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STUDY OF PRECAST CONCRETE CRAZING DUE TO MOIST CURING

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Abstract: Precast concrete has been widely used around the world to accelerate construction schedules and simplify construction management and logistics. Better quality owing to fabrication under controlled environment is an added benefit. Accelerated curing methods adopted in industry standards such as CSA A23.4 for precast concrete allow the manufacturer to maintain factory efficiency without compromising the structural and durability performance. This paper reports on surface crazing defects in precast concrete products subjected to four days of moist curing. Crazing cracks having depth of up to 2 mm resulted from drying in the case of specimens subjected to moist curing. A study was conducted to better understand surface crazing defects in precast self-consolidating concrete mixtures containing high-early (HE) and general-use (GU) cements. The effects of various curing regimes including air dry, immersion in potable water, lime water bath, wet burlap and various relative humidity drying process after specimens have been removed from moist curing were explored. The mechanical properties and chloride ions penetrability corresponding to the various curing regimes have also been assessed. It is shown that the rate of drying impacted the final surface condition of precast concrete and contributed to the occurrence of crazing defects commonly observed on the surface of precast concrete products.

1 INTRODUCTION

1.1 Background

Moist curing of precast concrete products is part of the requirements in most public jurisdictions, such as OPSS 909 and MTO SP999S31. It is essential to achieve the required compressive strength and durability requirements. However, experience has shown that this prescribed curing regime may result in surface crazing defects on the final product causing concerning appearance. Crazing is defined and documented in ACI 302.1R (2015) as a network map pattern of fine surface cracks caused by minor surface shrinkage. Crazing is also common as described in published guidance from the ready the mix industry (NRMCA), especially in concrete floor and flatwork construction (Dobson, 1995).

However, the occurrence of crazing in precast concrete could not be found in the open literature. There is perception that when concrete is produced in a controlled environment, precautionary actions in protecting concrete against the loss of moisture are taken, and hence crazing would not occur. Field inspection was conducted in 2015 on several precast concrete box culvert units (**Figure. 1**) after production and before final placement. The product was made using self-consolidating concrete (SCC) and cured in steel molds under controlled environment, followed by 96-hours of wet curing. The extended curing included full enclosure using two-layers of burlap with continuous sprinkling using portable water. Crazing pattern on the vertical concrete faces was accidentally observed in a rainy day and was nearly invisible on dry sunny days. No further action was taken to investigate the crazing because these units met all contractual requirements. Another box culvert project in 2018 exhibited a similar surface crazing pattern (**Figure. 2**) and was discovered in a similar fashion. Like the first case, the crazing pattern became visible upon wetting. This precast box unit was manufactured using the same SCC mixture under the same environment. However, unlike the first case, the units have gone through an extended 96-hour wet curing by immersing in portable water. Core samples retrieved from the precast unit also exhibited the crazing pattern when subjected to wetting (**Figure 3**), though invisible when it was dry (**Figure 4**). Conversely, the same product cured using a curing compound without extended moist curing in accordance with CSA A23.4 exhibited neither surface crazing nor another surface damage. This has led to a further investigation.

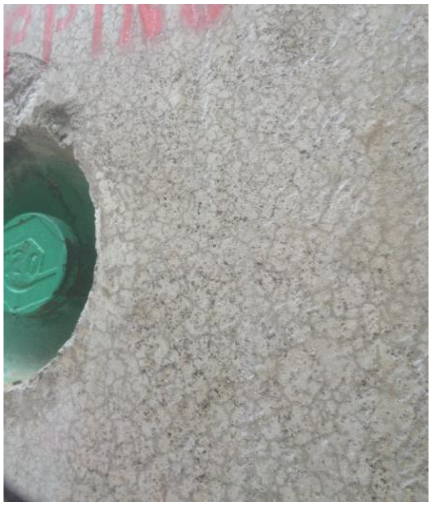

Figure 1: Box culvert surface for Kaskawan Creek, 2015, 96-hour cure by wet burlap and sprinkler

Figure 2: Box culvert surface Meatbird Creek, 2018, 96-hour cure by water immersion

Figure 3: Core sample taken from the box unit from Meatbird Creek Culvert in dry state

Figure 4: Core sample taken from the box unit from Meatbird Creek Culvert in wet state

1.2 Literature Review

Concrete surface crazing is a common phenomenon exhibiting a map patterned fine crack network covering entire or large surface area of concrete elements. In an early report, crazing was described as a disfigurement of concrete surface, but not an indication of its weakness (Moyer, 1906). Early investigation of the cause of crazing has led to an understanding of the colloidal behaviour of cement paste: it expands when wet and contracts when dry (White et. al., early 1920). The crazing cracks were related to variation of surface moisture with respect to the core caused by variation in temperature and relative humidity. White et al. (1920) also explained the mechanism of crazing, which is caused by contraction of the surface cement paste due to the drying action when constrained by the saturated cement paste and aggregate underneath it. The magnitude of the mechanism depends on the evaporation rate and the amount of colloidal cement. Higher cement content tends to cause higher risk of crazing. Though crazing does not constitute structural issues, it could create potential durability issues in the presence of drying and wetting cycles. Also, thermal gradients may stimulate further development of cracks.

Khan (2006) described crazing as cracking that occurs before concrete hardens and gets exposed to frost damage and as a common issue on concrete flooring and flatwork construction. Adding a dry cement shake to the fresh concrete surface to absorb bleeding water and assist in finishing tends to create moisture gradients. This gradient allows various levels of contraction with respect to the concrete below the surface, thus causing crazing. This was also reported by the ready-mix concrete industry in flatwork construction (NRMCA, unknown year). It is also a potential risk especially in dry environments. A small scale drying shrinkage was reported as a cause of crazing (ACI 224.1R-1, 1998). Temperature difference between the curing water and the concrete surface also could create potential crazing. ACI 302.1R suggested that the temperature difference should be less than 11ºC. The delay in protection to avoid moisture loss after finishing will also increase the risk of crazing.

Moist curing is a primary method in preventing cracks associated with plastic, autogenous and drying shrinkage. It can be achieved by wet burlap, sprinkling, misting or water immersion. Applying curing compounds can also prevent the loss of water but does not introduce an external source of moisture during curing, and thus cannot help resisting autogenous shrinkage, particularly in low water-binder ratio mixtures. In cast-in-place concrete construction, wet burlap and plastic sheeting are the most common and effective practice to retain moisture in fresh concrete, especially in hot climates (McCartar and Ben-Saleh, 2001). Many research activities have proven that wet curing reduces shrinkage cracks and produces higher strength given the same concrete mixture (Gonnerman 1930, Alsayed 1994, Naderi et. al. 2009, Radlinski and Olek 2015, Gokul et. al. 2016). In precast concrete manufacturing, process control is critical in achieving superior quality and consistency of the hardened concrete properties. Accelerated curing using steam and water immersion have become preferred options over wet burlap because the curing environment can be better monitored and controlled. Khaliq and Waqas (2017) reported that water immersion produced higher compressive strength than wet burlap curing.

1.3 Scope

In many occurrences, field observations have contradicted the commonly accepted belief in the open literature that moist curing eliminates cracking. Field evidence has shown that wet curing can produce crazing. Thus, further investigation is needed to scrutinize these observations. The scope of this study is to gain a better understanding of the influence of moist curing on surface defects of precast concrete elements and its corresponding mechanical properties.

2 EXPERIMENTAL PROGRAM

2.1 General

Total of 136 cylindrical concrete specimens having 100 mm in diameter by 200 mm in height were made according to CSA A23.2-3C (CSA, 2014) from four different concrete mixtures incorporating 25% ground granulated blast furnace slag 75% portland cement. Four mixture designs denoted GU, GUSCC1, GUSCC2, HESCC, as listed in Table 1, were made with general use (GU) cement. GUSLU is a control mixture with regular slump made with general-use (GU) cement, GUSCC1 is a self-consolidating concrete (SCC) mixture made with GU, GUSCC2 is an SCC mixture made with GU cement and an accelerator, and HESCC is SCC made with high-early (HE) cement. The water-to-cement (w/c) ratio for the four mixtures was 0.44, 0.39, 0.34 and 0.34, respectively. Such mixtures are commonly used in precast concrete manufacturing.

Table 1: Concrete Mixtures Design

Mixture Ingredient or Property	CONTROL	GUSCC1	HESCC	GUSCC2
Coarse Aggregate 19 mm (kg/m^3)	918.5	791	787	733
Fine Aggregate (kg/m^3)	774.9	915	866	972
Portland Cement GU (kg/m^3)	333.2	358		372
Portland Cement HE (kg/m^3)			360	
Slag (kg/m^3)	111	119	120	124
Water (kg/m^3)	197	185	165	142
AEA* (mL/100 kg cement)	128	146.8	360	541
Superplasticizer (mL/100 kg cement)		2848	3120	2500
WRA (mL/100 kg cement)	354			
Accelerator (mL/100 kg cement)				18000
Water-to-Binder Ratio	0.44	0.39	0.34	0.34
Slump (mm)	150			
Slump Flow (mm)		560	580	550
Air Content (%)	NA	6.80%	7.10%	8%
Batch Plant	A	A	B	C

* AEA = Air Entraining Admixture

Table 2: Secondary Curing Regime

Mark	Location	Duration	Temp.	Relative Humidity
B	(Bath) Water Saturated with $Ca(OH)_2$	96 hour	23 °C	100%
W	Potable Water	96 hour	23 °C	100%
Bur	Wet Burlap	96 hour	Room	95%-100%
C	Coated with Curing Compound, Ambient	96 hour	Room	Room
A	Ambient (Control)	96 hour	Room	Room

The concrete cylinders were initially cured inside plastic molds at room temperature (21-23°C) for 24 hours followed by the secondary curing regime listed in Table 2, and subsequent drying regime listed in Table 3. The design 28-day compressive strength for all mixtures is 40 MPa.

2.2 Curing Regime

To better understand the effect of curing on the development of crazing, five curing regimes were adopted to simulate the curing process in industrial precast concrete plants after the 24-hour initial curing. The first set of specimens was cured in a water tank saturated with calcium hydroxide according to CSA 23.2-3C. The second set of specimens was cured by submersion in clean portable water without addition of calcium hydroxide. This is one of methods prescribed by the Ministry of Transportation of Ontario and is preferred by precast producers since it provides best control of temperature and moisture. The third set of specimens was cured under wet burlap, which represents common practice for cast-in-place concrete and for precast manufacturers who do not have controlled curing facilities. The fourth set of specimens was coated with a water-based curing compound that meets ASTM C309-11 Type 1, Class A, and stored at room temperature, which simulates a common economic curing method preferred by precast manufacturers. Finally, the control specimens were cured at room temperature with no moisture retention to develop a worst control environment. All specimens (other than the control) were cured for at least 96 hours from casting before any visual and physical examination.

2.3 Drying Regime

Immediately after the secondary curing, specimens were subjectd to three different drying regimes as listed in Table 3. These three drying regimes were used to simulate three levels of surface evaporation rates. The first group were left to dry under ambient conditions, simulating the least amount of control after moist curing. This also represents the common practice in typical precast manufacturing plants. Another group of samples were dried in an oven at 40°C for one hour to simulate typical summer weather. Lastly, the remainder of specimens were covered by wet burlap for 24 hours without maintaining the moistening of the burlap, which provides slower change of surface moisture.

Table 3: Drying Regime

Mark	Drying Regime
A	Air dry in room condition
O	Oven dry at 40ºC for 1 hour
Bur	Covered with wet burlap

2.4 Examination

Each cylinder was marked with the mixture identification followed by the corresponding curing and drying regime labels. For example, *GUSCC1-BurBur* denotes a specimen made of the GUSCC1 mixture and subjected to wet burlap curing for 96 hours and dried under a burlap cover. After completing the curing and drying process, specimens were subjected to three types of examination: visual, microscopic and physical. The corresponding findings are presented in subsequent sections. Photos of specimens were taken before the secondary curing, at 7-days after the secondary curing, and at 14- and 28-days to verify whether there was any progress of the crazing pattern. Specimens that exhibited some degree of crazing are shown in Figures 5 to 8. Specimens displaying crazing patterns were subjected to further laboratory investigation under optical microscopy and X-ray Computed tomography. The remainder specimens were tested for 28-days compressive strength according to CSA A23.2-9C, air void system according to ASTM C457 (2016), rapid chloride penetrability (ASTM C1543-10a), and water absorption (CSA A23.2-11C).

3 FINDINGS

3.1 Visual Inspection

One cylinder from each curing method and drying regime was visually inspected for surface crazing at regular intervals. The surface of each cylinder was slightly moistened with a damp cloth to make the crazing pattern visible. If a crazing pattern was evident on the surface it was assessed for severity. The visual inspection of all specimens is summarized in Table 4.

It can be observed that specimens from all mixtures did not exhibit any surface crazing when ambient curing and ambient drying were used. When lime-saturated bath was used for curing and the drying method was ambient exposure or burlap, moderate levels of crazing appeared, in some cases on the vertical face of cylindrical specimens only. This tended to be more significant in specimens with more accelerated hydration reactions, namely when an accelerating agent was used or when high-early strength cement was used. When lime saturated bath curing was combined with oven drying, severe crazing appeared for the high-early strength cement mixture and moderate crazing appeared in the one incorporating the accelerating agent, while the other mixtures did not exhibit any crazing. Generally, the most severe tendency for crazing was observed when potable water was used for curing, followed by ambient drying or drying under burlap cover, which represents the most common scenario in precast concrete practice. With a few exceptions, severe to moderate crazing appeared. Interestingly, curing in potable water followed by more severe oven drying did not exhibit more severe crazing than the case of potable water curing followed by slower drying. The overall trend is that water curing appears to be the most dominant factor in the appearance of surface crazing. The true mechanism behind this behaviour needs further investigation. It appears at this preliminary stage that when the drying effect takes place very early, such as in the case of ambient curing, the moisture gradient travels deeper in the surface of the concrete that is still more pervious to evaporation due to non-advanced hydration reactions, and likely gets better restrained by aggregates. Conversely, in specimens submerged in water, when the drying action initiates, it only affects a colloidal surface of cement paste, with no aggregate restraint, while the rest of the concrete deeper in the surface is still moist and unwilling to contract, considering that it is less pervious to evaporation due to more advanced hydration reactions. This is further supported by the fact that the more rapid cement hydration reactions are (e.g. when HE cement or accelerating agent are used), the more is the likelihood of crazing and the higher the degree of its severity.

Figure 5:
(left) GUSCC1-BurBur, (right) GUSCC1-WA

Figure 6:
(left) GUSLUMP-WA1, (right) GUSLUMP-WBur1

Figure 7: (left) HESCC-BO, (mid) HESCC-WA, (right) HESCC-Bur,

Figure 6: (left) GUSCC2-WA1, (mid) GUSCC2-WBur1, (right) GUSCC2-WO1

Table 4: Visual Inspection for Crazing

Mark	Curing Regime	Drying Regime	GUSCC1	HESCC	GUSLUMP	GUSCC2
A-A	Ambient	Ambient	N	N	N	N
B-A	Bath	Ambient	N	**M-VF**	**M**	**M-VF**
B-Bur	Bath	Burlap	N	**M-VF**	N	**M**
B-O	Bath	Oven	N	**S**	N	**M-VF**
Bur-A	Wet Burlap	Ambient	**M**	**M**	N	N
Bur-Bur	Wet Burlap	Burlap	**S**	**M**	**M**	N
Bur-O	Wet Burlap	Oven	**M**	**M**	N	N
C-A	Curing Compound	Ambient	N	N	N	N
W-A	Potable	Ambient	**S-VF**	**S-VF**	**S-VF**	**S-VF**
W-Bur	Potable	Burlap	N	**S**	**S**	**S**
W-O	Potable	Oven	N	**M-VF**	**M**	**S**

N – No crazing, M – Minor crazing, S – Severe, VF – Vertical face only

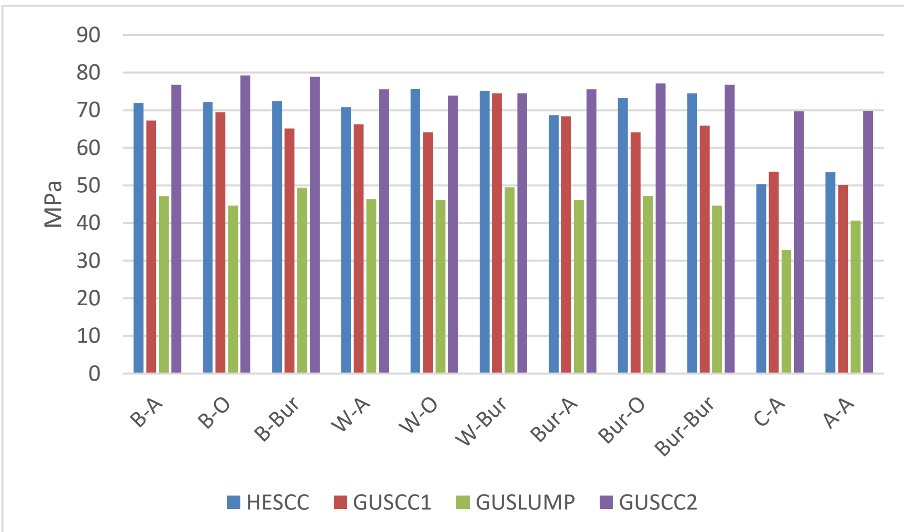

Figure 7: 28-day Compressive Strength versus Curing and Drying Regime.

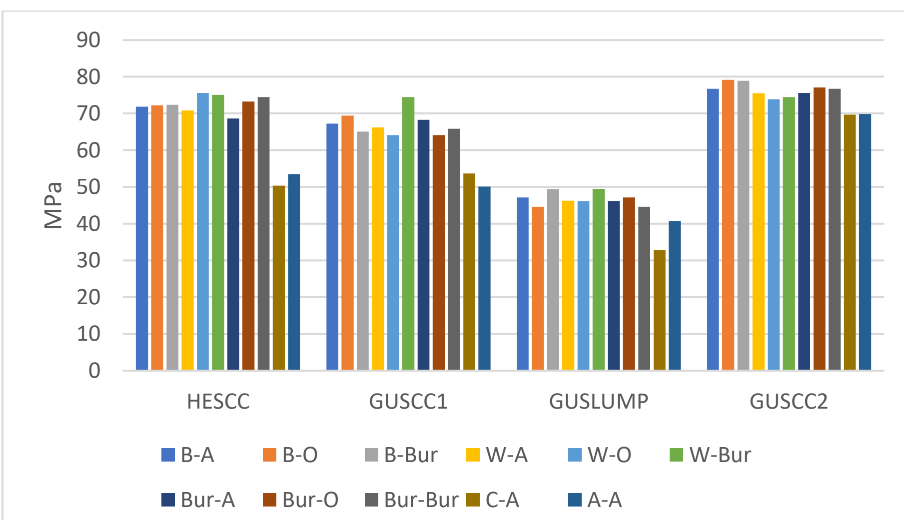

Figure 10: 28-day Compressive Strength Sorted by Mixture Design.

3.2 Compressive Strength

The effect of the initial curing regime and drying procedure on the 28-days compressive strength of specimens from the different mixtures is illustrated in Figure 9. Generally, there was no significant difference in compressive strength between specimens cured in lime saturated water bath, potable water, or wet burlap. Figure 10 displays the expected trend that curing under more abundant moisture yields generally higher compressive strength. Hence, specimens initially cured in ambient air or coated with a curing compound achieved lower strength results that of specimens submersed in water or which benefited from wet burlap cover to supply external moisture.

3.3 Rapid Chloride Ions Penetrability and Air Void System

Rapid chloride ions penetrability (RCPT) test results for all mixtures are illustrated in Figure 11 versus curing and drying regime and sorted out my mixture, fur further clarity, in Figure 12. Generally, initial curing in water led to lower RCPT. Ambient curing or using a curing compound were particularly detrimental to the normal slump control mixture, which had much higher RCPT results. It appears then that curing that mitigates surface crazing can compromise more fundamental properties such RCPT.

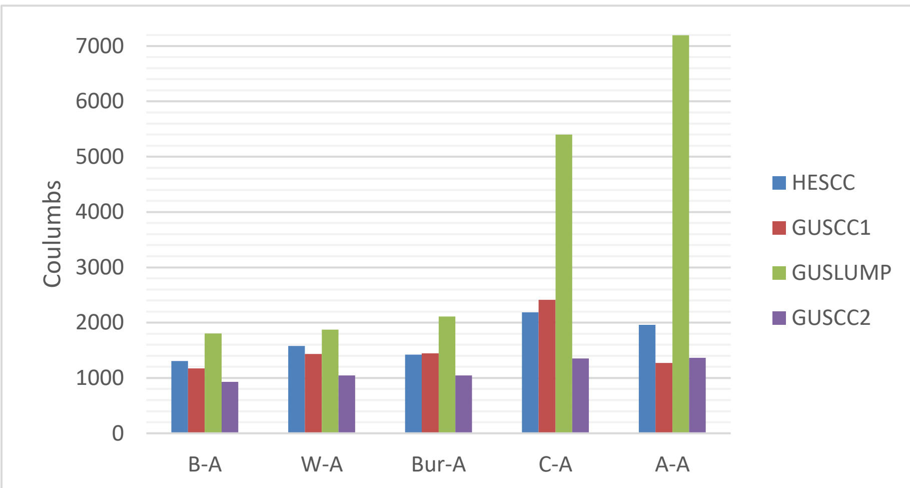

Figure 11: Rapid Chloride Ions Penetrability by Curing Regime.

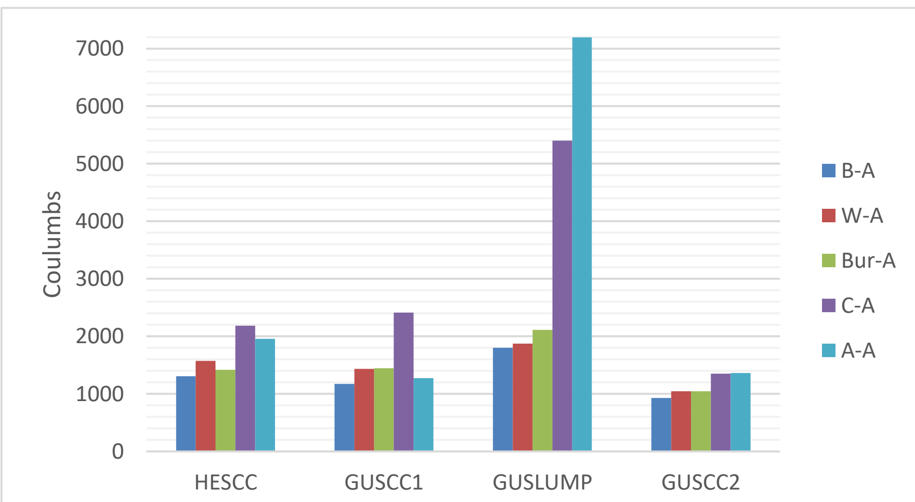

Figure 12: Rapid Chloride Ions Penetrability by Mixture Design.

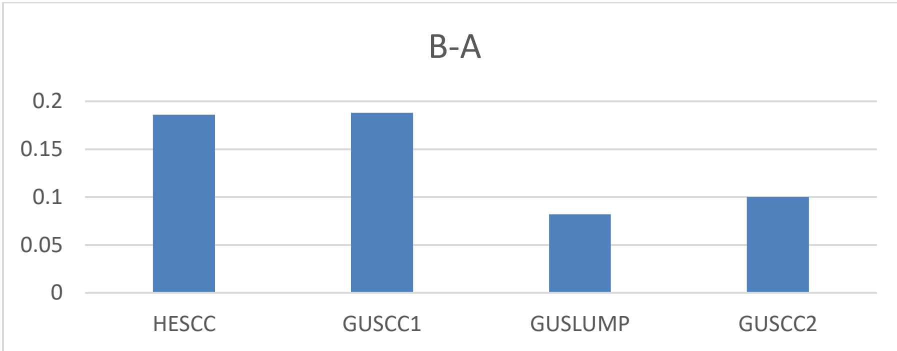

Figure 13: AVS by Mixture Design for Specimens Bath Cured and Air Dried.

Results of microscopical determination of parameters of the air-void system in hardened concrete are portrayed in Fig. 3. The results which are more related to the air void system in the cementitious matrix after setting do not depend on the curing approach or the occurrence of crazing and generally reflect good potential for durability to Freezing and thawing.

3.4 Mercury Intrusion Porosity and Microscopic Examination

Mercury intrusion porosity results showed that moist curing results in generally less intruded pore volume as expected. An example of results is shown in Figure 14. For instance, wet curing demonstrated less pore volume than curing specimens under wet burlap. Optical microscopy observations did not provide additional insight. For instance, Figure 15 shows crazed specimen, without much information on the depth of crazing cracks when present. Hence, it was decided to use X-ray computed tomography to identify crazing cracks in 3-D image analysis. This work is in progress at the time of submitting this article. Other results corroborate to indicate that crazing is rather an esthetic surface problem. However, X-ray micro-CT should provide direct evidence for this.

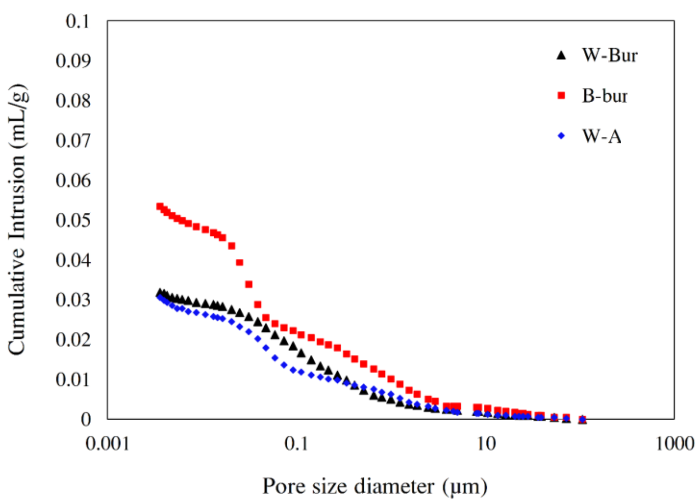

Figure 14 – Example of MIP test results.

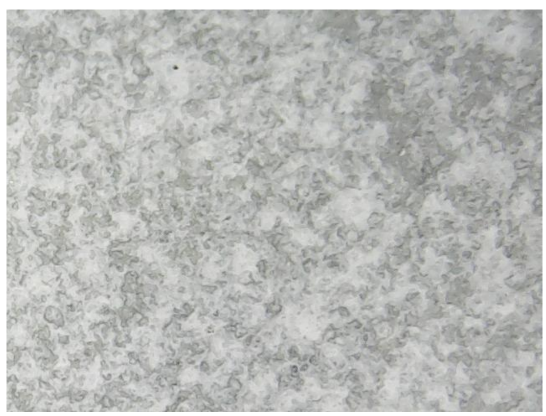

Figure 15 – Example of Optical image of crazed surface.

4.0 CONCLUSIONS

While standard provisions and other guidelines encourage moist curing of concrete, there is growing field evidence that moist curing tends to increase the occurrence of objectionable surface crazing. This study reports this problem in the case of precast concrete for the first time. A laboratory investigation was carried out to explore this problem. The preliminary conclusions that can be drawn are as follows:

- The experimental program reported in this paper demonstrated the field observation.
- Moist curing, particularly in potable water that is not lime saturated, seems to increase the likelihood of occurrence of surface crazing on concrete elements compared to curing in ambient conditions or under wet burlap.
- Acceleration of early-age cement hydration, for instance using an accelerating agent or high-early strength cement, seem to enhance the risk of surface crazing of wet cured concrete.
- Mechanical strength, mercury intrusion porosimetry and rapid chloride ions permeability testing corroborate to indicate that surface crazing is essentially an esthetic surface problem that does not appear to compromise the fundamental mechanical and durability characteristics of concrete.
- There is need for research on post wet curing treatments that can eliminate surface crazing, so that the benefits of wet curing are achieved without compromising surface appearance.

5. ACKNOWLEDGEMENT

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