arrested the crack growth. This action by the fibers prevented any significant drops in strain. The stress rate was approximately 63 psi/day (0.44 MPa/day), however the stresses did not open large cracks in the rings.

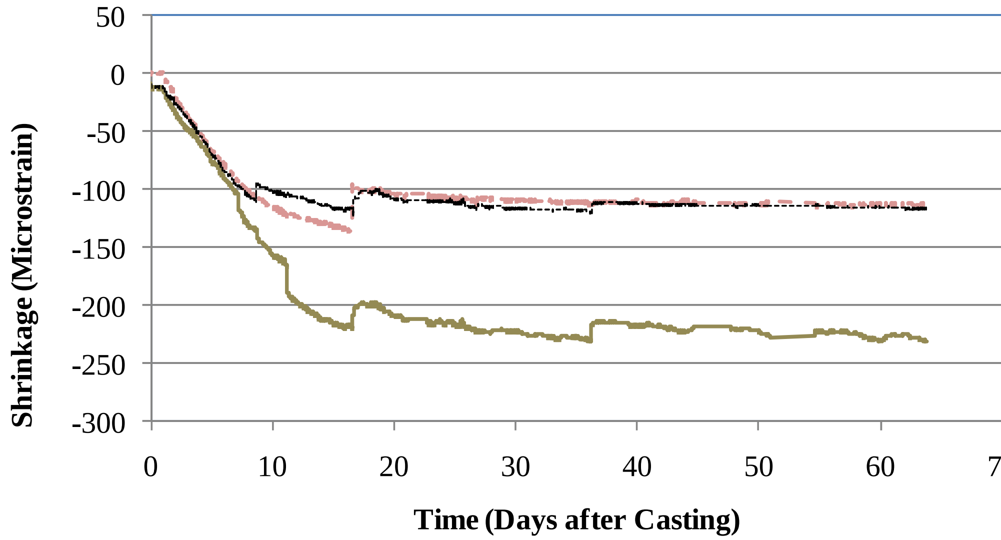

Figure 7 – Strain development in the inner ring over time for an individual UHPC specimen

The magnesium phosphate grout did not crack during testing. The ring was monitored for 121 days. During that period a strain rate factor was computed at 0.0000026 (in./in.)/day$^{1/2}$. The stress rate per day was 1.22 psi/day (0.01 MPa/day). This rate was computed with the strain readings after demolding (24 hours) through the end of the test. During the first 24 hours the strain gages indicated a large amount of expansion within the grout that was not used in computing the factors. It must be realized that all the shrinkage in the magnesium phosphate grout occurred after initial expansion, thereby partially relieving expansive strains.

The epoxy grout showed a small amount of shrinkage during testing and no cracks appeared either visually or with the strain gage data. A strain rate factor and stress rate factor of nearly 0 (in./in.)/day$^{1/2}$ and 0 psi/day (0 MPa/day), respectively, were computed. The strain gages did indicate that some shrinkage occurred within the first 24 hours prior to demolding the rings. However, this part of shrinkage was not included in the calculations.

Very little data was collected for the cable grout. The rings were demolded at 24 hours after casting and cracking was already prevalent. All values for computing the strain and stress rate factors were recorded starting at demolding. Since the rings had already cracked the test could not be completed.

SUMMARY OF RESULTS

Construction

1) Grouts 1 and 2 and the cable grout were the most workable and flowed better than other materials. However, all of the materials were workable and could be used in the field-casting of connections between precast concrete components. Every material except the magnesium phosphate grout remained workable for over 30 minutes. If magnesium phosphate grout is chosen, the short working time must be considered in the construction process.
2) Cleaning magnesium phosphate and epoxy grouts from forms and tools was difficult. These materials must be used with care and tools must be cleaned thoroughly to ensure future use. Plastic forms or coatings can simplify the demolding and cleaning processes.
3) The least expensive material was the deck concrete. The cementitious grouts, the UHPC, and the magnesium phosphate grout were approximately ten times more expensive. The epoxy grout was close to twenty times as expensive as the deck concrete.

Material Properties

1) The grouts exhibited between 10-30% less density than the deck concrete. The UHPC was about 7% heavier than the deck concrete. This should be taken into account when computing dead loads if significant amounts of these materials are used.
2) All of the materials tested had strengths of at least 4500 psi (31 MPa) within 7 days. The magnesium phosphate and epoxy grouts had 3000 psi (20.7 MPa) or more strength within 6 hours of pouring. Grouts 1 and 2 met this strength threshold within 24 hours.
3) In terms of the modulus of elasticity, grouts 1 and 2 behaved more like pastes. This is due to the lack of significant amounts of coarse aggregate. The moduli of the epoxy grout, the magnesium phosphate grout, and the UHPC are larger than that of typical grouts by a factor between 1.25 and 3.25. The UHPC had the highest modulus with a value over 50% more than the next highest material, the magnesium phosphate grout.
4) The epoxy grout had splitting tensile strengths approximately four times greater than the values observed for some other materials.
5) The majority of the volume change in the magnesium phosphate and epoxy grouts occurred within the first 24 hours, which is not captured via the ASTM C157 test method. As such, their ASTM C157 results were close to zero. The ASTM C157 test method is generally more applicable to deck concretes and most standard grouts, as these cementitious materials tend to exhibit comparatively less shrinkage during the

24 hours between casting and demolding. The cable grout had extremely high shrinkage values and cracked considerably.

6) The conventional grouts cracked within three days under restrained shrinkage testing. The deck concrete and the UHPC cracked between 2 and 3 weeks later. Although the UHPC cracked, it did not completely lose strain because of the steel fiber matrix. The epoxy grout and magnesium phosphate grout created very little strain and did not crack in the restrained ring test.

CONCLUSIONS

The test program discussed herein focused on characterizing basic mechanical and dimensional stability properties for seven field-cast materials which could be used in connecting precast concrete bridge components. The results demonstrate that the material characteristics, practical construction considerations, and cost can vary widely. These results and others must be carefully considered when selecting the appropriate material to use in a particular construction project.

For accelerated construction projects requiring high compressive strengths within one day, the epoxy grout displayed acceptable properties. It had sufficient strength gain, was one of the most dimensionally stable materials, had good workability, high tensile strength, and no evidence of cracking. However, its comparatively high cost may limit its viability.

An alternative for this type of project and for other projects requiring exceptionally rapid strength gain is the magnesium phosphate grout. The greatest concerns with this material relate to constructability considerations, including its very limited working time.

For construction that allows a slower strength gain, UHPC is a viable choice. This material has high compressive strength, high tensile strength, and internal fiber reinforcement that can arrest any cracking that may occur. Total shrinkage, although less than observed with the conventional grouts, is greater than that exhibited by the magnesium phosphate and epoxy grouts.

The deck concrete mix performed as well as the standard grouts in most cases. The standard grouts shrank more, had only modestly higher compressive strengths, cracked earlier, and cost substantially more.

ONGOING AND FUTURE RESEARCH

The research discussed herein is part of a larger program aimed at facilitating the use of prefabricated bridge elements and systems. Another portion of the program is investigating the interface bond performance of the grouts discussed in this paper. Future phases of the program will investigate structural performance various field-cast connection details both as subcomponents and as part of full-scale bridge structures.

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