# INFLUENCE OF ALKALI CONTENT OF CEMENT ON MECHANICAL AND DURABILITY PERFORMANCE OF UHPC

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### Abstract

Ultra-high performance concrete (UHPC) is characterized by high cement content and low water-tocementitious materials ratio, which presents an ideal scenario for potential localized alkali-silica reaction (ASR) to occur, particularly if the aggregate is reactive and the cement is rich in alkalis. The alkali content of the cement can also be a sensitive factor affecting fresh and hardened properties of concrete. However, there is limited information available in literature on the influence of cement alkalinity on properties of UHPC. In this paper, workability, setting time, mechanical and durability properties of the high performance cementitious mortar (HPCM) fraction of UHPC were studied as a function of the alkali content of cement ranging from 0.49% to 0.88% Na<sub>2</sub>Oeq in presence and absence of fly ash. For HPCMs with and without fly ash, an increase in alkali content of cement reduced the workability and compressive strength. The final setting time was prolonged as the alkali content increased. Rapid and significant expansion due to ASR was observed in HPCM without fly ash along with loss in both compressive strength and flexural strength of HPCM, as the alkali content of cement increased. In HPCM mixtures with fly ash, no significant expansion due to ASR or significant loss in compressive/flexural strength was observed, regardless of the alkali content of the cement.

Keywords: UHPC, alkali content of cement, workability, alkali-silica reaction, compressive strength, flexural strength

# 1 INTRODUCTION

Ultra-high performance concrete (UHPC) typically refers to cementitious mixture having compressive strength greater than 150 MPa at 28 days [1, 2]. The development of UHPC using local materials is increasingly gaining attraction as the benefits of using UHPC are being recognized [2-4]. However, this approach is challenged by the limited availability of high-quality materials in many regions. Typically, UHPC is characterized by the use of siliceous aggregates, high cement contents (often  $> 1000 \text{ kg/m}^3$ ) and water-tocementitious materials (w/cm) ratio less than 0.20 to achieve the desired properties [1-4]. When high alkali content cement is used to produce UHPC, an ideal scenario can exist for potential alkali-silica reaction (ASR) to occur particularly if the available aggregate is reactive. This situation can also exist when low alkali content cement is employed as the cement content of the mixture is typically high, and the total alkali content of concrete can be beyond the typical threshold levels required to minimize ASR distress. For conventional concrete the total alkali content of cement is typically restricted to less than 3 kg/m<sup>3</sup> as a preventive measure for ASR distress [5]. Previous studies on the effect of cement alkalinity on the properties of concrete were conducted primarily on conventional normal strength concrete. It was found that the increase in the alkali content resulted in reduction in the workability and compressive strength of concrete [6-14], and increase in the potential for ASR [15-17]. However, the available literature on the properties of UHPC affected by cement alkalinity is still limited.

The present study was carried out to investigate the effect of alkali content of cement on the properties of the portland cement mortar fraction of UHPC without the presence of steel micro-fibers. In this study, the mortar fraction of the UHPC is referred to as High Performance Cementitious Mortar (HPCM) which has typical 28-day compressive strength of 110 MPa. It was successfully used to develop UHPC by simply adding silica fume and steel fibers [3, 4]. In order to isolate the impact of alkali content of the cement on the properties of HPCM and avoid any variability resulting from other factors such as differences in the chemical composition of the cement and fineness, a cement having an alkali content of 0.49% Na<sub>2</sub>Oeq was used as a reference cement. Using the reference cement, a series of HPCMs with increasing alkali content were produced, wherein the alkali content of the cement was adjusted by adding reagent grade sodium hydroxide to the mix water. This was done to simulate HPCMs produced using higher alkali cements. The practice of adding reagent grade sodium hydroxide to a reference cement to elevate its alkali level is a commonly employed procedure in standard test methods and research studies investigating

alkali content affected properties of concrete [7-9, 13, 14, 18]. The properties of HPCM investigated included workability, setting time, compressive strength, ASR expansion and flexural/compressive strength loss due to ASR. Fly ash (FA) was also used in some of the HPCM formulations to understand the behaviour of FA under various alkali contents of cement.

# 2 EXPERIMENTAL PROGRAM

# 2.1 Materials

In the experimental study, a Type III portland cement meeting ASTM C150 specification was used. The specific gravity, Blaine's surface area and the alkali content of the cement were 3.15, 540 m2/kg and 0.49% Na<sub>2</sub>Oeq, respectively. In specific mixtures, a class F fly ash was used as a cement replacement material on a mass basis. The specific gravity of fly ash was 2.26. Table 1 lists the chemical properties of cement and fly ash. The fine aggregate used in this study was a reactive sand (containing volcanic glass) meeting the ASTM C33 gradation specification. The gradation of the fine aggregate is shown in Table 2. The specific gravity, water absorption, and fineness modulus of the fine aggregate were 2.58, 1.5%, and 2.93 respectively. Reagent-grade sodium hydroxide (NaOH) in pellet form was used to increase the alkali content of the cement. In this study, Melflux® 4930F, a powder form of polycarboxylate ether-based high-range water-reducing admixture (HRWRA) was used to improve the workability of HPCM.

### 2.2 Mixture proportions

A total of 9 HPCM mixtures were investigated to study the effect of alkali content of the cement on the properties of HPCM, with and without FA. The w/cm and the fine aggregate-cement mass ratio were fixed at 0.2 and 1.25, respectively, throughout the study. In mixtures with FA, a dosage of 17% by mass of the cementitious material was used. The alkali content of the mixtures was adjusted by adding reagent grade NaOH to the mixing water to achieve different alkali levels of 0.49%, 0.60%, 0.70%, 0.75%, and 0.88% Na2Oeq by mass of cement. The mixture proportions of the 9 HPCMs are shown in Table 3. The first five HPCM mixtures C, A1, A2, A3 and A4 had the same mixture proportions except that the alkali content was varied from 0.49% to 0.88% Na2Oeq by mass of cement. The dosages of HRWRA were kept constant at 0.75% by mass of cementitious materials. The next two HPCM mixtures A3a and A4a were prepared by increasing the dosage of HRWRA of HPCMs A3 and A4 to 1% and 1.5%, respectively, to match the workability of other mixtures, i.e. HPCMs C, A1 and A2 (see Table 4). The effect of alkali content on the ASR distressed properties of HPCMs without FA was determined by comparing HPCMs C, A1, A2, A3a, and A4a. The last two HPCMs CF and A4F were prepared by replacing 17% of the cement with FA in HPCMs C and A4, respectively, while maintaining a constant dosage of HRWRA at 0.75%. The effect of alkali content on the ASR distressed properties of HPCMs with FA was determined by comparing the performance of HPCMs C, A4a, CF and A4F. The quantities of materials used for 1 m3 HPCM are presented in Table 4.

## 2.3 Specimens preparation

Fresh HPCM mixtures were prepared by a UNIVEX M20 planetary mixer. For each HPCM mixture, the corresponding amount of NaOH was dissolved into the mixing water before use. At first, the cementitious materials, fine aggregate, and the HRWRA were dry mixed for 1 min at low speed (100 RPM). Then the mixing water or NaOH solution was added to the dry mixture. The mixing continued at low speed for 3 to 4 min before the mixture became flowable. Finally, the flowable mixture was mixed for another 1 to 2 min at medium speed (300 RPM). The entire mixing process lasted for 5 to 7 min. Soon after the mixing process was complete, flow tests were conducted on the mortar and samples for setting time test were prepared.

The specimens were cast on a vibrating table. Depending on the workability of HPCM, vibration was applied for 10-60 s to remove entrapped air. Then, the specimens were kept in the moist room maintained at 100% relative humidity and 23 °C in accordance with ASTM C511. Specimens were de-molded at 48 hr. after casting, due to the extended setting time and the slow development in early age strength. For the study of compressive strength, the specimens were stored in the moist room until the testing age. For the study of ASR induced expansion, after the initial curing of the mortar bars in water at 80°C, specimens were subsequently stored in 1N NaOH solution at a temperature of 80°C, as per the procedure in the ASTM C1260 standard. For the study of ASR induced loss in flexural strength, two sets of specimens were prepared – one set was stored in tap water and another in 1N NaOH solution, both maintained at a temperature of 80°C for 28 days before testing the specimens.

# 2.4 Test methods

#### Workability

A procedure to determine the workability similar to the one described in ASTM C1437 was followed. However, instead of using the specified flow table, the fresh HPCM mixture was allowed to spread freely on a level plastic plate without being dropped. When the mixture stopped spreading (about 5 min after the removal of the flow mold) the diameter of the mixture was measured for calculating the flow value as described in the ASTM C1437 method.

#### Setting time

The setting time of HPCM was determined by following the procedures in ASTM C403. Three samples were tested for each mixture. The ambient temperature ranged from 2°C to 24°C.

#### Compressive strength

Compressive strength of each HPCM was determined by testing three  $50 \times 50 \times 50$  mm cubes at the ages of 7 and 28 days. The compressive strength test was conducted in accordance with procedures in ASTM C109.

### ASR induced expansion

The testing procedures in ASTM C1260 were followed for the study of ASR induced expansion of HPCM. However, the mixture proportions of HPCM did not follow the requirement of ASTM C1260 test method. Three specimens with dimensions of 25×25×285 mm were prepared and stored in the 1N NaOH solution at a temperature of 80°C for each of the HPCMs studied. Length change readings of each specimen were taken at selected periods of exposure.

### ASR induced loss in compressive strength and flexural strength

Six cubes with dimensions of  $50 \times 50 \times 50$  mm were prepared for each of the HPCMs studied. Three cubes were cured in tap water at 80°C, and another three cubes were cured in the 1N NaOH solution at 80°C. At 28 days of exposure, the compressive strength of these six specimens was tested, following the procedures described in ASTM C109. Six prisms with dimensions of  $40 \times 40 \times 160$  mm were prepared for each of the HPCMs studied. Three prisms were cured in tap water at 80°C, and another three prisms were cured in the 1N NaOH solution at 80°C. At 28 days of exposure, the flexural strength of these six specimens was tested, following the procedures in the 1N NaOH solution at 80°C. At 28 days of exposure, the flexural strength of these six specimens was tested, following the procedures described in ASTM C348.

#### Scanning electron microscopy (SEM)

The specimens were prepared by sectioning samples from HPCM specimens subjected to the ASR distress using a slow speed diamond saw, followed by grinding and polishing the surfaces using resin-bonded diamond discs with grit sizes from #80 through #4000. Glycol was used the lubricant and isopropylene alcohol was used as the cleaning agent. The SEM examination was conducted in back-scatter mode using Hitachi TM-3000 microscope with energy dispersive X-ray analysis capability. The SEM was operated in a variable-pressure mode on samples without conductive coating.

# 3 RESULTS AND DISCUSSIONS

## 3.1 Workability

The influence of alkali content, dosage of HRWRA and addition of FA on the workability of HPCMs is presented in Figure 1. For HPCMs with HRWRA dosage fixed at 0.75% and without FA (HPCM C, A1, A2, A3 and A4), there appeared to be a threshold alkali content of 0.70% Na<sub>2</sub>O<sub>eq</sub>. When the alkali content was lower than 0.70% Na<sub>2</sub>O<sub>eq</sub>, no significant change in the workability of HPCMs was observed. When the alkali content was higher than 0.70% Na<sub>2</sub>O<sub>eq</sub>, the workability of HPCMs significantly decreased with the increase in the alkali content. The influence of alkali content on the workability of cementitious mixtures was reported differently in the literature [6, 10, 19-23]. In one study, the optimum alkali content was found to be between 0.4% and 0.5% Na<sub>2</sub>O<sub>eq</sub> at which the mixture exhibited the highest workability, and it was explained by the cement/HRWRA compatibility which was influenced by the alkali content of cement [19]. In other studies, a continuous decrease in the workability of fresh cementitious mixtures with increasing alkali content was observed [6, 10, 20]. This was explained by the fact that the additional alkali cations inhibited the effectiveness of gypsum by depressing the release of Ca<sup>2+</sup> from gypsum, therefore, accelerated the hydration of C<sub>3</sub>A [6, 21-23]. It is likely that both the cement/HRWRA compatibility and inhibited effectiveness of gypsum contributed to the observed results in this study.

It is shown in Figure 1 that the addition of FA improved the workability of HPCMs, particularly at high alkali content (0.88% Na<sub>2</sub>O<sub>eq</sub>). A comparison of the workability of HPCMs C, A4, CF and A4F showed

that the addition of FA increased the flow value by 250% when the alkali content was 0.88%  $Na_2O_{eq}$ , but only 13% when the alkali content was 0.49%  $Na_2O_{eq}$ . The increase in the flow value could be attributed to the ball bearing effect of FA particles [24], and dilution effect by replacing cement with FA.

It is shown in Figure 1 that the increase in the HRWRA dosage resulted in an increase in the workability of HPCM, by comparing the workability of HPCMs A3, A4, A3a and A4a. The flow values of both HPCMs A3a and A4a were all above 150%, which were similar to that of HPCMs C, A1, and A2. In the later part of this study, HPCMs C, A1, A2, A3a and A4a are used to investigate the effect of alkali content on the performance of alkali-silica reaction distressed HPCM.

It should be noted that the effect of alkali content on the workability of HPCM is also a function of cement composition, HRWRA type, alkali source and so on [6, 10, 19, 20, 22, 25]. Different results may be observed when other types of materials are used.

### 3.2 Setting time

The time of initial and final set of HPCMs with HRWRA dosage fixed at 0.75% is presented in Figure 2. As shown in Figure 2, for HPCMs without FA, the shortest time of initial setting was observed when the alkali content was 0.70% Na<sub>2</sub>Oeq. When the alkali content was increased from 0.49% to 0.70% Na<sub>2</sub>Oeq the time of initial setting of HPCMs was reduced by 23%. However, when the alkali content was increased from 0.70% Na<sub>2</sub>Oeq the time of initial setting of HPCMs was reduced by 23%. However, when the alkali content was increased from 0.70% Na<sub>2</sub>Oeq the time of initial setting of HPCMs was increased by 32%. The time of final setting increased continuously as the alkali content increased. The observed phenomena of the time of both initial and final setting appeared to be different from past studies where the increasing alkali content increased the rate of hydration of cement and promoted setting [6, 11, 26-28].

The possible causes of the presented results in this study are proposed as follows: First, the time of setting of HPCMs was tested using the penetration method in ASTM C403. This method actually evaluates the penetration resistance of fresh mortar which is more related to the strength of the fresh mortar [24]. Thus, the hydration of C3S was more influential than the hydration of C3A in this method [24]. Second, the effect of alkali content on the rate of hydration of C3S is related to the alkali source added into the system as well [6]. For instance, if alkali sulfates, alkali carbonate or alkali chloride were used as alkali sources, remarkable increase in the rate of hydration of C3S was observed [6, 11, 24, 26-28]. However, if NaOH was used, the influence of NaOH on the rate of hydration of C3S was not significant [6, 7, 29, 30]. In the present study, the NaOH was added into HPCM to achieve a certain level of alkali content. If the quantity of NaOH is expressed as a concentration of the mixing water as in the past studies [7, 29, 30], the maximum concentration (HPCM A4) was only 0.58 M which should be classified as low dosage. Third, many previous studies on the effect of alkali content on the early hydration of fresh mixture were conducted using pure C3S instead of cement [29, 30]. If gypsum or C3A were present in these mixtures, the mechanism of the hydration of C3S would be substantially different. For instance, gypsum is known to significantly accelerate the hydration of C3S [24, 31]. In such case, the presence of NaOH would depress the rate of hydration of C3S by depressing the dissolution of gypsum. Alternatively, depressed effectiveness of gypsum in presence of NaOH resulted in faster hydration of C3A, as discussed earlier [21-23]. In such case, the hydration products, like monosulfoaluminate and calcium aluminate hydrates, rapidly precipitate on the C3S grains and prolong the induction period [24], Thus the hydration of C3S is inhibited. These three explanations potentially contributed to the observed phenomena of time of initial and final setting. It should be noticed that the measured workability and setting time of HPCM were not necessarily related. Less flowable mixtures did not mean that a stronger micro structure of fresh mixture had been developed to resist penetration.

As shown in Figure 2, for HPCMs with FA, the addition of FA delayed the time of initial set by 26% and 42% at alkali content of 0.49% Na<sub>2</sub>Oeq and 0.88% Na<sub>2</sub>Oeq, respectively. Such a significant delay in the measured time of initial set was likely due to the lower early strength of HPCM developed under slightly higher actual w/c, as the w/cm was fixed for proportioning HPCM with FA [24]. The effect of higher actual w/c was less significant at later stage of early hydration, since the observed time of final setting was only increased by 16% at alkali content of 0.49% Na<sup>2</sup>Oeq, and decreased by 3% at alkali content of 0.88% Na<sub>2</sub>Oeq.

#### 3.3 Compressive strength

The effects of alkali content, dosage of HRWRA and addition of FA on the compressive strength of HPCM at the ages of 7 and 28 are presented in Figure 3. For HPCMs with HRWRA dosage fixed at 0.75% and without FA, there was a threshold alkali content of 0.60%  $Na_2O_{eq}$ . In all HPCMs with alkali content lower than 0.60%  $Na_2O_{eq}$ , no significant change in either 7-day or 28-day compressive strength was observed. When the alkali content was more than 0.60%  $Na_2O_{eq}$ , the 7-day and 28-day compressive strength of HPCMs significantly decreased with increasing alkali content. This was in agreement with previous findings from

literature, and attributed to the porous microstructure and lower strength of alkali-containing C-S-H gel of hardened concrete developed in high alkali condition [6-14].

It is shown in Figure 3a that the increase in the HRWRA dosage resulted in an increase in the compressive strength of HPCM, by comparing HPCMs A3, A3a, A4 and A4a. Reminding that the workability of HPCM with higher dosage of HRWRA presented significantly higher flow value, it is reasonable to believe that the better compactibility played a primary role in the increased compressive strength of HPCM with higher dosage of HRWRA.

As shown in Figure 3b, the mass replacement of 17% of cement by FA reduced the compressive strength at the ages of both 7 and 28 days. It is likely that the FA did not undergo significant pozzolanic reaction at the age of 28 days, due to the limited amount of  $Ca(OH)_2$  produced under low w/cm of 0.2 in this study. A comparison between HPCM CF and A4F revealed that the compressive strength of HPCM with alkali content of 0.88% Na<sub>2</sub>O<sub>eq</sub> was 34% and 28% lower than that of HPCM with alkali content of 0.49% Na<sub>2</sub>O<sub>eq</sub> at the ages of 7 and 28 days, respectively. The compressive strength of HPCM with FA also decreased with the increase in alkali content. The lower strength of alkali-containing C-S-H gel as discussed earlier was likely the reason of decreased compressive strength of HPCM.

### 3.4 ASR induced expansion

The effects of alkali content and addition of FA on the ASR induced expansion and loss in flexural strength of HPCM is presented in Figure 4. The criterion for categorizing reactive and non-reactive aggregate of 0.1% at 14 days as per ASTM C33 is presented as horizontal line in Figure 4 for reference. The ASR induced expansion of HPCMs without FA increased with the alkali content, which was evident between 10 and 49 days of exposure. However, for HPCMs containing FA, the ASR induced expansion was minimal even up to 49 days of exposure (expansion <0.05%), and the difference in expansion between alkali content of 0.49% and 0.88% Na<sub>2</sub>O<sub>eq</sub> was not significant. FA was found effective in suppressing ASR even at high alkali content, which was similar to the past studies [32-34].

### 3.5 Compressive strength and flexural strength of ASR distressed HPCM

The compressive strength and flexural strength of ASR distressed HPCM with and without FA is presented in Figure 5. For HPCM without alkali addition and FA (HPCM C), specimens cured in NaOH solution exhibited 4% lower compressive strength than those cured in water. For HPCMs with alkali addition but without FA (HPCM A1, A2, A3, A4, A3a and A4a), lower compressive strength was observed for specimens cured in NaOH solution than those cured in water. Compared with the compressive strength of specimens cured in water, the compressive strength loss of specimens due to curing in the NaOH solution ranged from 4% to 14%. However, for HPCMs containing FA, specimens cured in NaOH solution showed higher compressive strength than those cured in water at both low and high alkali contents (0.49% Na<sub>2</sub>O<sub>eq</sub> and 0.88% Na<sub>2</sub>O<sub>eq</sub>).

As shown in Figure 5b, For HPCM without alkali addition and FA (HPCM C), specimens cured in NaOH solution and water did not show noticeable difference in the flexural strength. For HPCMs with alkali addition but without FA (HPCM A1, A2, A3, A4, A3a and A4a), lower flexural strength was observed for specimens cured in NaOH solution than those cured in water. Compared with the flexural strength of specimens cured in water, the flexural strength loss of specimens due to curing in the NaOH solution ranged from 12% to 42%. However, for HPCMs containing FA, specimens cured in NaOH solution showed 19% higher flexural strength than those cured in water at low alkali content (0.49% Na<sub>2</sub>O<sub>eq</sub>), but 8% lower flexural strength at high alkali content (0.88% Na<sub>2</sub>O<sub>eq</sub>).

Based on the test results, it was noted that the ASR could result in a decrease in both the compressive strength and flexural strength of HPCM without FA. The flexural strength was more vulnerable to the ASR than the compressive strength of HPCM without FA. However, the ASR in HPCM was depressed in the presence of FA, which is evident by noticing that when at high alkali content (0.88% Na<sub>2</sub>O<sub>eq</sub>), specimens cured in NaOH solution exhibited 5% higher compressive strength and only 8% lower flexural strength than those cured in water.

# 3.6 Microstructures of ASR distressed HPCM

Backscatter SEM images of polished sections of ASR distressed HPCMs C, CF, A4a and A4F (cured in NaOH solution) were taken to investigate the microstructure of HPCM (see Figure 6). As shown in Figure 6, the HPCM contains a large amount of un-hydrated cement grains sue to the very low w/cm, and a large amount of pores due to the use of high dosage of HRWRA. As shown in Figures 6a and 6c, at low alkali content (0.49% Na<sub>2</sub>O<sub>eq</sub>), no significant micro-cracks were observed in the HPCMs regardless of presence or absence of FA. As shown in Figure 6b, at high alkali content (0.88% Na<sub>2</sub>O<sub>eq</sub>), significant of micro-cracks were observed, which indicated the significant ASR at high alkali content. However, the use of FA effectively

mitigated the ASR in HPCM (0.88% Na<sub>2</sub>O<sub>eq</sub>) even at high alkali content, by noticing that there was no significant micro-cracks observed in Figure 6d.

# 4 CONCLUSIONS

In this study, the influence of alkali content on several properties of HPCM including workability, setting time, compressive strength, ASR induce expansion, and ASR distressed compressive strength and flexural strength were investigated. Based on the experiment results, the following conclusions were drawn:

• The alkali content of cement affected the workability of HPCM. There was a threshold alkali content of 0.70% Na<sub>2</sub>Oeq, below which no significant change in workability of HPCMs was observed. When the alkali content of cement was higher than 0.70% Na<sub>2</sub>Oeq, the workability of HPCMs significantly decreased with increasing alkali content. The addition of FA increases the workability especially at higher alkali content of HPCM.

• The alkali content of cement affected the hydration of cement in HPCM. For HPCMs without FA, the shortest time of initial setting was observed when the alkali content was 0.70% Na<sub>2</sub>Oeq. However, the time of final setting showed a gradual increase with an increase in the alkali content of cement. The use of FA prolongs both the initial and final time of setting.

• From the perspective of compressive strength, there was an optimum alkali content of 0.60% Na<sub>2</sub>Oeq for HPCM without FA. When the alkali content was less than 0.60% Na<sub>2</sub>Oeq, the compressive strength of HPCMs was not significantly affected by the increase in the alkali content. When the alkali content was more than 0.60% Na<sub>2</sub>Oeq, the compressive strength of HPCMs significantly decreased with increasing alkali content. The effect of alkali content on the compressive strength of HPCM exists even in the presence of FA. The lower strength of alkali-containing C-S-H gel and porous microstructure of hardened HPCM as alkali content increased were considered to contribute to the phenomena observed in this study.

• Even when the w/cm ratio was as low as 0.20, significant ASR induced expansion was observed in test specimens. The ASR induced expansion of HPCM increased with the increase in the alkali content. Higher the alkali content of the cement used in the HPCM mixture, the earlier the occurrence of a rapid increase in ASR induced expansion of HPCM. Fly ash was effective in depressing ASR-induced expansion even at high alkali content (i.e. 0.88% Na<sub>2</sub>Oeq).

• The loss in the compressive strength and flexural strength of HPCM without FA due to the ASR distress was observed with an increase in the alkali content of the cement. However, when FA was used, the loss in the compressive strength was not observed, and the loss in the flexural strength was not significant.

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TABLE 1: Physical and chemical properties of materials.

Materials Name	Type III Cement	Fly ash	
LOI (%)	1.34	0.60	
SiO <sub>2</sub> (%)	20.4	54.1	
Fe <sub>2</sub> O <sub>3</sub> (%)	3.5	8.0	
Al <sub>2</sub> O <sub>3</sub> (%)	5.0	27.8	
CaO (%)	64.4	1.3	
MgO (%)	1.0	0.9	
Na2Oeq (%)	0.49	2.13	
SO <sub>3</sub> (%)	3.5	0.16	

# TABLE 2: Gradation of fine aggregate.

Sieve	Percent Passing
9.5-mm	100.0
4.75-mm	99.4
2.36-mm	90.2
1.18-mm	67.9
600-µm	40.6
300-µm	8.6
150-µm	0.68
75-µm	0.1

# TABLE 3: Relative proportions of materials in HPCM (by mass).

HPCM ID	c <sup>a</sup> /cm <sup>b</sup>	FA <sup>c</sup> /cm <sup>b</sup>	Water/cm <sup>b</sup>	HRWRA/cm <sup>b</sup> (%)	$Na_2O_{eq}/c^a$ (%)
С	1	0	0.2	0.75	0.49
A1	1	0	0.2	0.75	0.60
A2	1	0	0.2	0.75	0.70
A3	1	0	0.2	0.75	0.75
A4	1	0	0.2	0.75	0.88
A3a	1	0	0.2	1.0	0.75
A4a	1	0	0.2	1.5	0.88
CF	0.83	0.17	0.2	0.75	0.49
A4F	0.83	0.17	0.2	0.75	0.88
		1.			

<sup>a</sup> cement; <sup>b</sup> cementitious materials; <sup>c</sup> fly ash

TABLE 4: Quantities of materials used for 1 m <sup>3</sup> HPCM and the resulting workability
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LIDCM ID	Constituent (kg/m <sup>3</sup> )				$Elow(\theta/)$		
Cen	Cement	FA	Water	Fine aggregate	NaOH	HRWRA	FIOW (%)
С	1007	0	220	1259	0	7.6	175
A1	1007	0	220	1259	1.4	7.6	181
A2	1007	0	220	1259	2.7	7.6	190
A3	1007	0	220	1259	3.4	7.6	100
Α4	1007	0	220	1259	5.1	7.6	50
A3a	1007	0	220	1259	3.4	10.1	163
A4a	1007	0	220	1259	5.1	15.1	156
CF	821	164	215	1231	0	7.4	200
A4F	821	164	215	1231	4.1	7.4	175











