PERFORMANCE OF GROUTED CONNECTIONS FOR PREFABRICATED BRIDGE ELEMENTS-PART I: Material-Level Investigation on Shrinkage and Bond

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ABSTRACT

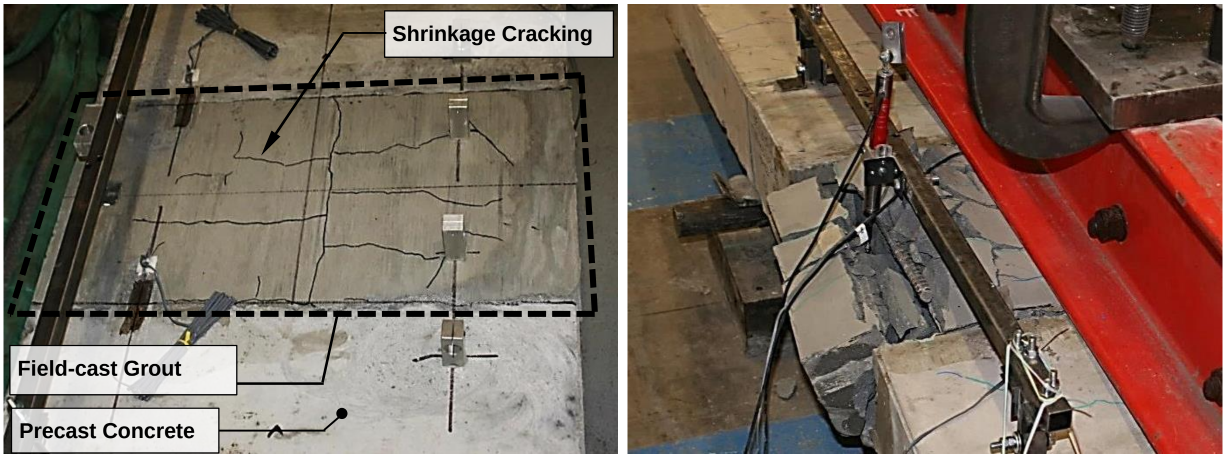
Accelerated bridge construction (ABC) projects commonly rely on prefabricated bridge elements (PBE) to meet tight construction schedules. In order to create structural continuity, prefabricated elements are typically connected using interlaced reinforcing bars and field-cast grout closure pours. However, some field-cast grouts have exhibited excessive shrinkage and poor bond which can result in connection cracking and related performance degradations. Results from a series of material-level tests on the shrinkage and bond properties of grout-type materials are discussed, along with the correlation between the properties. Various parameters that might affect bond are discussed, including the type of concrete surface preparation, the type of grout material used, and the moisture content at the grout-concrete substrate interface. A second phase of the research is also included in which some possible strategies for improving shrinkage and bond performance are discussed, including the addition of internal curing in some of the "non-shrink" cementitious grouts, and the use of a fiber reinforced ultra-high performance concrete (UHPC).

Keywords: PBE Connections, Grout-Type Materials, Shrinkage, Bond Strength, Internal Curing, UHPC.

INTRODUCTION

Accelerated bridge construction (ABC) is becoming more popular in the United States due to the advantages obtained in terms of safety, cost-effective construction, and congestion mitigation[1,2]. ABC can be used for both new and replacement bridge construction. ABC uses innovative planning, materials, design, and methods that provide a faster and safer way to construct a bridge. ABC commonly uses prefabricated bridge elements (PBE) that are built offsite and includes features that reduce the onsite construction time and mobility impact time that occur from conventional construction methods. Because these structural components are built off the critical path and produced under controlled environmental conditions, there are improvements in the product quality and the component long-term durability. In order to create structural continuity in the field, PBE are typically connected using interlaced reinforcing bars and field-cast grout closure pours. The most common connection grouts are those based on cement or cementitious materials (commonly referred to as “non-shrink” cementitious grout), but there are other types available, including epoxy-based, fly-ash based, and magnesium phosphate-based grouts.

The ideal grout for PBE connections would have self-consolidating properties, high early strength, and good durability. In relation to durability, it is critical that PBE connections employ grout materials that have good dimensional stability. A previous study conducted by the authors reports dimensional instability (primarily in the form of shrinkage) of a selection of commercially available grout-type materials[3]. If the connection grout material is not dimensionally stable, cracking and other durability issues may arise such as corrosion due mainly to the infiltration of corrosive agents. Furthermore, chemical bonding between the connection grout and precast concrete element may be compromised along with the mechanical bond between the connection grout and the embedded reinforcement. Some of these possible component-level consequences of poor dimensional stability were observed in a recent and related study at the Turner-Fairbank Highway Research Center of the FHWA that will be presented in Part II of this study[4]. A series of precast deck panel connection tests were carried out to advance the understanding of deck-level connections under low-level cyclic, fatigue, and ultimate loading. Fig. 1(a) shows that a significant amount of shrinkage cracking in the grouted connection region formed a few days after casting. Upon application of load, pre-existing shrinkage cracks grew and propagated continuously during fatigue cycles which resulted in deterioration and ultimate failure of the bond between the reinforcing bars and the connection grout material. (Fig. 1(b)).



(a) Shrinkage cracking observed prior to loading

(b) Failure of a deck panel specimen with excessive shrinkage cracking due to bond failure

Fig. 1. Observations from deck panel connection tests using a non-shrink cementitious grout[4]

As a continuation to the grout dimensional stability study previously mentioned[3], this paper focuses on bond performance of grout-type materials and how shrinkage might be correlated to it. It is normally accepted that bond between two materials can be enhanced by increasing the contact area at the interface between the two materials. In the cases where precast (or existing) concrete acts as the substrate, this can be achieved by provided by roughening the interface surface. Various techniques are available to prepare the precast concrete surface (substrate) before the application of the other material, such as sand blasting, pressure washing, hand chiseling, and exposing aggregate[5,6,7]. Additionally, it has been stated that the presence of moisture at the interface between the two materials can improve bond strength. This is typically achieved by pre-wetting the concrete substrate in the 24 hours that precede casting the new material. Theoretically, the presence of extra moisture will reduce the moisture transfer that might occur from the fresh material into the concrete substrate, thus allowing the fresh material to use of all its available mixing water for a better hydration as well as reducing shrinkage derived from the water migration. Shrinkage in the freshly poured material will not only increase the "gap" between the two materials, but it will also induce shrinkage stresses at the interface, typically causing microcracking, and thus decreasing bond.

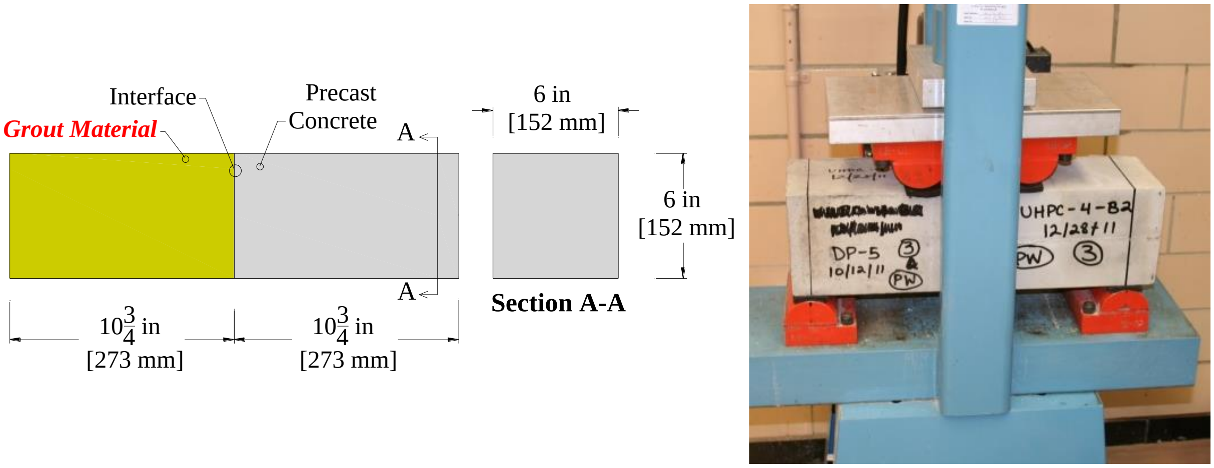
OBJECTIVES

Given the considerable amount of shrinkage observed in some of the grout-type materials[3] and the repercussions that this might have on the bond performance, the main objective of this study is the assessment of the bond strength of some of those grout-type materials when bonded to concrete. Three concrete surface preparation methods are investigated to promote bond between the field-cast grout and precast concrete; namely, pressure washing, sand blasting, and exposing the coarse aggregate of the precast concrete. Additionally, strategies to improve the bond strength of some of these materials are proposed, which include the provision of extra moisture at the grout-concrete interface, the addition of internal curing in the grout, and the use of a fiber-reinforced ultra-high performance concrete (UHPC) in lieu of the grout material. UHPC is a class of cementitious material designed to exhibit exceptional mechanical and durability properties. Its high initial workability and superior early strength development make this material a good candidate to replace grouts in PBE connections. Some of these strategies reduce shrinkage of the grout material, having a direct effect on the bond strength observed, as will be shown in this study.

This paper will support some of the conclusions taken from the performance evaluation of grouted connections in a structural level (Part II of this research).

EXPERIMENTAL

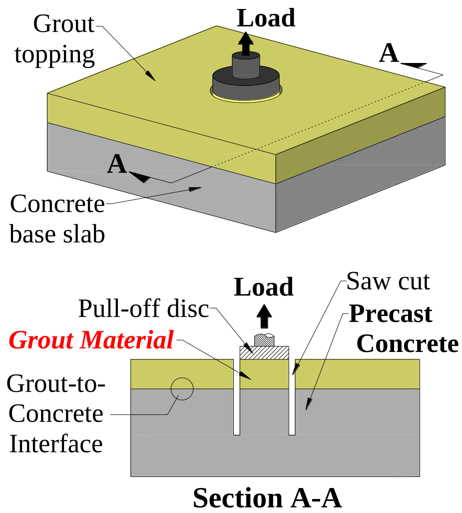
The study was divided into two phases. The first phase deals with the bond assessment of different grout-type materials bonded to a concrete substrate with different levels of surface roughness. Four commercially available grout materials were used, including: a non-shrink cementitious grout denoted as “C”, a magnesium-phosphate rapid-setting cementitious grout denoted as “M”, an epoxy grout denoted as “E”, and an ultra-high performance concrete denoted as “U”. Three concrete surface preparation methods were investigated to promote bond between the field-cast grout and precast concrete; namely, pressure washing (“PW”), sand blasting (“SB”), and exposing the coarse aggregate of the precast concrete (“EA”). The bond strength was measured using a flexural beam test based on the ASTM C78 test method, as shown in Fig. 2. Three specimens were tested after 1 and 7 days of grout curing, and a final test, denoted as “28+ Day”, which corresponded to the date the deck panels were tested in the previously mentioned deck panels study (deck panels results are not shown in this paper). It should be noted that the age of concrete at the time of testing was greater than 28 days in all cases. Prior to testing, cross-section dimensions where measured and recorded at the concrete-grout interface. Specimens were loaded in third-point bending, and had a shear span of 6 inches (153 mm). Load was applied at a rate that constantly increased the extreme fiber stress by between 125 and 175 psi/min (0.86 and 1.21 MPa/min) until rupture occurred. After failure, the maximum load and the crack distance from the concrete-grout interface (mid-span) were recorded. The main objective of this first phase was to evaluate bond strength differences among the concrete surface preparation and the type of grout material used.



(a) Specimen details (b) Test set-up

Fig. 2. Bond strength assessment via ASTM C78 flexural testing

The second phase of the study consisted of a further evaluation of the bond performance of the non-shrink cementitious grout "C" used in the first phase. The best surface preparation based on the results obtained in the first phase was selected (PW, SB, or EA). Bond strength in this phase was measured using the ASTM C1583 test method, which is otherwise referred to as a direct tension pull-off test) (Fig. 3). As shown in Fig. 3, the test specimen consisted of a concrete base slab that measured 36 x 36 x 4 inches. The slab was cured for 14 days after casting at laboratory conditions of 73.4 ± 1.8 ºF and a relative humidity of 50 ± 5 %. (14 days was selected for convenience purposes. The authors consider this age to be representative of the substrate age at the moment of the grout pour).The surface of the substrate was prepared and then a 2-inch thick layer of the non-shrink grout was cast over the top surface of the concrete panel so that an interface between the two materials is created. The grout was then cured for 14 days prior to execution of the pull-off bond tests. Therefore, the concrete slab was 28 days old at the end of the grout curing time period. The results are then presented as "14-day" bond strength which refers to the age of the grout when the bond test was performed. In this test, a 2-in diameter steel disc is glued on the top surface of the grout. The test specimen is formed by partially drilling a core perpendicular to the surface, and penetrating down to the concrete material (approximately 1 inch below the grout-concrete interface). A tensile load is applied to the steel disc at a constant rate of 5 ± 2 psi/sec until failure occurs. The failure load and the failure mode were recorded and the nominal tensile stress could be calculated. If failure occurred at the grout-concrete interface, then the true bond strength could be assessed. If failure occurs in either the concrete substrate or grout material, then the tensile strength of the failing material could be assessed and the interface bond strength could be recognized to be higher than the value achieved. Finally, the test was rejected if failure occurred at the epoxy-grout interface. At least three valid tests should be completed and the results averaged for any particular failure mode.



(a) Test details

(b) grout-concrete slab prepared for pull-off testing

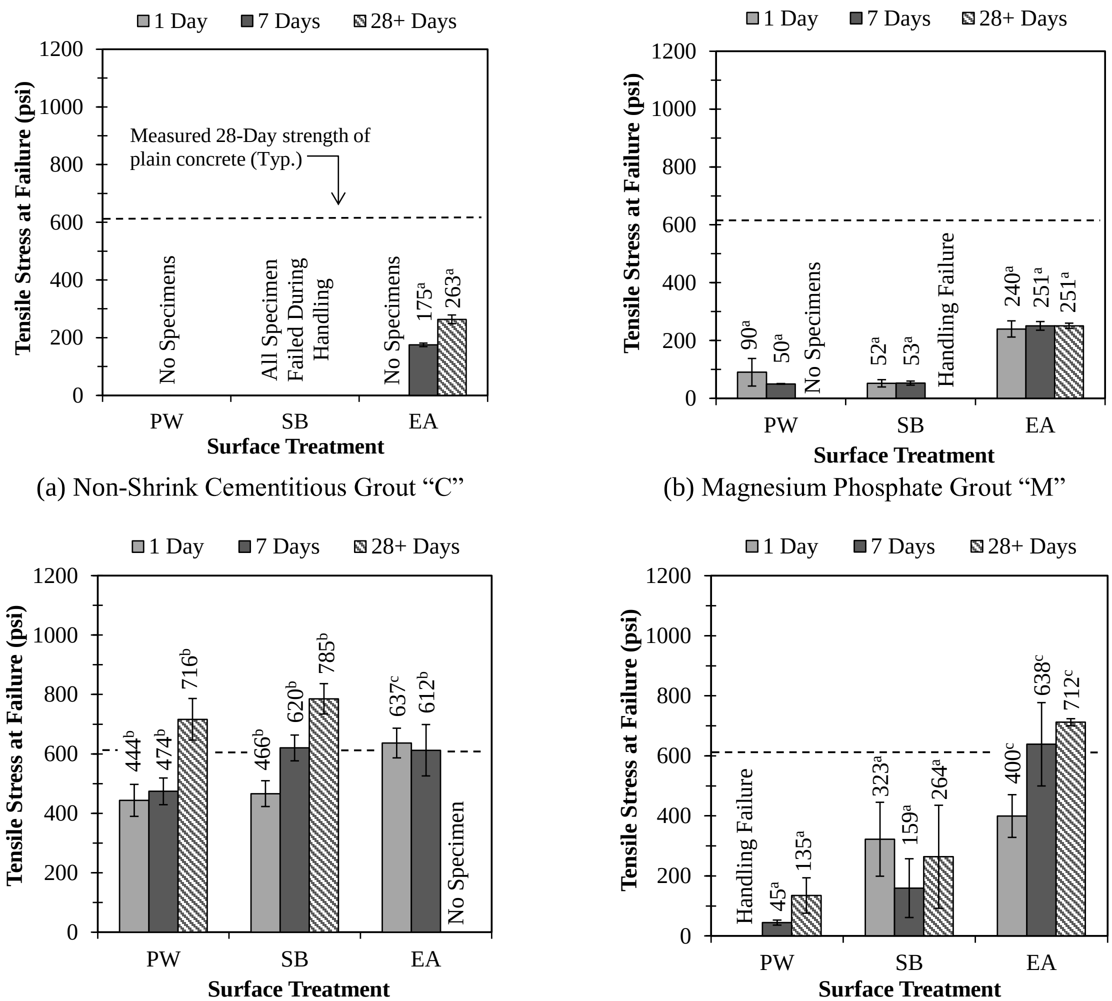
Fig. 3. ASTM C1583 Direct tension bond pull-off test

Direct tension pull-off tests were used to evaluate possible strategies to improve bond when using a non-shrink cementitious grouts. Although other grout materials such as UHPC may have superior properties, pre-bagged cementitious grouts are still commonly used because their lower cost compared to other types. The effect that extra moisture at the grout-concrete interface has on the bond performance was studied. In some of the slabs, extra moisture was added at the grout-concrete interface by either water-saturating the concrete surface during the 24 hours that precede the cast of the grout, so that a surface-saturated dried (SSD) condition is achieved (a paper towel is used at the end of the 24-hour period to manually dry the surface), or by means of internal curing (IC) through the use of pre-wetted light-weight aggregates (LWA) in the grout. Water from the LWA will be released at the appropriate time (typically after set[8,9]), and will theoretically migrate to the regions where water is demanded (e.g., grout-concrete interface). More information about the type of LWA material used and how it was included into the grout mixture design was explained by De la Varga et al.[3].

RESULTS AND DISCUSSION

EFFECT OF SURFACE TREATMENT AND GROUT-TYPE MATERIAL (FLEXURAL TESTS)

Fig. 4 shows the average flexural tensile strength of the grout materials included in the study, and Fig. 5 shows examples of the observed failure modes in beam specimens. In some cases failure occurred at the grout-concrete interface during handling, prior to loading. In general, C and M grouts exhibited low bond strengths to concrete regardless of surface preparation and age. EA surface preparation provided the best results for these two grouts. For PW and SB surface preparations, these grouts sustained less than 15% of the average tensile strength of plain concrete prior to failure, and in many cases, specimens broke apart during handling. Specimens cast with UHPC (U) as the grout material exhibited good bond performance using the EA surface preparation. Failure of these specimens typically occurred within the precast concrete with the exception of tests conducted after one day of grout curing, which typically failed within the U grout. The use of SB showed improved bond performance in U specimens compared with PW. However, the bond strength is still poor compared with the EA surface preparation. The bond performance of epoxy grout (E) was superior to that of the other grout materials investigated, although its unit cost is also higher compared to the other grouts used in the study. The majority of specimens with epoxy grout (E) failed within the precast concrete portion half away from the bond line which represents the case where bond between the two materials was strong, and the tensile capacity of one material was reached. From a qualitative perspective, using an exposed aggregate (EA) surface preparation can improve the bond between concrete at the grout material. Other than the E specimens, which exhibited good bond regardless of surface preparation, the power washing (PW) and sand blasting (SB) surface preparations did not improve bonding between the materials substrate concrete and the field cast grout.



(a) Non-Shrink Cementitious Grout "C"

(b) Magnesium Phosphate Grout "M"

(c) Epoxy Grout "E"

(d) UHPC Grout "U"

Fig. 4. Average tensile strength from flexural beam bond tests. (Error bars indicate one standard deviation from the average of three specimens. Failure Modes: [a]Bond failure occurred in all specimens; [b]Some specimens failed by bond failure and some by tensile rupture of concrete; [c]All specimens failure by tensile rupture of concrete)

(a) Example of interface bond failure (b) Example of failure by tensile rupture of concrete

Fig. 5. Observed failure modes in flexural beam bond tests

STRATEGIES TO IMPROVE BOND

Direction tension pull-off tests (ASTM C1583) were used in the second phase to evaluate possible strategies to improve the bond performance of the non-shrink cementitious grout by supplying extra moisture at the grout-concrete interface (SSD or IC). Prior to pouring the 2-in thick grout, the concrete surface was prepared using the EA surface treatment, since the highest bond strength results were obtained with this type of surface treatment (Fig. 4). The pull-off results are presented in Fig. 6. All specimens failed at the grout-concrete interface. It can be observed that when extra moisture is supply by either saturating the grout-concrete interface (SSD) or by including internal curing in the grout (IC), the bond strength is increased by about 30 % if compared to the control grout specimen (in this case, the concrete surface was cured at laboratory conditions at a temperature of 73.4 ± 1.8 ºF and a relative humidity of 50 ± 5 % during 14 days). The possibility of using an UHPC material (U) in place of the non-shrink cementitious grout was also evaluated. It can be observed how the bond strength is enhanced by about 64 % compared to the control grout specimen. Additionally, the tensile strength of each of the specimens was also measured. These were obtained by coring the test specimen only an inch below the top surface of the grout or UHPC material; that is, without going through the grout-concrete interface (note that the tensile strength of the SSD specimen is similar to the control, since the only modification is the supply of extra moisture at the interface, thus not altering the grout mixture design). The tensile strength of the concrete substrate was also measured for reference purposes. In all cases, the tensile strength is always higher than the interface bond strength of each of the specimens, confirming that the weakest zone of the specimens is located at the interface between the two materials.

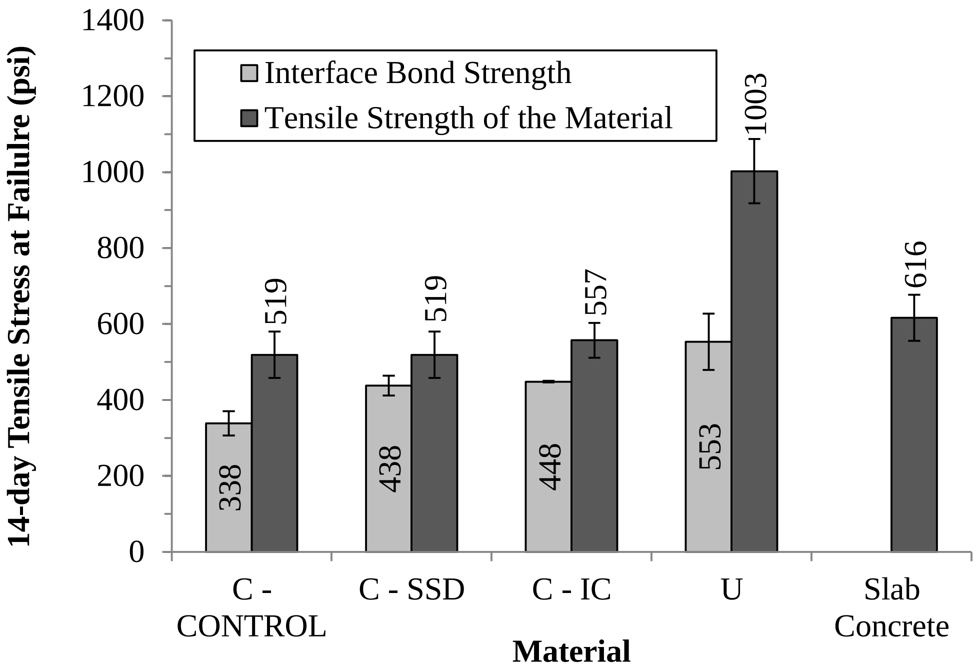


Fig. 6. 14-day pull-off bond strength: Effect of moisture at interface (SSD, IC), and use of UHPC material (U) (Error bars indicate one standard deviation from the average of four specimens)

Typically, when a freshly poured cementitious material is placed in contact with a (drier) concrete substrate, the latter will tend to absorb part of the available free water. The provision of extra moisture at the grout-concrete interface prevents this water migration from happening, allowing the grout material to use all of its available mixing water for a larger degree of hydration, and thus reducing the total porosity at the grout-concrete interface. By decreasing the porosity, the contact area between the two materials is increased. However, the extra moisture must be carefully provided, since an excessive amount of moisture at the interface might cause a reduction of the bond strength; although not shown in the paper, this effect has been observed in other grout-concrete slabs prepared in the lab. This is where the idea of including IC in the grout might be beneficial. In this case, the IC water is released from the LWA to regions of the matrix where water is being demanded (for instance, at the grout-concrete interface). This is a more controlled fashion of providing the extra moisture as the amount of extra moisture (IC water) is always constant.

The provision of IC, besides providing extra moisture at the interface, will have other effects such as: 1) shrinkage reduction of the material (thus reducing any differential shrinkage observed between the two materials), and 2) improvement of curing conditions of the material[8,9]. In regards to shrinkage reduction, IC has been proven to reduce self-desiccation caused by chemical shrinkage. Chemical shrinkage occurs when cement reacts with water as the reacted products occupy a smaller volume than the initial constituents[10,11]. When this volume reduction occurs, vapor filled spaces are left behind, thus decreasing the internal relative humidity of the system. This is commonly referred to as 'self-desiccation' (i.e., internal drying), which is the main cause of autogenous shrinkage. As shown in Fig. 7, the extra moisture provided by IC reduces both autogenous and drying shrinkage of the C grout used in the study. This has also been demonstrated in other cementitious grouts[3]. (It is important to note that shrinkage in cementitious grouts is typically higher than most conventional concretes, where the presence of coarse aggregate contributes in reducing the shrinkage of the paste fraction). The reduction in autogenous shrinkage is beneficial in terms of stresses reduction (i.e., less shrinkage cracking) as well as in reducing the "gap" between the grout and the concrete substrate (specimens are currently being analyzed to quantify the width of that "gap"). In other words, the lower the shrinkage, the higher bond strength that may be expected.

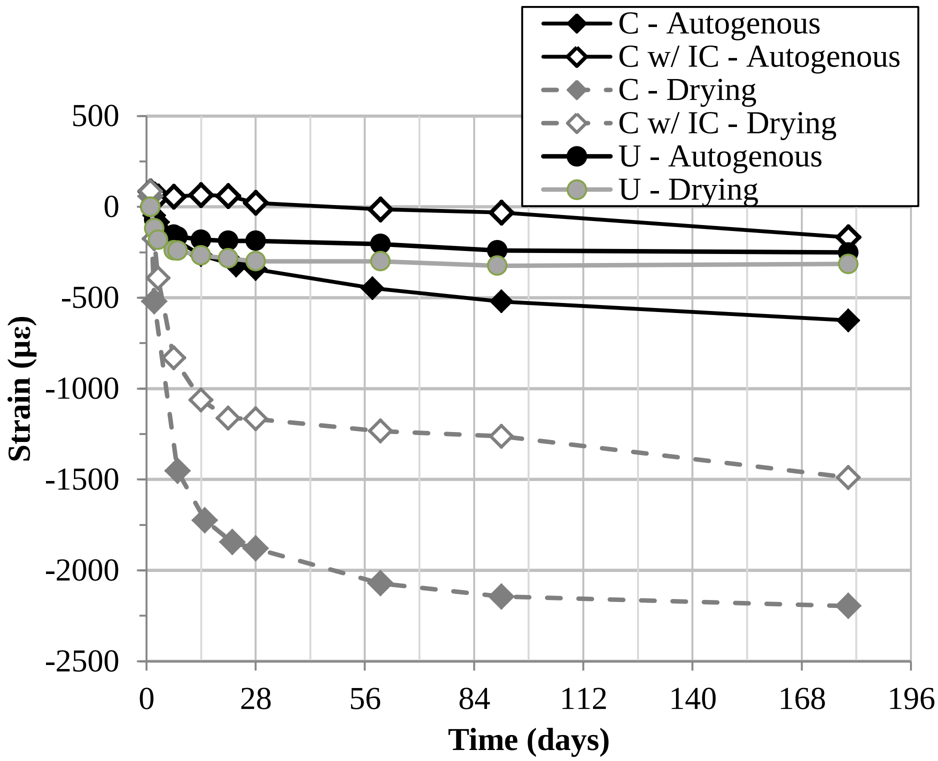


Fig. 7. Autogenous and drying shrinkage as a function of time

Fig. 7 also shows the autogenous and drying shrinkage of UHPC specimens. As observed, both autogenous and drying shrinkage values are considerably low compared to those of the C grout. This is attributed to the presence of steel fibers in the matrix. Again, the low shrinkage values are expected to improve the bond performance, as observed in Fig. 6. Additionally, this UHPC material consists of very fine particles that also contribute to reducing the size and amount of total porosity at the interfacial transitions zone (ITZ) between the UHPC material and the concrete substrate. It is widely accepted that as the freshly poured material settles on the surface of the concrete substrate, the packing efficiency of the particles decreases in the vicinity of the concrete surface. This is commonly referred to as 'wall effect'[12]. The result is an increased porosity at the interface. UHPC offers an advantage in this regard, as the packing efficiency is improved.

CONCLUSIONS

The current research study provides bond strength information of different grout-type materials that can potentially be used for PBE connections in ABC projects. The research is presented as a continuation of a recently published study on dimensional stability of this type of materials[3]. It was then conjectured that dimensional instability (mainly in the form of shrinkage) might have a negative effect on the bond performance of these materials. As such, a series of bond and shrinkage results are presented in the current study from which the following conclusions can be drawn:

1. Bond flexural tests indicated that the exposed aggregate (EA) surface treatment provides a better bond performance when compared to other surface treatments such as power washing (PW) and sand blasting (SB). Regarding the type of grout material used, epoxy grout (E) exhibited good bond to precast concrete regardless of surface preparation. Non-shrink cementitious grout (C) and the magnesium phosphate grout (M) both exhibited lower bond strengths to concrete regardless of surface preparation and age. Finally, the UHPC grout (U) exhibited good bond performance using the EA surface preparation.

2. Pull-off bond tests showed that the supply of extra moisture at the grout-concrete interface increased the bond strength of the C grout by about 30 %. This is attributed to a reduced porosity at the interface due to an increased degree of hydration achieved by the grout material. If no extra moisture is supplied, the concrete substrate tends to "steal" part of the grout mixing water. However, the extra moisture must be carefully supplied, as a reduction of the bond strength might occur due to excess water.

3. The inclusion of IC in the C grout through the use of pre-wetted LWA might be a good alternative for supplying the extra moisture. Pull-off bond results show bond strength improvements when IC is included in the grout material. It is conjectured that IC may have additional benefits besides providing extra moisture. As shown in the paper, IC reduces the amount of both autogenous and drying shrinkage, which will indeed reduce the amount of microcracking. This is important as microcracking at the interface is believed to reduce bond between the two materials.

4. UHPC provides about 64 % higher bond strength than the conventional non-shrink cementitious grout. This is attributed to two effects: 1) low shrinkage due to the presence of steel fibers in the matrix, and 2) finer and lower porosity at the ITZ between the UHPC and the concrete substrate. This, along with the superior mechanical performance provided by this type of material, makes the UHPC a good candidate material for PBE connections.

The research presented in this paper supports, from a materials perspective, the experimental results shown in Part II of this study.

ACKNOLEDGEMENT

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