Abstract. The use of full-depth precast concrete panels for rehabilitation of bridge decks allows fast installation and all-weather construction. Typically, precast panels are prefabricated in a well-controlled environment, resulting in strong and durable products. Undoubtedly, they will perform well under the traffic loading and weathering. However, the panel joints that are closed later with grout pour may degrade prematurely, leading to a less desirable composite action. Obviously, the lack of overall system performance causes concerns that limit the wider application of this innovative construction method. Conventionally, cementitious grouts, epoxy mortars or polymer concretes are used for the closure pour. In general, epoxy mortars or polymer concretes have extremely low permeability and dry shrinkage, as well as good adhesion with the substrate; but they are difficult to mix and clean, very sensitive to moisture variations, and incompatible with the substrate under thermal and mechanical loads. As a result, deficient bonding may occur, particularly when longitudinal post-tensioning is not provided, causing leaking and rusting. Oppositely, cementitious grouts are easier to mix and more compatible with the concrete substrate; however, they are more prone to shrinkage. More recently, advances in cementitious materials resulted in the development of Ultra-High Performance Concrete (UHPC). While this material has demonstrated exceptional performance when used for the closure pour; it requires special mixing to well disperse the particles and careful attention must be paid to the construction and curing practices to achieve enhanced mechanical and durability properties. As a result, testing of various types of grout materials is essential to establish the quality and serviceability of these materials. It is the intention of this paper to evaluate the performance of different cement-based grouting materials and to provide bridge engineers with useful database as to what materials are preferred for a specific project.

1. Introduction
The precast concrete deck system has been successfully used in the bridge construction for past decades [1-4]. It has increasingly become a viable option for the bridge engineers as it accelerates the construction process, allows the rapid public access, and minimizes the construction accidents and delays. It also uses high quality precast elements, thus increasing the service life and lowering life-cycle cost [5]. One of the primary challenges is the connection between the precast components because an inadequate joint may result in poor load transfer and facilitate the intrusion of aggressive chemicals [6]. Typically, the joint is achieved by pouring various grout materials. As a result, the selection of closure pour materials plays a key role in achieving the monolithic behaviour of precast panel system. Early documentation on the closure pour materials can be traced back to Mrinmay’s work [7], in which various grout products including cementitious and epoxy materials were applied to
different precast bridge constructions. In general, Portland cement-based grouts remained the most widely used materials for the closure pour. They were easy to mix and place, readily available, relatively economical, and more compatible with the concrete panels; however, they had relatively slow setting, high dry shrinkage, and slow strength gain. In contrast, special cement-based grouts (e.g., calcium sulfoaluminate cement and magnesium phosphate cement) had the advantage of rapid setting and strength gain [8,9]. The main disadvantages were the high cost and high early heat evolution. Similarly, the epoxy grout had the advantages of fast setting and rapid strength development. It also exhibited extremely low permeability, excellent bonding capacity, and negligible dry shrinkage. However, it generated high heat and was incompatible with the concrete panels under mechanical or thermal loading [10,11]. More currently, the ultra-high performance concrete (UHPC) was developed and its potential application in connecting the precast concrete deck panels was studied [12-15]. It exhibited good bond capacity, long durability [13] as well as low volumetric change [15]. Specifically, it allowed the use of small joints with less reinforcement. As a result, research is needed to compare how different grouts perform under various field conditions so that a suitable material could be potentially chosen for a specific construction. The main goal of this paper is to evaluate the performance of various cement-based grout materials under normal lab conditions and to provide a valuable database that assists the potential users in making appropriate selection when they face with a wide variety of choices.

2. Experimental programs

2.1. Materials and proportioning

Eleven cementitious mortar and concrete mixes were designed based on numerous trial tests in this studies. The materials and proportions are summarized in Table 1. The cement included type III Portland cement (Mixes #1 to #9) and special cements (Mix #10 CTS rapid-set cement and Mix #11 CTS DOT cement). The type III Portland cement was a high early strength cement manufactured by Buzzi Unicem USA; while the CTS rapid-set and DOT cements both were very high early strength cements (calcium sulfoaluminate-based) manufactured by the CTS Cement Manufacturing Corporation. Additionally, silica fume was used in some mixtures to improve the performance of materials. Two types of sand (river and fine masonry) were used. The river sand had the fineness modulus of 2.58, the specific gravity (SSD) of 2.68, and the absorption of 0.7%. For Mix #2, the river sand was sieved and the particles passing 0.6mm were used. The fine masonry sand had the fineness modulus of 1.82, the specific gravity (SSD) of 2.6, and the absorption of 0.66%. In addition, a crushed limestone with the nominal maximum size of 9.5mm, the specific gravity of 2.88, and the absorption of 0.88% was used for proportioning concrete mixes (#8 and #9). The aggregate gradation is shown in Figure 1.

![Figure 1. Gradation of aggregates used in this study.](image-url)
The chemical admixtures included a High-Range Water-Reducing (HRWR) admixture (W.R. Grace Advacast 575), an accelerator (W.R. Grace Polarset), an Air-Entraining Admixture (AEA) (W.R. Grace Darex), and a Shrinkage Reducing Admixture (SRA) (Sika Control 220). In addition, a set-controll admixture was used in the CTS rapid set and DOTcement mortars (#10 and #11) to stabilize the cement hydration. A ground quartz flour with a median diameter of 3.1μm and a steel fiber with a nominal diameter of 0.2 mm and a nominal length of 13 mm were used for proportioning UHPC mix (#7). All materials were mixed in a rotating drum mixer with a batch size of approximately 0.085m$^3$ following the procedure discribed in ASTM C192.

**Table 1.** Materials and proportions (by weight) for cementitious mortars and concretes.

| Mix # and characteristics | Cement | Silica Fume | Water | Sand | Accelerator | HRWR | AEA |
|---------------------------|--------|-------------|-------|------|-------------|------|-----|
| #1 III+ river sand        | 1      | 0           | 0.32  | 2    | 0.088       | 0.01 | 0   |
| #2 III + sieved river sand| 1      | 0           | 0.3   | 2    | 0.088       | 0.02 | 0   |
| #3 III + river sand       | 1      | 0.08        | 0.32  | 2    | 0.088       | 0.02 | 0.0059 |
| #4 III + river sand       | 1      | 0.275       | 0.3   | 1.43 | 0.12        | 0.043 | 0   |
| #5 III + river sand +0.026 SRA | 1      | 0.275       | 0.3   | 1.43 | 0.12        | 0.043 | 0.0044 |
| #6 III + fine masonry sand| 1      | 0.275       | 0.3   | 1.43 | 0.12        | 0.043 | 0   |
| #7 III + river sand + 0.22 steel fiber + 0.15 quartz flour | 1 | 0.325 | 0.3 | 1.43 | 0.24 | 0.043 | 0 |
| #8 III+ river sand + 2 crushed limestone | 1 | 0 | 0.32 | 2 | 0.08 | 0.018 | 0.0053 |
| #9 III+ river sand + 2 crushed limestone | 1 | 0.08 | 0.37 | 2 | 0 | 0.019 | 0.0069 |
| #10 CTS rapid-set + river sand + 0.0028 set control admixture | 1 | 0 | 0.4 | 2 | 0 | 0.05 | 0 |
| #11 CTS DOT + river sand + 0.0036 set control admixture | 1 | 0 | 0.35 | 2 | 0 | 0.067 | 0 |

2.2. **Test methods**

A mini-slump test, similar to ASTM C1437, was conducted in this study to assess the flowability of cementitious mortars. The 25 drops were not performed during the test due to high flowability of mortar. In addition, a slump flow test was used in this study to evaluate the flowability of concrete mixes (#8 and #9) following the procedures in ASTM C1611. The pin penetration test (ASTM C403) was used to evaluate the time of setting. The time when the penetration resistance approached 4000 psi was defined as the final setting time. The compressive strength was evaluated at 1, 7, and 28 days using 50.8mm cubes for cementitious mortars following ASTM C109 and 101.6×203.2mm cylinders for concrete following ASTM C39. Three specimens were tested at each age and the average value was used to represent the strength of the mortar/concrete at that age.

The flexural bond test was conducted on the composite specimens following ASTM C78 and the test setup is shown in Figure 2.
The mixture proportion for the substrate concrete of flexural bond test was: cement: water: crushed limestone: river sand = 1: 0.4: 2.43: 1.35. HRWR and AEA were used to achieve a slump of approximately 101.6mm, a unit weight of 2240 kg/m³, and a fresh air content of approximately 6.5%. The 28-day compressive strength of substrate concrete using 101.6×203.2mm cylinders was approximately 38.6MPa. After 28 days curing, the substrate concrete was brushed, washed and cleaned, and pre-conditioned to the saturated surface dry condition. It was then positioned into the mold and the fresh mortar was immediately poured into the key joint and finished. The composite specimen was then covered with plastic sheet, stored in air at approximately 22°C for 24 hours, demolded, and subsequently cured in the lime-saturated water at 22°C until the time of testing.

The free dry shrinkage of mortar/concrete was examined following the procedures in ASTM C157. For each material, 3 specimens were prepared and measured. The average value was used for the data analysis. The Rapid Chloride Penetrability Test (RCPT) of mortar/concrete was performed following ASTM C1202. The total charge in Coulombs passed through each slice of mortar/concrete over a period of 6 hours was recorded. The average value of three slices was used to represent the permeability of each material. The rapid freeze and thaw test was conducted in a chamber following the procedure described in ASTM C1202. The durability factor (DF) and the weight loss were calculated. The specimen was defined as failure when the DF was below 60 or a substantial mass loss (more than 20%) was noticed. The test for a specific specimen was stopped at 300 cycles or when the failure was noticed for that specimen.

3. Results and analysis

Table 2 summarized the flowability (spread), the final setting time, the compressive strength, and the flexural bond strength. It can be seen that the normal mortar mix (#1) successfully provided adequate flowability, setting, compressive strength development, and bond capacity. The use of air entrainment (#3 vs. #1) further facilitated the flow, but slightly reduced the compressive strength and the bond capacity. The use of sieved river sand (#2 vs. #1) substantially reduced the flowability and the bond capacity, but slightly increased the compressive strength at late ages. It should be noted that the mixture with sieved river sand was observed to exhibit excessive bleeding. One reason was that the sieved river sand was finer and relatively more gap-graded (Figure 1). Without increasing the paste content, the mixture would become lean, easy to bleed, and less flowable.

The high performance mortar (#4), proportioned by incorporating a high percentage of silica fume into the normal mortar (#1), showed the reduced flowability and the decelerated setting. It also exhibited a slight decrease in the early-age compressive strength and the flexural bond capacity. However, the late-age compressive strength was greatly improved. Adding AEA and SRA into the high performance mortar (#4 vs. #5) was found to increase the flowability and the late-age compressive strength. This may be ascribed to the reduced cohesiveness of mix as a result of air entrainment. It should be noted that for conventional concrete mixes, air entrainment typically increases the stickiness of mix and reduces the compressive strength. However, for high silica fume mixes (very sicky), air entrainment may help to reduce the stickiness, which may aide in increasing the flow and

![Figure 2. Flexural bond test setup.](image-url)
improving the self consolidation, leading to higher compressive strength. It can also be seen that the use of AEA and SRA slowed down the setting and reduced the early-age compressive strength. This may be due to the interaction between AEA and SRA that caused delays in setting and strength development.

Replacing the river sand with the fine masonry sand (#6 vs. #4) significantly improved the flowability and the compressive strength at all ages. As a result, the fine masonry sand would perform better particularly when silica fume was used.

The ultra high performance concrete (UHPC) (#7), proportioned by adding the quartz flour and the steel fiber into the high performance mortar (#4), displayed adequate flowability, good bond capacity, and excellent compressive strength. However, the mixture became extremely sticky and very difficult to mix and place due to the addition of extra fines (quartz flour), which may negatively influence the properties of grout materials. That was why the UHPC showed the lower compressive strength and bond capacity than the high performance mortar (#6).

The conventional concrete (#8) with accelerating admixture, designed in this study as a baseline for comparison, demonstrated good flowability, adequate setting, and acceptable compressive strength development. Without using accelerator (#9), the concrete showed relatively slower setting and compressive strength development at the early age, however, its 28-days compressive strength was higher.

The CTS rapid-set and DOT cement-based mortars (#10 and #11) had good or acceptable flowability, quick setting, and very high compressive strength gain. However, their bond strength was relatively low.

Table 2. Test result summary on spread, setting, and compressive and bond strength.

| Mix # and characteristics       | Spread, mm  | Final setting time, min | Compressive strength, MPa | Flexural bond strength, MPa |
|---------------------------------|-------------|-------------------------|---------------------------|-----------------------------|
|                                 |             |                         | 1 day                     | 7 day                       | 28 day                     |
| #1 III+ river sand              | 190.5       | 210                     | 40.3                      | 63.0                        | 72.5                       | 5.9                        |
| #2 III + sieved river sand      | 114.3       | 330                     | 34.8                      | 64.2                        | 76.2                       | 3.8                        |
| #3 III + river sand             | 215.9       | 230                     | 42.5                      | 56.2                        | 62.4                       | 4.1                        |
| #4 III + river sand             | 152.4       | 225                     | 38.3                      | 73.2                        | 85.6                       | 5.1                        |
| #5 III + river sand +0.026 SRA  | 266.7       | 340                     | 27.5                      | 65.2                        | 91.2                       | 5.0                        |
| #6 III + fine masonry sand      | 215.9       | 200                     | 52.9                      | 80.1                        | 101.5                      | 5.1                        |
| #7 III + river sand + 0.22 steel fiber + 0.15 quartz flour | 165.1       | 180                     | 46.3                      | 68.9                        | 95.3                       | 4.5                        |
| #8 III+ river sand + 2 crushed limestone | 584.2       | 230                     | 44.7                      | 56.7                        | 66.0                       | 3.9                        |
| #9 III+ river sand + 2 crushed limestone | 635.0       | 500                     | 41.9                      | 61.8                        | 68.1                       | 4.8                        |
| #10 CTS rapid-set + river sand + 0.0028 set control | 235.0       | 88                      | 55.9                      | 63.9                        | 69.8                       | 2.9                        |
| #11 CTS DOT + river sand + 0.0036 set control | 184.2       | 72                      | 39.1                      | 48.3                        | 55.0                       | 4.1                        |

Table 3 summarizes the results of 28-day free dry shrinkage, rapid chloride permeability, and freeze/thaw durability. Almost all type III cement-based mortar mixes and the UHPC mix showed medium (0.05% to 0.1%) to high (> 0.1%) free dry shrinkage. This implied that these materials had high risks of debonding or developing dry shrinkage cracking. Conversely, the two concrete mixes and two CTS cement-based mortars demonstrated low free dry shrinkage (<0.05%), meaning that they would have low potentials to debonding or dry shrinkage cracking.
The normal mortar (#1) showed very high rapid chloride permeability, but good resistance to cyclic freezing/thawing. The high permeability may be due to the use of high early strength cement (Type III) and the absence of silica fume. The rapid hydration reaction of type III cement created more porous hydration products. Without the refinement of pozzolanic reaction by silica fume, these porous pastes would result in high permeability. The good freeze/thaw durability may be associated with the presence of air voids in the mix (3.3%). In contrast, the normal mortar (#2) with AEA and a small percentage of silica fume (8% by weight of cement) exhibited a slight decrease in the rapid chloride permeability and the excellent resistance to the freeze/thaw cycles with essentially no deterioration after 300 cycles. This further confirmed that the use of silica fume was able to reduce the permeability; while the entrained air voids helped to increase the freeze/thaw durability.

The high performance mortar (#4) demonstrated low permeability and acceptable freeze/thaw durability. The high percentage of silica fume and the high dosage of superplasticizer created a very cohesive mix, which caused high entrapped air voids (5%). This high level of entrapped air may aide in improving the freeze and thaw resistance. Interestingly, adding AEA and SRA into the high performance mortar (#5) was found to increase the permeability and to reduce the freeze and thaw durability. The use of SRA together with AEA surprisingly caused the air loss possibly due to the incompatibility of AEA with SRA in the mix, leading to lower freeze/thaw resistance.

The UHPC (#7) displayed high permeability and high freeze/thaw durability. The high permeability may be caused by the high percentage of steel fibers present in the specimen. As a result, it was not a direct reflection of porosity of the material. In fact, RCPT was not applicable to steel-fiber reinforced cementitious materials such as UHPC. The high freeze/thaw durability may be associated with the dense paste as well as the presence of high entrapped air voids (4.7%).

The concrete mix with 8% silica fume and air entrainment (#9) performed very well. It exhibited low permeability and high freeze/thaw durability. Adding accelerator (#8 vs. #9) increased the permeability and reduced the entrained air content. The increased permeability can be again ascribed to the accelerated hydration reaction that led to porous microstructure of paste; while the reduced air entrainment can be due to the incompatibility between the accelerator and the AEA.

The two CTS cement-based mortars performed very poorly. They showed high permeability and very low freeze/thaw resistance, which was likely due to high porosity of paste and the lack of air entrainment.

| Mix # and characteristics | RCPT, coulombs | Freeze/thaw durability | Dry shrinkage at 28 days, % |
|---------------------------|----------------|------------------------|-----------------------------|
|                           | Fresh air, %   | Relative dynamic modulus, % | Weight loss, % |
| #1 III+ river sand        | 8461           | 3.3                    | 97.5                        | -0.3                        | 0.1065                        |
| #3 III + river sand       | 7929.7         | 9                      | 100                         | -0.15                       | 0.101                         |
| #4 III + river sand       | 1563.7         | 5                      | 70                          | -0.15                       | 0.119                         |
| #5 III + river sand +0.026 SRA | 3804         | 2.9                    | 39                          | -0.15                       | 0.093                         |
| #7 III + river sand + 0.22 steel fiber + 0.15 quartz flour | 6730.7 | 4.7 | 100 | -0.1 | 0.099 |
| #8 III+ river sand + 2 crushed limestone | 2781 | 4.9 | 100 | 0.1 | 0.048 |
| #9 III+ river sand + 2 crushed limestone | 1066 | 7.2 | 100 | 0.05 | 0.046 |
| #10 CTS rapid-set cement + river sand + 0.0028 set control | 5812 | 2.2 | 0 | 10.1 | 0.037 |
| #11 CTS DOT cement + river sand + 0.0036 set control | 6241 | 2.6 | 37 | 14 | 0.048 |

4. Summary and conclusions
The cementitious grouts developed in this study exhibited a wide variety of performance under normal temperature and moisture conditions. The cementitious mortars without silica fume provided good flowability, adequate setting, high compressive strength, high bond capacity, and good freeze/thaw durability. The main limitations were high dry shrinkage and relatively high permeability. The high performance mortars with high percentage of silica fume showed better compressive strength and bonding capacity as well as lower permeability. The main disadvantages were low freeze and thaw durability and high dry shrinkage. The UHPC demonstrated similar behaviours as the high performance mortars except that the UHPC exhibited high freeze and thaw durability. The concrete mixes displayed the best performance in this study. It had good flowability, normal setting, good compressive strength development, excellent bond strength, low permeability, low dry shrinkage, as well as excellent freeze and thaw durability. The CTS rapid-set cement-based mortars showed relatively low bond strength, high permeability, as well as poor freeze and thaw durability; although they had low free dry shrinkage and gained strength extremely fast at the very early age.

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