Dimensional Stability of Grout-Type Materials Used as Connections between Prefabricated Concrete Elements

Igor De la Varga[1] and Benjamin A. Graybeal, P.E., M.ASCE[2]

Abstract: Prefabricated bridge elements and systems (PBES) construction relies on field-cast, grout-type materials to complete the connections between precast concrete elements. This PBES construction facilitates and accelerates bridge construction (ABC), increases safety, and minimizes the inconveniences to the traveling public while delivering a superior product. Although prefabricated concrete components are produced in a controlled environment, field-cast grouts have at times shown serviceability issues mainly associated with dimensional stability. This paper assesses the dimensional stability (primarily shrinkage) of a total of seven prebagged grouts currently used in the construction industry. Their shrinkage performance is compared to that of an ultrahigh-performance concrete. The feasibility of the test methods used for evaluating the dimensional stability of nonshrink grouts is also discussed. Although many grouts are referred to as nonshrink materials, the results show shrinkage, especially in drying conditions. The use of the internal curing technology as an emerging solution for mitigating shrinkage in grout-type materials is also discussed. The results obtained in two of the cement-based grouts, including internal curing, show a reduction of both autogenous and drying shrinkage. Based on the results obtained, recommendations are given to end-users to provide guidance in selecting an appropriate grout-type material. **DOI: 10.1061/(ASCE)MT.1943-5533.0001212.**

Author keywords: Grout; Dimensional stability; Shrinkage; Bridge construction; Connections; Internal curing.

Introduction and Research Objectives

Grout-type materials are widely used in the construction industry for different applications such as joint sealing [G. J. Vanderlans, U.S. Patent No. 4,421,698 (1983), V. Weber, U.S. Patent No. 4,098,047 (1978), W. J. Clarke, U.S. Patent No. 4,318,835 (1982)], flooring [J. McIntosh and N. C. Sperling, U.S. Patent No. 7,543,417 (2009)], and structural repair (Shannag 2002; Khayat and Yahia 1998; Allen 1993), among others. In recent years, the use of grouts to connect precast concrete sections in bridges and other structures has become more prevalent (Culmo 2009). Grout is generally a mixture of cement, sand, water, and powder chemical admixtures. However, other types are also available, such as epoxy-based, fly ash-based, and magnesium phosphate-based grouts, to name just a few. They are normally proprietary materials that are prepackaged and ready to mix on site.

One common use for grouts is in accelerated bridge construction (ABC) as connections between prefabricated bridge structural elements (an example is shown in Fig. 1). The use of prefabricated elements is one strategy that can meet the objectives of ABC. These structural components are built off-site and include features that reduce the on-site construction time and mobility impact time that occur with conventional construction methods. Because they are built off the critical path and produced under controlled environmental conditions, there are improvements in construction safety, product quality, and component long-term durability. Nonshrink cementitious grouts are most often used to easily and efficiently provide a connection between these precast concrete elements. Other types of grout may be acceptable for precast connections, but they are typically more expensive compared to cementitious grouts and may introduce the need for nonstandard considerations on the part of the designer. However, the field casting of the connections is a labor-intensive, critical part of making the overall system work successfully. This is why grout-type materials need to meet several high-level performance criteria, including high fluidity, relative impermeability, high early strength, corrosion protection, sulfate resistance, and in some cases frost durability.

Several research studies on the performance of grout-type materials have been carried out in the last few decades (Culmo 2009; Gulyas et al. 1995; Issa et al. 2007; Ma 2010). However, the field-cast, grout-type materials specified for use in bridge connections have undergone limited research as to their relevance within this application. Graybeal et al. (2013) conducted extensive research in which the performance of different grout-type materials intended for use as bridge connections was evaluated. One of the outcomes of that research was the wide range of grout performance that can be obtained, as well as the propensity of the materials to undergo volumetric deformations (e.g., expansion and shrinkage). The purpose of the current study is to expand upon this work and investigate the potential risk of shrinkage in grouts used as connections between prefabricated bridge structural concrete elements. The paper also addresses some of the issues behind the execution of some of the ASTM test methods used to evaluate volume changes in grouts.

Although the use of grout-type materials as connections between prefabricated concrete elements in bridges has been shown as a promising technique to facilitate ABC, the fact that they are designed with a low water-to-solids ratio (w/s) makes them prone to early-age shrinkage. "Nonshrink" grouts are covered under ASTM C1107 ("Standard Specification for Nonshrink Packaged Dry, Hydraulic-Cement Grout") (ASTM 2014a); however, this standard lacks specificity in its definition of shrinkage limits.

[1]Concrete Materials Engineer, SES Group & Associates, Turner-Fairbank Highway Research Center, 6300 Georgetown Pike, McLean, VA 22101 (corresponding author). E-mail: igor.delavarga.ctr@dot.gov

[2]Team Leader, Bridge and Foundation Engineering Research, Federal Highway Administration, Turner-Fairbank Highway Research Center, 6300 Georgetown Pike, McLean, VA 22101. E-mail: benjamin.graybeal@dot.gov

Note. This manuscript was submitted on June 24, 2014; approved on October 3, 2014; published online on November 10, 2014. Discussion period open until April 10, 2015; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Materials in Civil Engineering***, © ASCE, ISSN 0899-1561/04014246(10)/$25.00.

Fig. 1. Longitudinal connections between the top flanges of two deck-bulb-tee prestressed concrete girders being cast with UHPC (reprinted with permission from New York State Department of Transportation)

Shrinkage under restraint can cause the development of tensile stresses within the grout, leading to premature cracking when the tensile strength of the material is still low, or can cause stresses at the interface, leading to loss of bond between the grout and the concrete substrate. In this paper, several types of commonly used prepackaged grouts were selected for testing their dimensional stability at both early and later ages. In some of the cementitious grouts, the inclusion of internal curing through the addition of prewetted, fine lightweight aggregates (LWA) was evaluated. The internal curing technology in concrete has been broadly studied within the last decade, and its implementation in the concrete mixture design procedure is well defined at this point. In this study, internal curing is included in grout-type materials, and the challenges encountered in doing so are discussed. This is proposed as a method of improving curing conditions because most grouts are poured in either confined locations or at points that are difficult to access for providing external (or conventional) curing. The results are expected to provide guidance to designers and end-users in selecting the right grout-type material for use in connections between prefabricated concrete elements in bridges and other concrete structures.

Experimental Details

Seven grout-type materials of different nature and manufacturer were used in this study. An ultrahigh-performance concrete (UHPC) that can potentially be used as a connection between prefabricated concrete elements was also included in the study. This UHPC is a class of cementitious material designed to exhibit exceptional mechanical and durability properties (Graybeal 2006, 2009, 2011). The grout category, specific gravity, and nomenclature used to define the materials throughout the paper are summarized in Table 1. The grouts were supplied in bags containing the solid fraction (cementitious materials, additives, and fine aggregates) that is mixed with a certain amount of water (following the recommendations of each grout's manufacturer), with the exception of the epoxy-based grout, which is mixed with a resin and a hardener in the amounts also recommended by the manufacturer. The UHPC manufacturer also sent a technical specification sheet describing the details of mixture proportioning.

Table 1. Grouts Used in the Present Study

Grout category	Solids specific gravity[a]	Nomenclature[b]
Nonmetallic cement-based	2.93	C1 - 0.16
Nonmetallic cement-based	2.93	C2 - 0.18
Nonmetallic cement-based	2.68	C3 - 0.17
Metallic cement-based	3.16	C4 - 0.167
Fly ash-based	2.84	F1 - 0.08
Epoxy-based	2.62	E1 - fluid[c]
Magnesium phosphate-based	2.59	M1 - 0.08
Ultrahigh-performance concrete	2.78	U1 - 0.18

[a]Specific gravity of the solids fraction measured using a gas (He) pycnometer.
[b]Grout nomenclature followed by the w/s used for each of the grouts.
[c]The supplier of E1 recommends two formulations: dry and fluid. In this study, the fluid formulation was used.

Because the materials selected in this study are intended to be used in the same type of application (i.e., connections between prefabricated concrete elements), the comparative criterion chosen was to have similar fresh properties in terms of workability. This was done using the consistency definitions described in ASTM C1107, where the consistency is classified in three categories (flowable, fluid, and plastic), based on the flow measured in accordance with ASTM C1437 (ASTM 2013c). In this study, plastic consistency was chosen, which is between 100 and 125% of the original base diameter of the mold used in the flow test. The flow of the grout is measured on the standard flow table after five drops in 3 s. Then, the diameter is measured along the four lines marked on the table, and the average is recorded.

Besides having the same consistency, it was important to ensure that the materials comply with the performance requirements described in Table 1 within the ASTM C1107 specification (that is, compressive strength and height change). To evaluate the compressive strength, three 51-mm (2-in.) cube specimens [like those described in ASTM C109 (ASTM 2013b)] were prepared according to ASTM C1107 and using a SRM20 Univex Mixer (Univex, Salem, New Hampshire), except for the fly ash-based grout, which was mixed in a 5-gallon bucket using a drill with a paddle, as recommended by the manufacturer. Mixing times for each of the grouts were selected following each manufacturer's recommendations. The cubes were tested at several ages: 4 h, 8 h, 1 day, 3 days, 7 days, and 28 days. The cube specimens were kept in their molds for 24 h, at which time they were demolded and sealed within plastic bags until the age of testing, unless the testing age was within the first 24 h, in which case the specimens were tested right after being demolded.

The other performance requirement stated in ASTM C1107 defines the volume change as measured in terms of the height change. The height change of a 76 mm diameter × 152 mm tall (3 × 6 in.) cylindrical specimen was measured in accordance with ASTM C827 (ASTM 2010a) and ASTM C1090 (ASTM 2010b) test methods (fresh and hardened stages, respectively). For the fresh-stage measurements, a modification of the ASTM C827 test method was made where a noncontact laser is placed above the specimen and used to measure the vertical distance from the laser to the indicator ball placed on the top surface of the specimen [Fig. 2(a)]. This approach provides more simplicity to the execution of the test, rather than using a projector lamp, magnifying lens, and indicator charts as described in ASTM C827 (Fig. 3). The laser approach has been compared to the original setup, and similar results are obtained (Di Bella and Graybeal 2014). The measured vertical distance corresponds to the increase or decrease in height (expansion or shrinkage) of the material laterally confined in the cylindrical mold from the time of molding to when the mixture becomes hard

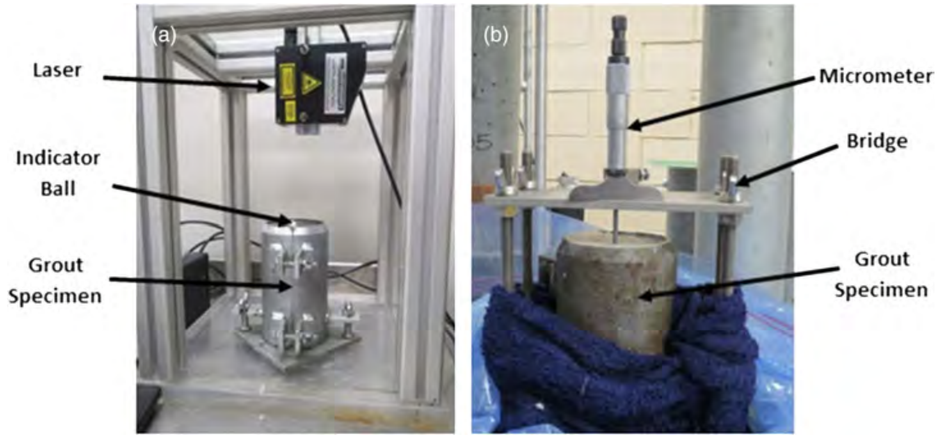

Fig. 2. (a) Modified ASTM C827 setup; (b) change length in a hardened specimen with ASTM C1090 (ASTM 2010b) (images by Igor De la Varga)

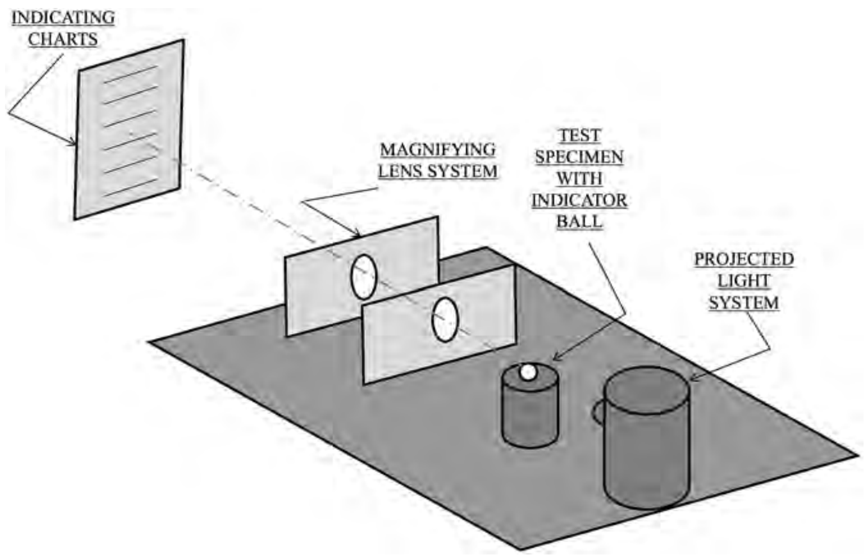

Fig. 3. Illustration of the apparatus for early change in height adapted from ASTM C827 (data from ASTM 2010a)

(i.e., final set). As for the hardened height change, two 76 mm diameter × 152 mm tall (3 × 6 in.) cylindrical specimens were prepared in which the change in height was measured at four points on the top surface of the specimens using a micrometer, in accordance with ASTM C1090, at the ages of 1, 3, 7, 14, and 28 days [Fig. 2(b)]. An initial four-reading measurement was taken right after placing a glass plate on top of the fresh sample surface. The glass plate was removed from the top of the test specimen after 24 h. After removal, the thickness of the glass plate was measured with a caliper at the points of contact between the glass plate and the micrometer. This thickness was then added to the four-reading initial measurement. In both test methods, there is always a certain degree of friction between the specimen's sides and the inner surface of the metallic mold. The degree of restraint varies with the mixture viscosity and degree of hardening. Therefore, in order to provide the lowest friction possible, an acetate sheet was used in between the test specimen and the mold. The height change results in both test methods are expressed in terms of percentage increase or decrease of the original specimen height.

Autogenous deformation was assessed using an automated version of the sealed corrugated tubes test, as described in ASTM C1698 (ASTM 2009). Three replicate specimens were evaluated concurrently. The tubes were placed over supports provided with spring-loaded LVDTs at each end, and the displacement (converted to strain) was measured every 5 min until the age of 7 days. The autogenous deformations were zeroed at the final time of set, measured as described in ASTM C403 (ASTM 2008b). To guarantee isothermal conditions, the specimens were kept in an environmental room at 23 ± 1°C (73.4 ± 1.8°F) and a relative humidity (RH) of 50 ± 5%. The mass of the samples was taken at the beginning and after 7 days of testing, to confirm that the specimens were properly sealed. For later age measurements, four prismatic specimens with dimensions 25 × 25 × 305 mm (1 × 1 × 12 in.) were prepared in accordance with ASTM C157 (ASTM 2008a), in which all four faces were sealed with two layers of aluminum tape after removal from the molds (i.e., 24 h). Similar samples were prepared without aluminum tape for shrinkage assessment in drying conditions. The specimens were kept in the same environmental room as the corrugated tubes. Length change measurements and mass measurements were taken every week for the first month and once a month for the next three months.

Results and Discussion

The first part of the results section covers the performance requirements described in ASTM C1107 in order to check that the grouts

Table 2. Flow Measurements Using ASTM C1437 Methods (ASTM 2013c), Time of Set (ASTM 2008b), and Fresh Air Content (ASTM 2014b)

Grout	Number of drops	Flow at 5 min (%)[a]	Flow at 15 min (%)[a]	Final time of set (ASTM C403) (h)	Air content (ASTM C231) (%)
C1 - 0.16	5	112	106	7.7	3.4
C2 - 0.18	5	117	84	6.8	5.1
C3 - 0.17	5	111	100	10.3	12.0
C4 - 0.167	5	110	91	6.8	3.6
F1 - 0.08	5	101	109	0.7	4.6
E1 - fluid	N/A[b]	N/A[b]	N/A[b]	3.5	8.5
M1 - 0.08[a,c]	5	115	75	0.4	6.9
U1 - 0.18	5	N/A[d]	>125	6.9	3.2

[a]Flow slightly changes depending on mixer used. These values were measured using a medium-sized Univex mixer.
[b]Material sticks in mold. Test cannot be performed.
[c]Flow was measured at 2 and 5 min because of final setting time limitations.
[d]Flow was measured only at 15 min because of mixing time requirements.

used in the study comply with the standard. Though not considered by this ASTM standard, the second part will focus on the results obtained for autogenous and drying deformations. Note that the exact formulation or composition of grout-type materials is typically unknown to the end-user because they are proprietary materials. As such, it can be challenging to fully explain their performance in terms of workability, reactivity, strength, and volume change.

Grout Consistency and ASTM C1107 Requirements (Strength and Height Change)

The initial grouts' consistency is summarized in Table 2. The measurements were taken at 5 and 15 min after the solid-water first contact. In every case, the material consistency at 5 min is within the plastic consistency range stated in ASTM C1107, which is between 100 and 125% of the original base diameter of the mold used in a flow table test. The flow of the epoxy grout could not be measured because of the "sticky" nature of the material, which made it difficult to lift the mold without disturbing the material. The fact that all grouts have similar initial consistency is indicative of the possibility of using these materials in the same type of application (i.e., connections between prefabricated concrete elements). However, the consistency is not within the mentioned range for some of the grouts at 15 min. The degree of workability loss is normally related to the type of chemical admixtures used in the material. Because the formulation in most of the materials is unknown, it is difficult to make conclusions in this regard. The 5-min flow for the U1 material couldn't be measured because of mixing time requirements; however, it exceeded the upper limit of 125% at 15 min.

It is interesting to note how the workability of the F1 grout increases from 5 to 15 min if one considers the fast-setting behavior that develops (final set is achieved at 45 min). Grouts F1, E1, and M1 show very short setting times (less than 4 h), which is explained by the fact that these materials are designed to be fast-setting repair materials. The kinetics of the chemical reactions is different from that of the cement-based grouts. For instance, F1 appears to be a high-calcium, fly ash-based material, whereas M1 is a polymer-modified cementitious material (i.e., magnesium phosphate), and E1 is an epoxy-resinous material. The other grouts show final set times in the range of 6–10 h, as typically observed in fast-setting, cement-based materials.

The grout-type material performance requirements described in ASTM C1107 are provided in Table 3, and the strength and height change results obtained for the grouts included in this study are presented in Table 4, Fig. 4, and Table 5, respectively. As can be observed in Table 4, all of the grouts comply with the minimum strength requirements at all ages. Particular attention is given to U1, which shows strength values that considerably exceed the minimum requirements. This is normal because this type of material is designed to exhibit exceptional mechanical and durability properties. The F1, E1, and M1 materials develop strength within the first 8 h (which is consistent with the rapid setting times previously reported), and a slower strength development is observed in the four cement-based grouts (C1, C2, C3, and C4), but it is still enough to exceed the minimum strength required at each age.

As in the case of flow measurements, a detailed material characterization would be needed to better understand the differences in the strength development among the grouts used. Strength gain, at least for the cement-based grouts and the UHPC, directly depends on the raw material composition, reactivity, fineness, capillary porosity (i.e., initial water content), and the degree of hydration achieved (0 to 1). The degree of hydration is expected to be close to 1 for the cement-based grouts because the water-to-binder ratio (w/b) is likely high if one considers the binder content of each of the grouts. This will be further explained later in the paper through the discussion of internal curing.

The height change results obtained during the fresh stage are presented in Fig. 4. The measurements were carried out following a modified version of the ASTM C827 specification [Fig. 2(a)]. The new approach, besides being less time-consuming, facilitates the automated recording of the measurements. Using the original set-up shown in Fig. 3 (i.e., projector lamp, magnifying lens, and indicator charts) makes it difficult to clearly define the edge of the ball on the indicator charts because the shadow loses focus as the ball moves up or down. The test provides information about volume changes occurring between the time right after mixing and that of

Table 3. Performance Requirements according to ASTM C1107

Parameters	
Minimum compressive strength for 51-mm (2-in.) cubes (MPa)	
1 day	7
3 days	17
7 days	24
28 days	34
Early age height change maximum percent at final set (ASTM C827)	
Maximum (%)	4
Hardened height change maximum percent at 1, 3, 14, and 28 days (ASTM C1090)	
Maximum (%)	0.3
Minimum (%)	0

Note: 1 MPa = 145 psi.

Table 4. Compressive Strength Results for Grout Cubes

	Average compressive strength (MPa)					
Grout	4 h	8 h	1 day	3 days	7 days	28 days
C1 - 0.16	—[a]	—[a]	30.5 (0.83)[b]	48.9 (2.21)	52.4 (1.17)	67.6 (2.00)
C2 - 0.18	—[a]	—[a]	25.6 (0.41)	41.1 (0.90)	45.1 (0.97)	50.2 (2.35)
C3 - 0.17	—[a]	—[a]	16.6 (0.48)	26.2 (0.76)	35.5 (0.21)	43.7 (0.41)
C4 - 0.167	—[a]	—[a]	34.6 (0.76)	49.3 (1.52)	60.9 (0.07)	67.6 (1.52)
F1 - 0.08	31.1 (0.21)	34.6 (1.38)	34.9 (1.04)	44.0 (0.90)	55.5 (1.04)	56.1 (0.35)
E1 - fluid	—[a]	8.42 (0.14)	56.1 (1.45)	73.6 (0.35)	77.3 (0.41)	93.5 (3.24)
M1 - 0.08	32.0 (2.07)	31.3 (0.41)	43.0 (2.14)	44.9 (1.93)	44.2 (1.24)	54.0 (2.35)
U1 - 0.18	—[a]	—[a]	93.15 (0.28)	129.7 (3.45)	132.1 (1.59)	170.4 (0.90)

Note: 1 MPa = 145 psi.
[a]Material had not set yet, or it was still too weak to be tested.
[b]Numbers in parentheses indicate one standard deviation in MPa as determined for three replicate specimens tested at each age.

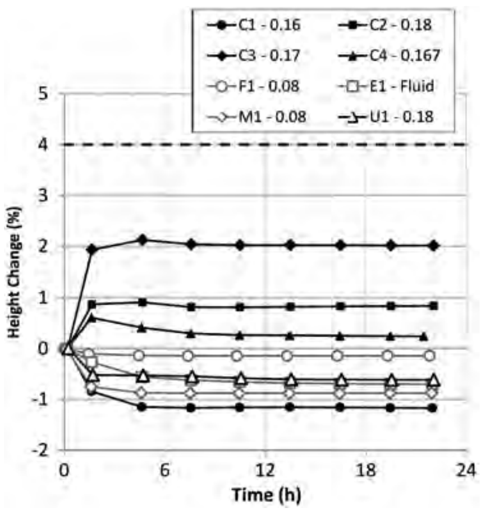

Fig. 4. Change in height at early ages according to a modified version of ASTM C827. Only one specimen was tested for each grout

Table 5. Height Change of Hardened Grouts via ASTM C1090 Test (ASTM 2010b)

	Average height change of hardened grout at a given age (%)[a]				
Grout	1 day	3 days	7 days	14 days	28 days
C1 - 0.16	−1.2	−1.2	−1.2	−1.2	−1.2
C2 - 0.18	0.0	0.0	0.0	0.0	0.0
C3 - 0.17	0.0	0.0	0.0	0.0	−0.1
C4 - 0.167	0.0	0.0	0.0	0.0	0.0
F1 - 0.08	−0.2	−0.2	−0.2	−0.2	−0.2
E1 - fluid	−0.2	−0.2	−0.2	−0.2	−0.2
M1 - 0.08	−0.1	−0.1	−0.1	−0.1	−0.1
U1 - 0.18	−0.4	−0.4	−0.4	−0.4	−0.4

[a]Maximum and minimum expansion allowed by ASTM C1090 is 0.3 and 0.0%, respectively.

final set. The volume changes measured would include expansion (e.g., expansive agents, thermal), chemical and autogenous shrinkage [which before set have similar values (Sant et al. 2006)], surface settlement, plastic shrinkage that is due to drying of the specimen from the top surface, and some error given by the settlement of the ball on the top surface of the sample. Because of the presence of all of these parameters, the measurements are primarily useful for comparative purposes.

The results in Fig. 4 show that none of the mixtures exceed the 4% maximum expansion allowed by ASTM C827 (indicated by a dashed line). However, five of the grouts show a certain degree of height reduction. These include one of the cement-based grouts (C1), the UHPC (U1), and the non-cement-based grouts (F1, E1, and M1). The reduction in height is less than 1% for all cases, except for the C1 that barely exceeds this value. In any case, ASTM C1107 does not specify any minimum value during the fresh stage (Table 3), so if it is assumed that the specification does not allow any reduction in height (because of shrinkage or any other phenomena mentioned in the previous paragraph), then these grouts would not comply with the standard. In all cases, a fast increase or decrease in height is observed from the beginning of the test until each of the grouts reaches final set (see Table 2 for setting times), the moment at which the curves enter a plateau.

One of the issues of using the original setup described in ASTM C827 is that the cylindrical specimen is not completely unrestrained. As previously mentioned, there is always a certain degree of friction between the specimen's sides and the inner surface of the metallic mold. This is why, in order to provide the lowest friction possible, an acetate sheet was used in between the test specimen and the mold. Although not shown in this paper, specimens were also prepared without the acetate sheet, with the results demonstrating the effect of the restraint. Thermal effects (normally expansion) could be also corrected by measuring the temperature of the test specimen throughout the test. It is recommended to consider these modifications in ASTM C827. Another ambiguity of the standard specification is that a mixture could expand more than 4% during its fresh stage and return to a value below 4% before reaching final set. This should be further clarified in the standard in order to avoid confusion.

Table 5 shows the height change results obtained during the hardened stage according to ASTM C1090. Theoretically, it would not be possible to compare the results obtained during the first 24 h with those in Fig. 4 (fresh stage) because the curing conditions are different. In this case, the specimens are sealed in a plastic bag throughout the test duration; therefore, the parameters that can be considered in this test are chemical and autogenous shrinkage and surface settlement. In other words, the change in height does not include the effects of drying. As with the early height change test, the results are merely comparative.

The results show that three of the cement-based grouts (C2, C3, and C4) do not exhibit any shrinkage or expansion throughout the test duration. It is interesting to note that these are the same grouts that exhibit expansion in the ASTM C827 test (Fig. 4). One aspect to point out about the ASTM C1090 test procedure is that the glass plate used to cover the top surface of the specimen during the first 24 h prevents the specimen from expanding. The glass plate is held down with a plunger that is attached to the bridge. This is why none of the grouts show expansion within the first day, when expansive agents (if present) would act to counteract the possible shrinkage. The rest of the grouts (M1, F1, C1, E1, and U1) show a decrease in the specimen height, especially C1. These are the same grouts that show a height reduction in Fig. 4. As already mentioned, the curing conditions of ASTM C827 and ASTM C1090 test methods are different (sealed versus drying); however, the same trends are observed in the height increase or reduction. Therefore, as with the ASTM C827 test method, M1, F1, C1, E1, and U1 would not comply with ASTM C1107.

This procedure to measure height changes at later ages has the previously mentioned inconvenience of not allowing the specimens to expand during the first hours of the material's properties development because of the presence of the glass plate. And in fact, as can be seen in Fig. 4, some expansion occurs within the first 24 h. Another issue is that sometimes it is difficult to remove the glass plate from the top surface of the specimen, especially when using grout-type materials different from cement-based materials (e.g., epoxy-resinous). This can be resolved by using a piece of acetate sheet in between the glass plate and the top surface of the specimen. It is also recommended to use acetate sheet to reduce most of the friction (i.e., restraint) between the specimen and the mold. These aspects should be considered as possible modifications to the ASTM C1090 standard.

In conclusion, the grouts used in this study comply with ASTM C1107 in terms of strength development and expansion. However, some of the grouts show a certain degree of shrinkage that would not meet the standard requirements. The shrinkage performance is further evaluated in the next section.

Autogenous Deformation and Drying Shrinkage

The results obtained in the previous section showed a certain degree of shrinkage in some of the grouts. However, it is not possible to conclude that the reduction in the specimen height is primarily due to shrinkage because there are other parameters such as surface settlement and possible errors associated with the test procedures. As such, this section is focused on the measurement of pure shrinkage deformations in both sealed (i.e., autogenous) and drying conditions. The curing condition is important from the viewpoint of the materials' application because some of the precast connections will be completely confined (sealed), but others will be partially exposed to the environment (drying).

The autogenous shrinkage results measured in accordance with ASTM C1698 are presented in Fig. 5. The results are expressed as a function of time, from the time of final set to 7 days of hydration. As can be observed, some of the grouts undergo just shrinkage (C1, C4, and U1), others show an initial expansion followed by shrinkage (C2 and C3), and others show a fairly constant expansion at all times (F1 and M1). Grout E1 could not be tested because of the difficulty of pouring the material into the corrugated tubes, and U1 was prepared without steel fibers because of the "poor" fiber distribution in the corrugated tubes. If fibers were added, less shrinkage deformation would be expected because of their internal restraint.

As can be seen in Fig. 5, all of the cement-based grouts used in the study, including the UHPC (dark color), show autogenous shrinkage at some point, which is common in cement-based materials. It is worth mentioning that the cement-based C2 grout also shrinks, despite showing a net positive deformation of about 70 $\mu\varepsilon$ after 7 days. When evaluating the risk of shrinkage cracking, one should consider the (net) difference between the maximum and minimum deformations achieved during the test (Cusson 2008).

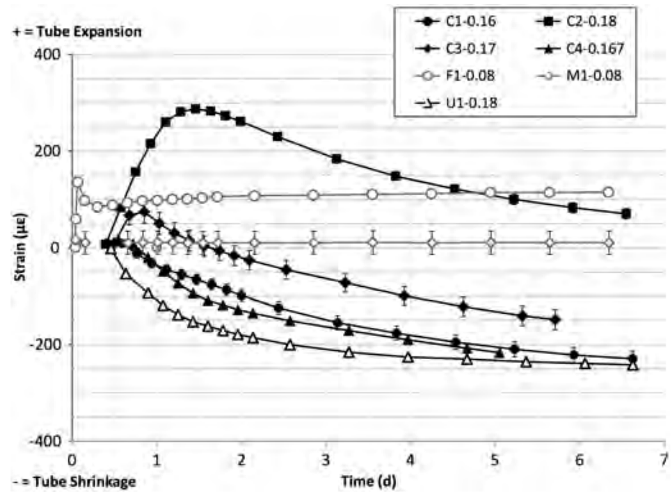

Fig. 5. Autogenous (sealed) shrinkage as a function of time based on ASTM C1698 (ASTM 2009). Error bars indicate one standard deviation as determined for three replicate specimens

Typically, in cement-based grouts, low w/s decreases particle spacing (and pore sizes), contributing to an increase of the autogenous shrinkage. However, nonshrink grout-type materials are usually designed to undergo autogenous expansion during the first hours of the hydration reaction, by means of additives such as ettringite, gas generation, or air release (Culmo 2009). Therefore, a competition between autogenous shrinkage and autogenous expansion occurs. In this regard, it is interesting to note that some of the curves are basically flat during the first few hours after initial set, as in the cases of the C1 and C4 grouts, which suggests a balance between expansion and contraction, not an absence of both. This is a desirable attribute for these grouts, but as evidenced by the illusory nature of this attribute for these and other grouts, it is clear that maintaining dimensional stability during setting and curing is a challenge. In the case of noncementitious grouts (F1 and M1), the autogenous deformation is practically constant throughout the test. This might be attributed to the different type of chemical reaction taking place in these systems. Their chemical reaction might not involve any volume changes (chemical shrinkage or local expansion) at all.

Special attention is given to the reason that some of the cement-based grouts expand. As mentioned before, the first expansion and subsequent shrinkage might be due to expansive reactions such as the formation of ettringite (and small thermal effects). Then, when the ettringite is later converted to monosulfate or monocarbonate phases, the stress producing the expansion might be released, and the specimen would shrink back toward its former state. If the materials are mainly calcium aluminate-based to promote expansion, the water requirements for forming ettringite are much higher than hydrating calcium silicates, so autogenous shrinkage due to self-desiccation could also occur when large amounts of ettringite are forming, even at high w/b. While the main scope of the current paper is to simply evaluate volume stability in grout-type materials, the authors are currently working on better characterizing the grouts so that the shrinkage results can be further explained from a fundamental basis. The internal relative humidity in these materials is being measured to indicate whether there is any self-desiccation. In addition, quantitative X-ray diffraction over time and isothermal calorimetry are being used to give some indication of what is happening chemically.

Long-term autogenous shrinkage has been measured by means of the ASTM C157 test method. The four sides of prismatic specimens with dimensions $25 \times 25 \times 305$ mm ($1 \times 1 \times 12$ in.) were sealed, and the length change was monitored. The results over the first three months are presented in Fig. 6(a). Although not shown in the paper, the autogenous shrinkage obtained using the corrugated tubes and the (sealed) ASTM C157 test procedure were compared during the first 7 days, resulting in similar deformations in all cases. This was also previously demonstrated by Sant et al. (2006). Therefore, sealed specimens can be used with ASTM C157 to determine long-term autogenous shrinkage. Other specimens were also maintained in drying conditions at 50% RH to evaluate drying shrinkage [Fig. 6(b)]. All of the curves in Fig. 6 start at 1 day and have been zeroed to the corresponding strain measured with the ASTM C1698 corrugated tubes test at 1 day for each of the grouts.

The results show that drying shrinkage is at least 1,000 $\mu\varepsilon$ larger than sealed shrinkage for each of the cement-based grouts (C1 through C4) because the additional drying effect contributes to shrinkage. Drying shrinkage is typically dependent on the water content (i.e., w/c or w/b). The higher the w/b, the larger the capillary pores, and the faster they will dry out. This might be the case in all of the cement-based grouts because the drying shrinkage values are considerably high. In contrast, while F1 and M1 do not show any autogenous shrinkage and low drying shrinkage after 3 months (on the order of 300 $\mu\varepsilon$), E1 does not show any difference regardless of the curing condition, having shrinkage values of about 300 $\mu\varepsilon$ in both curing conditions. Finally, U1 shows considerably lower shrinkage in both sealed and drying conditions (about 200 $\mu\varepsilon$) compared to the cement-based grouts. It is interesting to note that U1 showed larger autogenous shrinkage in the corrugated tube test during the first 7 days compared to the other cement-based grouts (Fig. 5). As a reminder, the corrugated tube test was performed without steel fibers (the fibers are not well dispersed when pouring the material into the corrugated tube). This is a good indication that the steel fibers typically included in the U1 mixture design contribute considerably in eliminating some of the shrinkage taking place in the system. In fact, the top surface of two previously cast UHPC slabs with and without fibers was examined. The UHPC without fibers was maintained in laboratory conditions (constant temperature and humidity), and the UHPC with fibers was placed in a lower humidity environment with greater temperature fluctuations outside of the lab. The former shows visible cracks even before 24 h. No signs of macrocracks are observed in the UHPC with fibers after pouring alcohol on the surface.

In summary, the results show considerable amounts of shrinkage (especially in drying conditions) for the cement-based grouts, which are the most commonly used type of grout in the construction industry. Consequently, this might have a detrimental effect on the mechanical performance in the form of shrinkage cracking and loss of bond when used as connections in bridge elements.

Potential Shrinkage Mitigation through Internal Curing

Internal curing (IC) has become more popular during the last several years within the concrete community (Bentz and Weiss 2011; RILEM 2007; Roberts 2005). It is indeed a technology that has shown multiple benefits in terms of concrete durability, especially in reducing shrinkage cracking (Cusson et al. 2010; Zhutovsky et al. 2002; De la Varga et al. 2012; Barrett et al. 2011; De la Varga et al. 2014). Although IC has been fortuitously included in concrete (particularly lightweight concrete) for many years, it is only within the last few years that this technology has been intentionally incorporated into the system through the use of a variety of materials, including prewetted lightweight aggregates (LWA), superabsorbent polymers (SAP), and prewetted wood fibers. This section summarizes results obtained using prewetted LWA in two of the cement-based grouts. The LWA used in this study consisted of shale expanded in a rotary kiln with a specific (dry) gravity of 1.56 and a 24-h water absorption of 16.95% by dry mass.

The amount of IC water needed in a cementitious system is based on the chemical shrinkage occurring in the sample, as described by Bentz et al. (2005). They formulated an equation that permits the calculation of the amount of LWA needed [Eq. (1)]. However, that approach has some difficulties for the case of grout-type materials. The main inconvenience is that the amount of reactive material in the solid fraction of a grout is typically unknown to the end-user. This is important in order to estimate the binder factor (C_f), chemical shrinkage (CS), and maximum expected degree of hydration ($\alpha_{\max}$) in Eq. (1)

$$M_{\text{LWA}} = \frac{C_f \times CS \times \alpha_{\max}}{S \times \Phi_{\text{LWA}}} \tag{1}$$

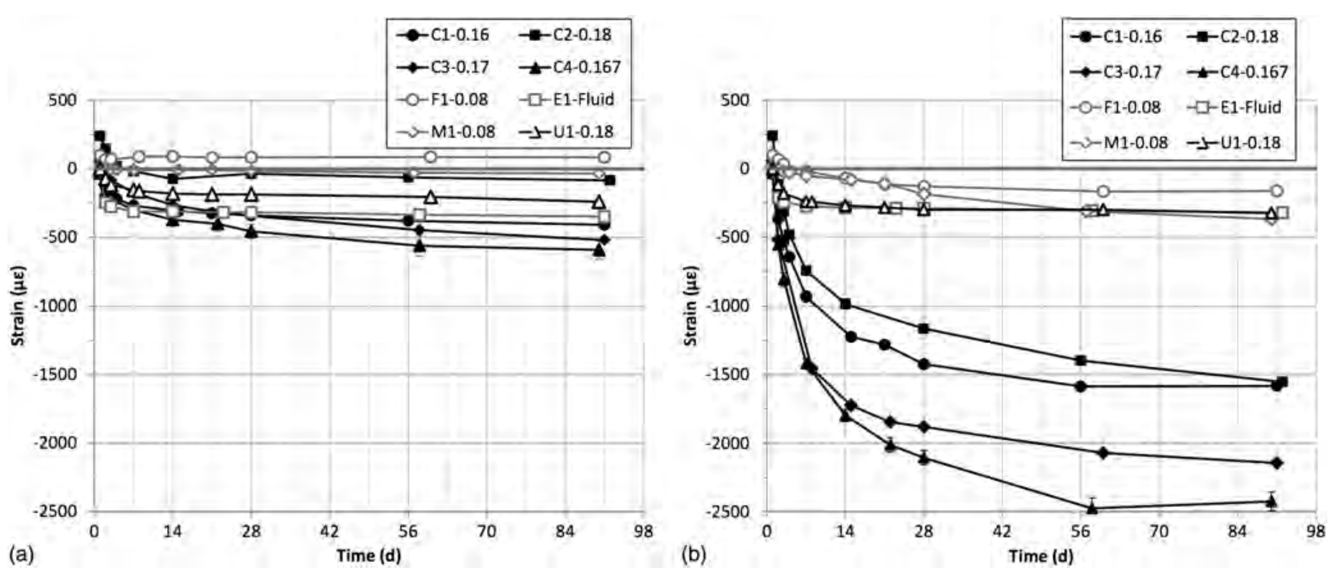

Fig. 6. (a) Autogenous (sealed) shrinkage; (b) drying shrinkage as a function of time. Error bars indicate one standard deviation as determined for four replicate specimens

where M_{LWA} (kg/m^3) = mass of LWA (in a dry state) that needs to be prewetted to provide water to fill in the voids created by chemical shrinkage; C_f (kg/m^3) = binder content of the mixture; CS (mL of water per g of binder) = measured infinite chemical shrinkage of the binder as per ASTM C1608 (ASTM 2012); α_{max} (unitless) = expected maximum degree of hydration; S (unitless) = expected degree of saturation of the LWA and was taken to be 1 in this study when the dry LWA was soaked for 24 h; and ϕ_{LWA} (kg of water/kg of dry LWA) = absorption capacity of the LWA [taken here as the 24-h absorption measured value as per ASTM C1761 (ASTM 2013a)].

As previously mentioned, the binder factor (C_f) is typically unknown in grout-type materials. In order to quantify this parameter, the approach followed in this study was to use petrography. This technique uses a polarized-light microscope to differentiate between crystalline and amorphous materials. In addition, cementitious materials have sufficient differences in their raw feeds, burning temperatures, mineral phases, and microstructure that it is possible to differentiate them, thus identifying cement, fly ash, and slag particles, for instance. This was done with two of the cement-based grouts used in the study, C3 and C4, resulting in cementitious contents of approximately 35 and 30% by mass, respectively. With this, the theoretical w/b for each of the grouts can be calculated, resulting in $w/b = 0.49$ and $w/b = 0.56$ for C3 and C4, respectively. Consequently, α_{max} in Eq. (1) is considered to be 1 because the w/b in both cases is above 0.42 (Powers and Brownyard 1946). Likewise, chemical shrinkage of the two grouts was measured according to ASTM C1608, and the results were normalized by the amount of reactive material of each of the grouts. The infinite chemical shrinkage can be then evaluated by plotting the chemical shrinkage over the inverse of the time, resulting in values of 0.14 mL of water/g binder and 0.13 mL of water/g binder for C3 and C4, respectively. These values are high compared to plain cement [about 0.064 mL of water/g binder (Lura et al. 2003)], which is an indication of the presence of other cementitious materials with higher values of chemical shrinkage. Note that although petrographic images showed fly ash and slag particles, scanning elecron microscopy (SEM) images confirmed the presence of silica fume in both grouts.

An appropriate IC design in cementitious materials is crucial from the viewpoint of durability. In an overdosed system, if some LWAs remain filled with water, it may have detrimental effects from a freeze-thaw perspective. In this study, prewetted LWAs were added to the base grout formulation at a mass calculated using Eq. (1) for each of the grouts. It is recognized that this addition of LWA will change the paste content of the formulation with respect to the total volume, thus influencing the shrinkage performance. However, it is judged to be a reasonable path given the lack of knowledge of the proprietary grout constituents.

The autogenous shrinkage results of the internally cured grouts are shown in Fig. 7. When IC is added, the shrinkage component is removed and the "true" expansive nature of the binder is revealed. Long-term results are also presented in Fig. 8. Again, the curves start at 1 day and have been zeroed to the corresponding strain measured with the corrugated tubes test at 1 day for each of the grouts. As can be observed, IC totally eliminates autogenous shrinkage during the first days of hydration reaction, resulting instead in a small autogenous expansion, perhaps because of ettringite formation or a swelling of the cement hydration products that is due to water absorption. Less drying shrinkage is also observed despite their higher overall water content and greater mass loss during drying. The partial reduction would presumably correspond to two different reasons: (1) mitigation of autogenous (or internal) drying, and (2) extension in the time it takes to reach equilibrium with the local drying environment because it may take longer to empty out the same-sized pores in the system with IC versus the system without IC.

The inclusion of prewetted LWA to provide IC is not expected to reduce the strength development of the grouts. In fact, other researchers have reported increases in the strength development at later ages, presumably because of an increase in the degree of hydration and the formation of a finer microstructure (De la Varga et al. 2012). The effect that IC has on the strength development of the grouts used in this study is presented in Table 6: IC clearly increases the strength in the C4 grout and maintains it in the case of C3. The reason for the different strength development of the two internally cured grouts is not clear because they are proprietary materials with unknown formulations. Normally, IC would increase the degree of hydration of the system; however, this parameter was not measured, so the strength results could not be better analyzed. Nevertheless, these two grouts have shown enough early strength with or without IC that the strength requirements in ASTM C1107 are fulfilled.

Grouts are typically "extended" with normal-weight aggregates for elements with thicknesses of 153 mm (6 in.) or more. As such, IC in grouts can be thought of as an extension of the grout using LWA instead. The idea behind using IC is to emphasize the importance of reducing autogenous shrinkage, especially during the

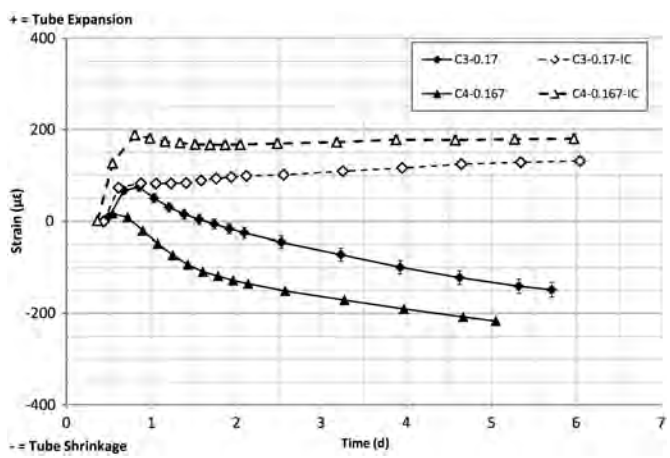

Fig. 7. Effect of internal curing on the autogenous shrinkage. Error bars indicate one standard deviation as determined for three replicate specimens

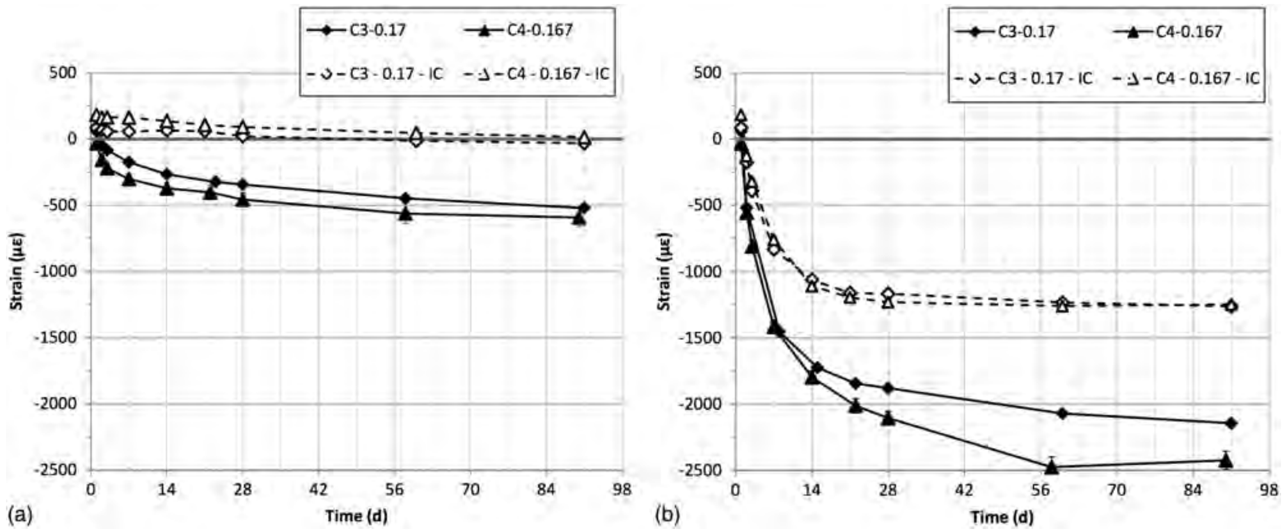

Fig. 8. Effect of internal curing on the (a) autogenous (sealed) shrinkage; (b) drying shrinkage as a function of time. Error bars indicate one standard deviation as determined for four replicate specimens

Table 6. Effect of Internal Curing on Compressive Strength

	Average compressive strength (MPa)			
Grout	1 day	3 days	7 days	28 days
C3 - 0.17	16.6 (0.48)[a]	26.2 (0.76)	35.5 (0.21)	43.7 (0.41)
C3 - 0.17—IC	13.9 (0.14)	27.5 (0.21)	33.8 (2.42)	41.1 (1.59)
C4 - 0.167	34.6 (0.76)	49.3 (1.52)	60.9 (0.07)	67.6 (1.52)
C4 - 0.167—IC	31.3 (0.35)	51.5 (0.28)	70.2 (0.97)	89.7 (3.52)

Note: 1 MPa = 145 psi.
[a]Numbers in parentheses indicate one standard deviation in MPa as determined for three replicate specimens tested at each age.

first days, when the tensile strength of the material is still low. In addition, this technology might be helpful in improving curing conditions in some locations where conventional (external) curing is difficult or impossible to implement, as well as in providing some robustness to the surface preparation (in terms of moisture content) of the precast (or existing) concrete elements because prewetted LWA also may serve as an additional reservoir if water is drawn from the grout into the substrate. Research is needed to further optimize the internal curing design in grout-type materials. As an alternative, super-absorbent polymers might be an option worthy of evaluation.

Summary and Conclusions

The volume stability of different types of grout-type materials has been evaluated. The types included were cement-based, fly ash-based, magnesium phosphate-based, and epoxy-based grouts, along with a UHPC. The grout-type materials are intended to be used as connections between prefabricated concrete elements in bridges and other concrete structures. Several standardized and nonstandardized test methods have been used, leading to the following conclusions and recommendations:

1. The grouts evaluated in this study comply with the ASTM C1107 specification in terms of strength and expansion. However, most of them show a certain degree of autogenous and drying shrinkage, especially the cement-based grouts. This will have a detrimental effect on their performance in terms of shrinkage cracking and loss of bond. A limitation to the amount of shrinkage should be stated in the ASTM C1107 standard. Therefore, test methods such as ASTM C157 and ASTM C1698 are recommended for inclusion in the ASTM C1107 specification.
2. The test methods recommended by ASTM C1107 for assessing volume changes in grouts present some difficulties when testing non-cement-based grouts such as epoxy-based and magnesium phosphate-based materials. These test methods are ASTM C827 and ASTM C1090. The use of a piece of acetate sheet between the specimen and the mold in both tests is highly recommended in order to reduce error in the results that is due to friction. Also, a modification of the ASTM C827 test method is recommended in which a noncontact laser is used instead of a projector lamp, magnifying lens, and indicator charts. The interpretation of the results in this test can be ambiguous because the standard does not state a shrinkage requirement nor does it define whether grouts are allowed to expand more than 4% and shrink back to a value below that before the specimen sets.
3. Internal curing through the use of prewetted lightweight aggregates mitigated most of the autogenous and part of the drying shrinkage in the two cement-based grouts tested. Although this will likely reduce shrinkage cracking and improve bond and curing conditions, further research is needed to better design IC in grouts because there is a lack of information regarding the reactive fraction of the grout. An overdose of prewetted LWA in the system could be detrimental from the durability point of view.

Acknowledgments

We would like to thank Daniel Balcha for his technical assistance, Dr. José Muñoz for collecting SEM images, and Dr. Mengesha Beyene for his assistance in the petrographic analysis. Special thanks go to Dale Bentz for all of his valuable comments. The research that is the subject of this document was funded by the U.S. Federal Highway Administration. This support is gratefully acknowledged. The publication of this report does not necessarily indicate approval or endorsement of the findings, opinions,

conclusions, or recommendations either inferred or specifically expressed herein by the Federal Highway Administration or the United States Government.

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