Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) Applications and Best Practices

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Abstract

Since the development of ultra-high performance fibre reinforced concrete (UHPFRC) in the late 1990s, the use of this type of concrete has grown significantly. This is due to the superior mechanical and durability characteristics of UHPFRC compared to regular concrete. The Ontario Ministry of Transportation (MTO) utilizes UHPFRC in field-cast joint applications between precast concrete bridge deck panels. MTO has recognized the benefits that could be achieved with the use of UHPFRC including the superior flexural strength that ensures continuity of the precast panels and the good long-term performance due to the extremely low porosity and superior toughness. MTO's first use of UHPFRC was in 2006, for field cast joints. MTO has tendered the use of UHPFRC in this application for over 120 structures. Every year, nine to fifteen bridges are constructed with UHPFRC field-cast joints. The majority of bridges where UHPFRC has been used by MTO are located in the province's Northeast and Northwest Regions, where primarily precast concrete is used for bridge construction. Currently, for a UHPFRC product to be used in MTO work, the product must pass the designated sources of materials (DSM) approval criteria and be listed on DSM list 9.25.50. This paper aims to present MTO's experience with UHPFRC used in field-cast joints. This includes the best practices for material handling and storage, mixing, placing, finishing, curing and surface preparation. The advantages and limitations of the UHPFRC will also be presented based on MTO's experience. Furthermore, the paper will present the steps that MTO has taken through the pre-approval acceptance criteria, specifications and quality assurance testing to ensure the successful use of UHPFRC in field-cast joints.

Keywords: ultra-high performance fibre reinforced concrete, bridges, flexural strength, durability, field-cast joints, curing.

1. Introduction

In recent years, there has been a growing interest in the development and use of ultra-high performance fibre reinforced concrete (UHPFRC) in the construction industry due to its high compressive and tensile strength, low permeability, excellent durability, and ductility, which make it an attractive alternative to regular concrete in various applications [1-3]. UHPFRC is a special type of concrete that can achieve superior mechanical properties and long-term performance compared to regular concrete. This is typically achieved by using a higher cement content and supplementary cementing materials such as silica fume, fly ash or slag with a low water-to-cement ratio that is typically in the range between 0.15 to 0.25 [4-5]. High-quality fine aggregates such as quartz sand or silica sand with a maximum aggregate size of up to1.0 mm are typically used in

UHPFRC [6-7]. UHPFRC can achieve a compressive strength of 150 MPa or more at 28 days. The rapid chloride permeability is typically below 500 coulombs at 28 days. In addition, UHPFRC contains steel fibres that are typically added as a percentage by volume of the concrete [8-9]. The addition of steel fibres improves the mechanical properties including the tensile strength, ductility, toughness and impact resistance of the concrete. The steel fibres also improve the durability of the UHPFRC by enhancing the volume stability of the concrete and providing crack-bridging effect [10].

These superior properties have made UHPFRC an attractive type of concrete used in critical applications where superior mechanical properties and long-term durability are required. Currently, UHPFRC is used in highway infrastructures including bridges and pavements [11-12]. UHPFRC has been used to construct bridge decks and girders when the bridge is exposed to heavy loads and harsh environmental conditions. In addition, UHPFRC has been used in bridge decks to eliminate expansion joints in jointless bridges. For the repair and rehabilitation of bridges and pavements, UHPFRC has been utilized in applications such as overlays and patches. UHPFRC is also used in other applications such as seismic retrofitting, industrial flooring, cladding systems, sound barriers and architectural elements.

The use of UHPFRC in field-cast joints between precast deck panels is one of the most common applications of UHPFRC in North America. Precast concrete panels are typically used for bridge deck construction due to their ease of installation, durability, and long-term performance. Currently and since its first use in 2006, the Ontario Ministry of Transportation (MTO) utilizes UHPFRC mainly for field-cast joints. In this application, UHPFRC provides continuity of the precast panels and enhanced long-term durability due to the superior flexural strength, low porosity and superior toughness. In Ontario, MTO has used UHPFRC in more than 120 bridges and every year, 9 to 15 bridges are tendered with UHPFRC. These contracts are typically in the province's Northeast and Northwest Regions. This paper presents MTO's pre-approval acceptance criteria, specifications and quality assurance testing that are used to ensure the successful use of UHPFRC in field-cast joints. In addition, this paper presents MTO's experience with UHPFRC used in field-cast joints. The best practices for material handling and storage, mixing, placing, finishing, curing and surface preparation are discussed along with the advantages and limitations of using UHPFRC in field-cast joints based on MTO's experience to date.

2. MTO Criteria for UHPFRC Listing on the Designated Sources of Materials (DSM) List

In MTO work, UHPFRC products must meet the acceptancecriteria and be listed on the designated sources of materials (DSM) list 9.25.50 "Ultra-High Performance Fibre Reinforced Concrete (UHPFRC) for Field Cast Joints" before it can be used for MTO contracts. DSM listing is specific to an individual UHPFRC mix design and pre-blend production plant. Any changes to the ingredients of the approved UHPFRC mix design or production plant requires a new approval process. The UHPFRC is required to be packaged in bulk bags containing the pre-blend (consisting of cementitious materials, sand, powder mineral and powdered admixtures, if used) to which water, liquid admixtures and fibres are added at the site at the time of placement. The pre-blending production plant is required to meet ISO 9001:2015 certification. Calibration certificates are required for scales used in the production of the pre-blend. A material identity card is required based on CSA 23.1 Annex U [13].

The DSM acceptance criteria covers some material requirements for the constituent materials of the UHPFRC. The cement and the supplementary cementing materials used in the UHPFRC are required to be in conformance with CSA A3001. Chemical admixtures should not contain any chlorides. The UHPFRC should not contain any coarse aggregate. The maximum size of the fine aggregates is 2.5 mm. The steel fibres used should be made of high-carbon steel with a minimum tensile strength of 2,500 MPa when tested according to ASTM A820. The minimum fibre content in the UHPFRC is 6.5 % by weight.

The DSM acceptance criteria includes a trial batch used to evaluate the fresh, hardened and transport properties of the UHPFRC in addition to durability performance testing. Table 1 presents the testing requirements and acceptance limits. During the trial, the supplier is required to cast a mock-up joint as presented in Figure 1. The mock-up is 3.6 m long, 0.85 m wide and 0.225 m deep and is cast in two stages. The first stage includes casting the normal concrete portion of the mock-up, which is 0.3 m wide, as shown in Figure 2(a). This part represents the precast concrete bridge deck panels. The normal concrete is required to have a minimum 28-day compressive strength of 30 MPa and be at least 28 days before placing the second stage. The surface of the normal concrete on which the UHPFRC will be placed is roughened through abrasive blasting or by using a retarder placed on the forms to produce an exposed aggregate finish, as shown in Figure 2(b). The second stage includes placing the UHPFRC into the joint, as shown in Figure 2(c). The joint is required to be moist cured for a minimum of 4 days. The joint is cast higher than the adjacent surface and later ground flush, as shown in Figure 2(d). Once the curing of the mock-up joint is complete and the joint surface is ground, the joint is inspected for exposed defects, cracking and delamination. The joint is cut perpendicularly and cored at the interface to inspect the inside of the joint and the interface between the UHPFRC joint and the surrounding normal concrete, as shown in Figure 3(a). The fibre distribution in the joint is also inspected, as shown in Figure 3(b). Once the UHPFRC meets all the requirements of the DSM approval criteria, the product is listed on DSM list 9.25.50.

Table 1: DSM Testing and Acceptance Limits

Property		**Test Method**	**Samples**	**Acceptance Limit**
Flow		ASTM C1856	Fresh concrete	± 25 mm of target flow Max. flow 235 mm.
Temperature		CSA A23.2-17C	Fresh concrete	Between 10 and 25 °C.
Compressive Strength	4 days	MTO LS-426	3 cylinders 75 mm × 150 mm	Min. 80 MPa
	28 days	MTO LS-426	3 cylinders 75 mm × 150 mm	Min. 130 MPa
Flexural Strength at 28 days		ASTM C1609	6 beams 150 mm ×150 mm × 500 mm	Min. 15 MPa (peak strength)
Rapid Chloride Permeability		LS-433	2 cylinders 100 mm × 200 mm Without steel fibres	Max. 300 coulombs at 28-32 Days
Linear Shrinkage		LS-435	3 prisms 75 mm × 75 mm × 285 mm	Max. 0.06%
Freeze-thaw Resistance		ASTM C666	3 prisms 75 mm × 75 mm × 285 mm	Min. durability Factor 98%

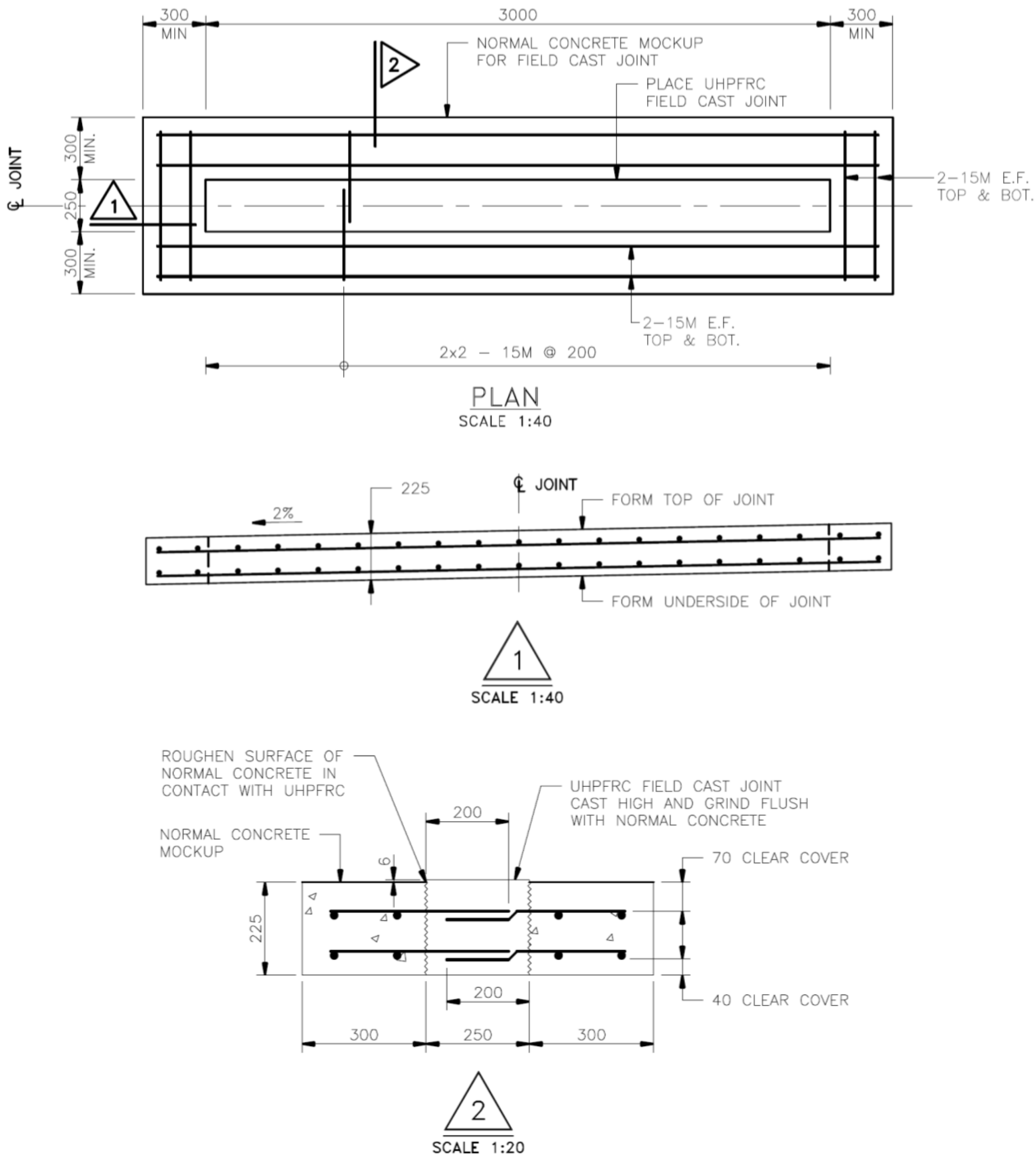

Figure 1: Assembly for Field Cast Joint Mock-Up

(a) (b) (c) (d)

Figure 2: UHPFRC Mock-up (a) After Casting the Normal Concrete Part, (b) Exposed Aggregate Finish of the Normal Concrete, (c) Casting the UHPFRC Joint and (d) After Curing and Grinding the UHPFRC Joint

(a)

(b)

Figure 3: UHPFRC Mock-up (a) Saw-cutting the Joint, (b) Extracted Cores and Saw-cut Joint

3. MTO UHPFRC Specification

The use of UHPFRC in MTO work is covered by a non-standard special provision (NSSP) CONC0005 which covers the requirements for submissions, materials, equipment, construction and quality assurance [14]. It is worth mentioning that the requirements mentioned in the previous section for the DSM acceptance are required one time only when the UHPFRC is being considered for preapproval. However, some of the tests are conducted as quality assurance testing for each contract. These tests include the flow and the temperature for each UHPFRC batch, compressive strength at 4 and 28 days and flexural strength at 28 days. The hardened properties tests are conducted for each lot. For the compressive strength test, the lot size is all the UHPFRC placed in one day. For flexural strength, the lot size is all the UHPFRC placed in one structure during one calendar year. The acceptance of UHPFRC joints is based on the quality assurance results and surface condition and finish including the absence of defects, cracks, delamination and excessive voids.

4. UHPFRC Best Practices

Although UHPFRC has superior properties compared to normal concrete, it requires stringent control over the material's quality and workmanship to ensure a successful placement. This section covers the best practices for material handling and storage, mixing, placing, finishing, curing and surface preparation of UHPFRC used in field-cast joints based on MTO's experience.

4.1. Handling and storage

UHPFRC is typically packaged in three parts. The first part is the pre-blend containing the cementing materials, sand and powdered admixtures, if used. The second part is steel fibres, which are packaged separately. The third part is the liquid admixtures. Water is added to the mix using a water meter. The UHPFRC pre-blend can be packaged in different bag sizes from small 25 kg bags to large bulk bags that contain approximately 600 kg to up to 1200 kg of the pre-blend. The use of small bags has been shown to increase the batch-to-batch variation compared to bulk bags. In addition, when small bags are used, the UHPFRC batch size would typically be small, which increases the time required to fill one field-cast joint. Since the field-cast joints are filled from one end and the UHPFRC must flow to the other end to fill the joint, any delay in the placement increases the risk of cold joints, air entrapment and improper consolidation. Figure 4 shows a typical field-cast joint placement. Furthermore, the small bags mixing typically produce more dust compared to bulk bags. This increases the health and environmental risks in the work environment. Currently, MTO only accepts the use of bulk bags. For field-cast joints, the typical UHPFRC batch would range between 0.3 m^3 to 0.5 m^3 in volume when bulk bags are used.

UHPFRC is typically more sensitive to moisture exposure and therefore, the bags containing the pre-blend need to be well packaged. This is typically not a problem with bulk bags as they are made of plastic and can provide good protection from moisture. On the other hand, small bags are typically paper bags and cannot provide sufficient moisture penetration resistance. For MTO work, the bagged pre-blend can only be used within six months of packaging. If the bagged pre-blend is stored at the site, it should be protected from moisture and any impact that could damage the bags. Before use, the dry pre-blend should be inspected to ensure there is no damage to the bags. During emptying of the dry pre-blend in the mixer, if there are any signs of hardened lumps, the material should not be used in the work. The storage temperature is important as well since the temperature of the pre-blend will have a significant influence on the temperature of the fresh UHPFRC. For MTO work, the temperature of the fresh UHPFRC at the discharge time needs to be between 10 °C and 25 °C. This requires the preconditioning of the concrete ingredients including the pre-blend, water and admixtures during cold and warm weather. In warm weather, the ice is typically used to reduce the temperature of the fresh concrete.

Figure 4: Typical Field-cast Joint Placement

4.2. Mixing

UHPFRC is made with a high content of cementing materials and a low water-to-cement ratio. This makes the concrete viscous and requires a high-shear mixer to ensure proper mixing, as shown in Figure 5(a). The high-shear mixer is required to ensure proper distribution of the steel fibres. Before mixing, it is important to consider how the dust released during mixing will be handled to minimize any health or environmental risks. It is important to ensure that all workers involved in the UHPFRC mixing are well protected from the dust. The entire body including the face need to be covered. This is typically done by using a face cover mask and a full Tyvek suit. It is not recommended to mix UHPFRC indoors without proper ventilation. The mixing sequence of the UHPFRC includes the mixing of the pre-blend with the water and the admixtures before adding the steel fibres. The steel fibres are added gradually to ensure proper dispersion and prevent accumulation, as shown in Figure 5(b). The time required to mix the UHPFRC is typically longer than for normal concrete and is typically in the range of 12 minutes to 20 minutes. During mixing, it is critical to inspect the inside of the mixer to ensure no material builds up on the interior surfaces of the mixer. Any material builds up needs to be removed and incorporated in the batch to ensure batch-to-batch uniformity and to prevent impacting the subsequent batches. During any UHPFRC placement, the first batch is typically the most difficult one to control and requires the most attention to ensure proper mixing and smooth placement throughout the working day. The water and the admixtures are typically adjusted during the first batch to optimize the flow and the temperature of the fresh concrete. UHPFRC with flow less than 160 mm may ensure the stability of the mix but would make the process of filling the joint difficult and could increase the risk of improper consolidation and air entrapment. On the other hand, UHPFRC with a flow of more than 235 mm can be prone to fibre segregation. Figure 6 shows a comparison between a stable UHPFRC and a segregated mix. Currently, MTO sets the maximum flow at 235 mm. In addition, the flow of the fresh UHPFRC needs to be within ± 25 mm from the target flow identified by the concrete supplier. Figure 5(c) shows the flow test of UHPFRC.

(a) **(b)** **(c)**

Figure 5: UHPFRC Mixing (a) Typical High Shear Mixer, (b) Adding Steel Fibres (c) Flow Test

(a)

(b)

Figure 6: UHPFRC Field-cast Joint - Steel Fibre Distribution (a) Joint Showing Uniform Fibre Distribution and (b) Joint Showing Fibre Segregation

4.3. Placing and Finishing

Once the UHPFRC batch is mixed, the concrete is tested for flow and temperature. Once the testing is completed, the concrete is discharged into a wheelbarrow and delivered to the joint. The concrete is typically placed into the joint through ports that are approximately 3.0 m apart, as shown in Figure 4. Plastic pails attached to each port are typically used to facilitate the placement and create a hydrostatic pressure that will help with the flow of the UHPFRC to the next port. Before placing the UHPFRC, the concrete surfaces against which the UHPFRC will be placed have to be prewet for at least 1.0 hour. Because the UHPFRC is required to be cast higher than the adjacent precast panels, spacers are used under the top formwork to allow the joint to be approximately 6 mm higher. Once the top form is secured and sealed, the UHPFRC is placed in the first bucket/port and allowed to flow to the next bucket/port. This placement method is recommended to achieve the best fibre orientation of the UHPFRC. The bridge deck is typically designed with a slope, therefore, the placement of the UHPFRC has to start at the lower side of the joint to minimize the risk of air entrapment. Air vent holes throughout the top formwork of the joint are required to allow the air to escape the joint as the UHPFRC fills the joint. These vent holes are also used as an indication of the filling progress with UHPFRC. Tapping the top formwork can help with the consolidation below the formwork and the escape of entrapped air. Once the UHPFRC reaches the next bucket/port, the placement of the UHPFRC is shifted to the next bucket/port. For each joint, it is important to take into consideration the number of batches required to fill the joint and the time required to complete each batch. The first batch that is placed in the joint will lose workability over time and could impact the ability to properly fill the entire joint if the time required to fill the joint is more than one hour. This typically needs to be discussed with the UHPFRC supplier as some UHPFRC mixes have a working time of less than 30 minutes.

4.4. Curing

Curing is critical for UHPFRC to minimize the risk of cracking or debonding. Currently, MTO requires the UHPFRC to be cured for a minimum of 4 days. There are two methods of curing that are accepted. The first method is curing with two layers of wet burlap. The burlap has to be immersed in water for a minimum of 24 hours before use. The burlap layers are covered with a layer of moisture vapour barrier. The second method is curing under formwork. In this method, the formwork is left in place and removed at the end of the minimum curing period. For both methods, the curing can be interrupted for the grinding operation but for a period that does not exceed 30 minutes and for a section of the joint that does not exceed 5.0 m long. UHPFRC field-cast joints can suffer from cracking and debonding if sufficient curing is not provided. Figure 7 shows a comparison between a field-cast joint that was properly cured [Figures 7(a) and 8(a)] and another joint that suffers from cracking and debonding due to insufficient curing [Figures 7(b) and 8(b)].

(a)

(b)

Figure 7: UHPFRC Field-cast Joint - Effect of Curing (a) Joint Cured Properly for a Minimum of 4 Days and (b) Cracked Joint Due to Insufficient Curing

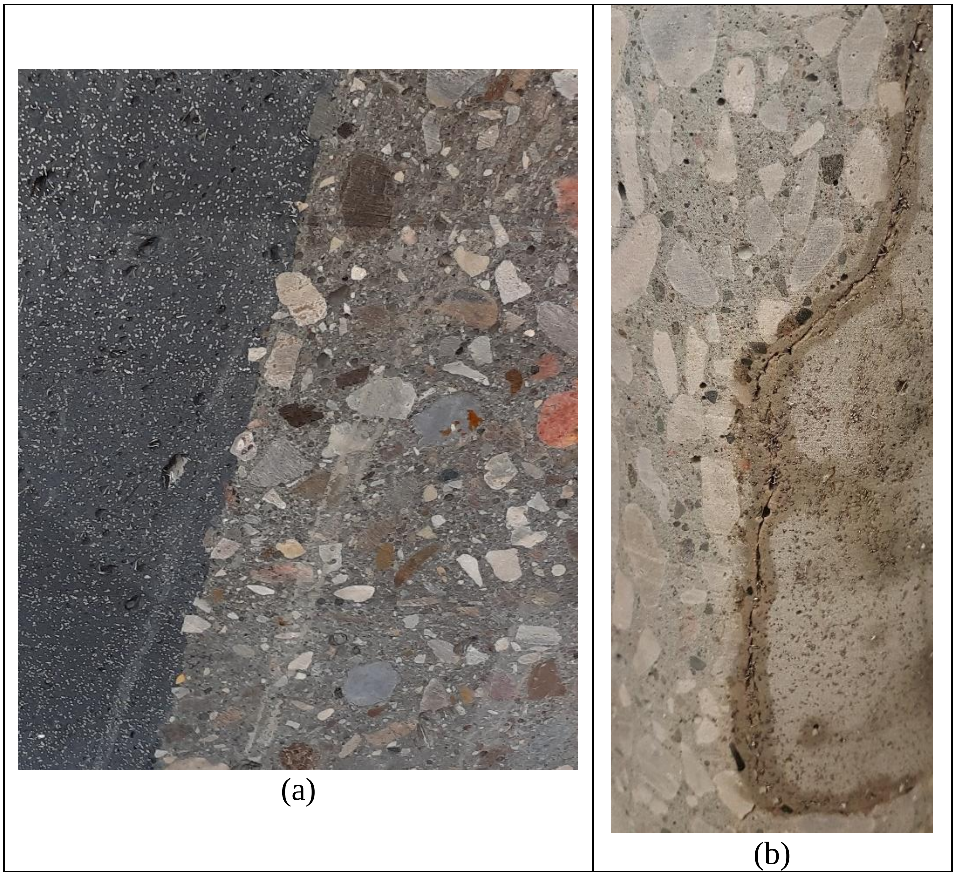

Figure 8: UHPFRC Field-cast Joint - Effect of Curing (a) Properly Cured Joint No Signs of Debonding (b) Joint Debonding Due to Insufficient Curing

4.5. Surface Preparation

In MTO work, the UHPFRC is cast high and ground flush with the adjacent precast panels. The grinding of the UHPFRC surface typically removes surface defects and exposed voids. The ground surface of the UHPFRC should not contain any localized bumps or depressions greater than 3 mm. The ground surface is typically the final surface finish. MTO uses hot-applied rubberized asphalt waterproofing membrane with protection boardto waterproof bridge decks followed by application of asphalt pavement. In specific cases where the bridge deck is exposed to traffic for a period of time before waterproofing and paving are applied, no further surface preparation of the UHPFRC joints is done beyond the initial grinding.

5. Conclusions

The use of UHPFRC in field-cast joints can provide advantages over regular concrete. However, UHPFRC is more sensitive to any variation in the mix design or shortcomings in the mixing or placing operations. Proper control over raw materials is required to ensure batch-to-batch uniformity. Proper mixing and placing procedures are critical to minimize the risk of cracking, debonding and segregation and to ensure long-term durability.

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