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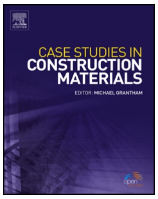

Case study

Developing high performance concrete for precast/prestressed concrete industry

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ABSTRACT

High performance concrete (HPC) is a new class of concrete that has superior characteristics compared to conventional concrete. Despite of its superior characteristics, HPC is not widely used in local and international markets due to its high constituent materials cost.

This paper presents the research done to develop economic HPC mixes using local materials and conventional mixing and curing techniques. HPC characteristics were attained using supplementary cementitious materials as silica fume and class C fly in partial replacement of Portland cement. Superplasticizers were used to maintain a high flowing ability using a low water-to-powder ratio. Concrete mixes were produced using a high energy mixer to maintain sufficient mix consistency. As a result, concrete mixes with 24 -h compressive strength of 70 MPa and 28-day strength of 105 MPa were produced. Concrete samples tested for expansion using accelerated mortar bar test (AMBT) showed that developed concrete is not susceptible to alkali-silica reaction. Improved characteristics can be used in improving the performance of concrete construction projects, reduce required maintenance, and increase construction projects life-span.

1. Introduction

The term high performance concrete (HPC) is used to describe concrete mixes produced with selected high-quality mix constituents, optimized mix design, and low water-to-powder (W/CM) ratio. According to the American Concrete Institute (ACI), HPC is defined as concrete meeting special combination of characteristics and uniformity requirements, which cannot be achieved using conventional constituents, and regular mixing and curing procedures [1]. The characteristics and requirements considered for HPC definitions are: 1) ease of placement (good filling and passing abilities), 2) high early strength, 3) long-term mechanical properties, 4) volume stability, and 5) long life in severe environment.

In 1987, the Congress initiated a five-year Strategic Highway Research Program (SHRP) to investigate different concrete products to improve the standards of the nation's highways and bridges, and reduce the maintenance, repair, and replacement activities of the United States highways and bridges inventory. A SHRP study [2] specified the following criteria for HPC definition: 1) A maximum water-to-powder ratio of 0.35, 2) a minimum durability factor of 80% as determined by ASTM C666, and 3) strength criteria of 21,000 MPa at age of 4 h, 35,000 MPa at age of 24 h, and 70,000 MPa at age of 28 days.

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Nomenclature

f_c'	Specified compressive strength of concrete
w_c	Unit weight of concrete
f_r	Modulus of rupture of concrete
f_{sp}	Split cylinder cracking strength of concrete
E_c	Modulus of elasticity
f_r	Modulus of rupture

In 1993, the Federal Highway Administration (FHWA) initiated a national program to introduce HPC to the bridge construction industry. The FHWA program included the construction of HPC demonstration bridges in all FHWA regions. The technology and results of HPC bridge construction were presented at showcase workshops to introduce the advantages of HPC in bridge construction. According to the FHWA, HPC is defined as “A concrete made with appropriate materials combined according to a selected mix design; properly mixed, transported, placed, consolidated and cured so that the resulting concrete will give excellent performance in the structure in which it is placed, in the environment to which it is exposed and with the loads to which it will be subjected for its design life”. A FHWA study [3] has broken down the HPC into different grades according to the mix characteristics, as shown in Table 1.

1.1. Literature review

HPC mix development depends mainly on the selection and proportioning of mix constituents to achieve an optimized packing order of the granular material. The optimized particle gradation results in a low void ratio, lower permeability, and higher strength. A typical HPC mix incorporates two supplementary cementitious materials (SCMs) for optimized granular particles gradation. First, silica fume which is used as a highly reactive pozzolanic to form additional binder to increase concrete strength; and improve concrete durability due to the reduced voids. Second, quartz flour is used as a SCM with particle size lager than silica fume and smaller than cement. Quartz flour results in a well graded granular material matrix with lower permeability, which increase concrete resistance to chloride attacks, alkali-silica reactivity, and reduce the steel bars rate of corrosion.

The National Cooperative Highway Research Program (NCHRP) report 579 presented different HPC mix designs, developed using silica fume, with an average 28-day compressive strength of 124 MPa [4]. In a different research, HPC mixes were developed at the University of Nebraska-Lincoln that attained a 28-day compressive strength of 126 MPa. The developed mixes had a high content of SCMs, which reduced the workability of the concrete mix [5]. In a relevant research, the effect of silica fume on concrete compressive strength was investigated; an average of 105 MPa and 126 MPa were reported on 28-day and 3-year compressive strength testing [6]. Concrete mix designs incorporating a 2% of nano-silica successfully increased the compressive strength of concrete by 8% [7]. The positive effect of silica fume on the conditions of structural members was investigated by evaluating the conditions of steel reinforcement after 25–27 years of exposure in marine environment. The research results showed that 10% incorporation of silica fume in concrete (by weight) is sufficient to inhibit the reinforcing steel corrosion due to the substantial reduction of concrete voids [8].

The effect of SCMs in concrete mix design is optimized when type III Portland cement is used in concrete production. The positive impact of type III cement is achieved in achieving early high strength (f_c'); and increased split cylinder cracking strength and MOE [9]. Researchers at the State of Texas investigated the mechanical properties of different HPC mixes sampled from different precast facilities using SCMs in concrete mix designs. The research investigation showed that the current AASHTO LRFD specifications and ACI 318 code equations conservatively estimate the concrete MOR and MOE [10]. The increased strength of concrete and higher levels of confinement allowed precast facilities to fabricate bridge I-girders

Table 1
FHWA performance grades [3].

Performance Characteristics	FHWA HPC Performance Grades			
	1	2	3	4
Freeze-thaw durability (X = relative dynamic mod. of elasticity after 300 cycles)	$60\% < X < 80\%$	$80\% \leq X$		
Scaling resistance (X = visual rating of the surface after 50 cycles)	X = 4, 5	X = 2, 3	X = 0,1	
Abrasion resistance (X = avg. depth of wear in inch)	$2/25 > X > 1/25$	$1/25 > X \geq 1/50$	$1/50 > X$	
Chloride penetration (X = coulombs)	$3000 \geq X > 2000$	$2000 \geq X > 800$	$800 \geq X$	
Strength (ksi) (X = compressive strength)	$6 \leq X < 8$	$8 \leq X < 10$	$10 \leq X < 14$	$X \geq 14$
Elasticity (psi) (X = modulus of elasticity)	$4 \leq X < 6 \times 10^6$	$6 \leq X < 7.5 \times 10^6$	$X \geq 7.5 \times 10^6$	
Free Shrinkage (X = micro-strain)	$800 > X \geq 600$	$600 > X \geq 400$	$400 > X$	
Creep (per psi) (X = micro-strain/pressure unit)	$0.52 \geq X > 0.41$	$0.41 \geq X > 0.31$	$0.31 \geq X > 0.21$	$0.21 \geq X$

with superior characteristics incorporating large sized prestress strands. Fabricated girders had a very high span-to-depth ratio with superior flexural and shear capacities [11,12].

HPC mixes have higher durability due to the improved packing order of its granular content. The use of silica results in early concrete setting and a high early strength. Silica fume results in a lower voids ratio within the concrete, which reduces the ability of moisture to penetrate the hardened concrete surface. Lower voids ratio and reduced moisture content significantly mitigate the alkali-silica reaction; and hinders its deleterious effect on hardened concrete [13].

The afore-mentioned research findings prove the advantages of producing HPC mixes using SCMs. The HPC advantages include the ability to construct different concrete projects with longer service life, and reduced life cycle cost. The fabrication of bridge girders using HPC results in smaller girder sections, lighter weights, and expedites the construction process. The main impediments of utilizing HPC on a larger scale are: 1) high material cost, 2) absence of user-friendly batching, mixing, and curing procedures, and 3) increased mixing duration, which results in the formation of cold joints.

The objective of this research is to develop economic, user-friendly, self-consolidating concrete HPC mixes to be used in fabricating bridge girders with superior characteristics. The developed mixes minimum 24 -h compressive strength is 70 MPa, and 28-day compressive strength is 105 MPa. Developed mixes are required to have self-consolidating concrete flowing ability by attaining a spread diameter ranging from 550 mm to 750 mm [14]. The developed mixes should contain sufficient SCMs to mitigate potential long-term alkali-silica deleterious reaction; and minimize its destructive effect on hardened concrete. Concrete batching and mixing time should not exceed 20 min to avoid the formation of cold joints between consecutive concrete pours.

2. Experimental investigation

HPC mix constituents were selected based on their availability in the local market. The initial mix design was modified in three ways, as compared to conventional HPC mixes. First, type III Portland cement was used in replacement of type I and type II cements. This is a requirement of precast/prestressed concrete industry to achieve high early strength sufficient for strands release to increase the precast yard productivity. Second, silica fume and class C fly ash were used in step-wise replacement of Portland cement to improve granular particles gradation, minimize the voids, enhance strength characteristics, and mitigate ASR [15]. Third, a nominal maximum size of 0.9 cms was used for coarse aggregates. The coarse aggregate size restriction was followed to attain a faster and safer mixing of the HPC mixes. Given the targeted high strength required for the developed mixes, a maximum water-to-powder ratio of 0.2 was predetermined for all the lab experimental work. Due to the low water-to-powder ratio and required self-consolidating cement properties (spread diameter ranging from 550 mm to 750 mm), a high energy paddle mixer, shown in Fig. 1, is selected for concrete mixing.

2.1. Selection of HPC mix constituents

In this research project, gradation of different types of sand was investigated including overlay sand, block sand, C33 sand, fine (#10) sand, and 47-B sand. Based on sieve analysis results, shown in Fig. 2, fine (#10) sand was picked for the development of different HPC mixes. The selection of the fine (#10) sand is based on the relatively high cumulative passing percentage of sand particles through smaller sieves that conforms with relevant ASTM standard. Other sand types didn't meet the designated standards for gradation of fine aggregates [16].

High range water reducers (HRWR), commercially known as superplasticizers, are used to maintain sufficient mix rheology, flowing ability, and passing ability due to the predetermined low water-to-powder ratio. The use of Type F and Type G HRWR results in a water content reduction of 30% while maintaining the same level of consistency and working ability [17]. The final HRWR content in the HPC mix is determined using small-sized trial batches in an attempt to attain the

Fig. 1. High energy vertical shaft paddle mixer.

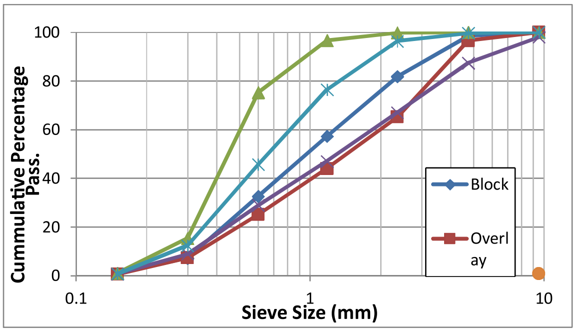

Fig. 2. Results of sieve analysis – fine aggregates.

SCC specified range of flowing ability (450 mm–750 mm). The performance-based approach for HRWR quantity determination in HPC mixes is selected due to the lack of design charts for HPC mix designs.

A high content of Type III Portland cement is used in mix development. High cementitious content is required to increase final strength, given the low water-to-powder ratio. Type III cement is selected to ensure early high strength required for precast facility productivity rates, and due to its finer particle size, which lowers the concrete voids ratio. Finally, two types of SCMs are used in step wise replacement of cement in mix development. First, class C fly ash as an economic byproduct of coal industry will be used for improved gradation of granular material, and to reduce the cost of the cementitious mixture [18]. Second, silica fume as a micro-sized pozzolanic material with average diameter about 0.15 μm – about 100 times smaller than average cement particle – will be used to increase mix final compressive strength and relevant mechanical properties as MOE, MOR, and mitigate the ASR potential reaction [19]. SCMs are used in step wise replacement of Type III Portland cement. According to available research literature, a maximum SCMs content of 40% of the total binder weight was predefined for the experimental program trial mixes.

2.2. Experimental program

Current prescriptive codes in the United States have no clear guidelines, design equations, or design charts that can be used in designing HPC mixes. To-date, multiple research programs depends on performance-based criteria to select HPC mix constituents, determine mix proportions, and optimize the designed mix to attain its predetermined characteristics without violating the economic and environmental aspects of the construction project. This research utilizes different performance criteria to achieve its objectives. The predetermined criteria include fresh concrete properties, mechanical properties of hardened concrete and long-term performance criteria, as follows:

1 *Concrete mixing time:* should not exceed 20 min to avoid the development of cold joints when consecutive layers of concrete are poured. This duration is recommended by surveying multiple batch plant managers, prestress concrete fabricators, and department of transportation (DoT) technical engineers and project managers.
2 *Concrete flowing-ability:* should attain a spread diameter ranging from 450 mm to 750 mm. SCC is increasingly used in precast/prestressed industry, especially with HPC, due to the heavy reinforcement of I-girders cross section. High flowing ability is preferred to avoid the development of internal voids and honeycombs in the poured concrete section. In addition, high flowing ability results in an improved surface finishing, which increase the productivity of the precast facilities.

Table 2
High performance concrete mix designs.

	Cement	Silica fume	Fly ash	Total Binder	Fine Sand	C. Aggregate	Water	HRWR
Mix 1	720	235	215	1170	1000	0	150	70
Mix 2	720	235	215	1170	1000	0	150	95
Mix 3	725	220	215	1160	1000	0	175	65
Mix 4	665	145	145	955	890	350	145	45
Mix 5	615	145	190	950	1250	0	145	45
Mix 6	615	145	190	950	900	350	145	40
Mix 7	615	190	145	950	875	350	130	45
Mix 8	570	190	190	950	860	350	150	45
Mix 9	560	165	205	930	1240	0	155	25
Mix 10	540	70	230	840	1275	0	170	20
Mix 11	620	70	80	770	1440	0	155	35
Mix 12	620	70	80	770	500	890	170	15
Mix 13	620	70	80	770	1440	0	170	15
Mix 14	620	70	80	770	1440	0	170	15

3. *Early (24 -h) compressive strength:* of 70 MPa is predetermined for the mix development. A 70 MPa strength is sufficient for large (18 mms) strands release without the development of end zone cracks. The early high strength allows for early strands release, which increases the productivity rates of precast/prestressed concrete producers [20].
4. *Final (28-day) compressive strength:* of 105 MPa is predetermined for the HPC mixes. The final compressive strength is determined based on maximum concrete strength to be used given the current AASHTO LRFD equations and charts [21].
5. *Potential ASR using accelerated mortar bar test (AMBT):* will be conducted to mortar bar specimens using same aggregates. The bar expansion rates should not exceed relevant expansion rates for no potential ASR [22].

Based on the afore-mentioned performance criteria, available literature, and interviews conducted to material suppliers, batch plant managers, precast facilities engineers, the following guidelines are considered for HPC mix development:

1. Maximum binder content (cement + SCMs) is 1200 kgms per cubic meter of concrete
2. SCMs can be used in step-wise replacement of cement is allowed up to a maximum of 40% of the total binder content (by weight).
3. Maximum water-to-binder ratio is not to exceed 0.25. HRWR can be used in partial replacement of mixing water. Minimum water-to-powder ratio, given the inclusion of HRWR, is 0.15.
4. Granular materials including Portland cement, SCMs, and aggregates are preblended for a total duration of 2 min. Dry mixing is required to enhance the mix packing order and to attain minimum voids ratio for hardened concrete
5. Mixing water, infused with HRWR, is added to the preblended granular mixture after 2 min of dry mixing, and wet mixing is continued for 18 min (total mixing time is 20 min).

A total of 14 different concrete mix designs were developed and poured using the afore-mentioned guidelines. Developed concrete mix designs are shown in Table 2. The workability of different concrete mixes was investigated by measuring the average spread diameter of the mix. Concrete mixes with a spread diameter ranging from 450 to 750 mms were considered for further mechanical properties testing. HPC mix designs that failed to meet the SCC spread diameter criteria were considered as failing mixes. Hence, no further mechanical properties or long-term performance investigation is required.

Results of fresh and hardened concrete properties testing for the developed HPC mixes (mix 1 through mix 14) are shown in Table 3:

According to the test results of HPC mixes properties, shown in Table 3, the following decisions were made:

1. *Mixes 1 through 3:* displayed a low flowing ability when spread test was conducted after a total mixing duration of 20 min. Low flowing ability is indicated by an average spread diameter less than 450 mms. The low spread diameter of mixes 1 through 3 is mainly attributed to the high cementitious content, and the inclusion of a large percentage of silica fume. Given the mixes failures in attaining the flowing ability performance criteria, no further testing was performed. *Hence, mixes 1 through 3 are rejected.*
2. *Mixes 4 through 11:* attained an average spread diameter ranging from 500 mms to 700 mms. The average spread diameter attained, as shown in Fig. 3, meets the SCC performance criteria. Compressive strength cylinders were poured for 24 -h compressive strength testing. The average compressive strength testing measured ranged from 68 to 70 MPa. The attained values meet the preset strength target of 70 MPa. *Mixes 4 through 11 are approved by the research team for further optimization.*
3. *Mixes 12 through 14:* displayed sufficient flowing ability, with an average spread diameter of 700 mms. However, further compressive strength testing didn't meet the preset requirement. The average 24 -h compressive strength test resulted in an average compressive strength less than 56 MPa, as compared to a predefined strength requirement of 70 MPa. *Hence, mixes 12 through 14 are rejected*

Table 3
Fresh concrete properties of high-performance concrete mixes.

	Total Binder	W/CM	Mixing Time	Flowing Ability	Early Strength	Results
Mix 1	1170	0.17	20 min	< 450 mms	N/A	N/A
Mix 2	1170	0.19	20 min	< 450 mms		
Mix 3	1160	0.19	20 min	< 450 mms		
Mix 4	955	0.19	20 min	500 mms	fc' =68 MPa to 72 MPa	Accepted
Mix 5	950	0.19	18 min	650 mms		
Mix 6	950	0.18	18 min	650 mms		
Mix 7	950	0.17	18 min	650 mms		
Mix 8	950	0.19	18 min	650 mms		
Mix 9	930	0.19	18 min	650 mms		
Mix 10	840	0.22	18 min	675 mms		
Mix 11	770	0.24	17 min	700 mms		
Mix 12	770	0.24	17 min	700 mms	f_c' <56 MPa	Rejected
Mix 13	770	0.24	17 min	700 mms		
Mix 14	770	0.24	17 min	700 mms		

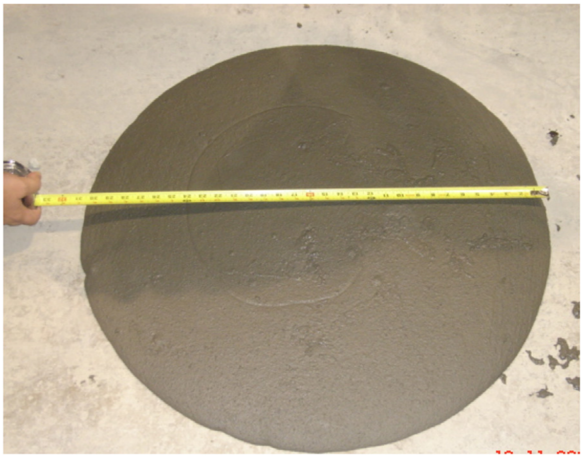

Fig. 3. Spread diameter of SCC (Flowing ability test).

The afore-mentioned results of testing HPC mixes 1 through 14 resulted in the following conclusions:

1 Maximum amount of binder should not exceed 900 kgms per cubic meter. Higher binder amount will not be efficiently mixed, thus flowing ability test will not be passed.
2 The minimum amount of binder required for HPC mix designs is 770 kgms per cubic meter. This binder amount is sufficient to attain a minimum compressive strength of 70 MPa at 24 -h.
3 Water-to-binder ratio ranging from 0.18 to 0.22 is sufficient to attain mixing flowing ability. The water-to-binder ratio includes the total weight of mixing water added to the mix and 75% of HRWR weight.

HPC mixes 4 through 11, approved for further research investigation, are being optimized to enhance their fresh and hardened concrete properties. Optimized mixes were produced in larger batches to pour enough specimens for further mechanical properties testing. Cylinders (100 mms diameter x 200 mms height), modulus of elasticity (E_c) cylinders (150 mms diameter x 300 mms height), modulus of rupture (f_r) beams (150 mms x 150 mms x 500 mms), ASR mortar bars, and split cylinder cracking strength cylinders. All specimens are prepared and cured according to relevant ASTM standards [23]. The optimized HPC mix designs are batched in 0.15 m^3 batches, as shown in Table 4.

HPC mixes A through E were successfully mixed using high energy paddle mixer. Mixing duration ranged from 18 to 20 min, and flowing ability test results displayed an average spread diameter ranging from 550 mms to 650 mms. Mechanical properties are tested to investigate different performance criteria. HPC mix performance is shown in the following section.

2.3. Mechanical properties investigation

2.3.1. Compressive strength (f_c')

The compressive strength of HPC mixes is affected by several parameters, including the high binder content, the presence of silica fume as a reactive pozzolan, reduced water-to-powder ratio, and the high packing order resulting from the use of well graded fine sand. The use of Type III Portland cement, silica fume, and thermal curing [24] resulted in high early strength (day 1) concrete strength.

Compressive strength for different mix designs was calculated as the average value of testing 3 cylinders at any given age [25]. Tested cylinders were end-ground prior to compressive strength test to attain fair cylinder testing surface. The 24 -h compressive strength test values ranged from 70 MPa (mix B) to 85 MPa (mix D), while the 28-day compressive strength values ranged from 105 MPa (mix B) to 121 MPa (mix C). Compressive strength test values are shown in Fig. 4.

Table 4
Optimized HPC mix designs.

	Cement	Silica fume	Fly ash	Total Binder	Fine Sand	C. Aggregate	Water	HRWR
Mix A	630	90	180	900	1353	0	135	37
Mix B	625	80	80	785	1455	0	156	21
Mix C	630	90	180	900	948	403	144	37
Mix D	670	145	145	960	1353	0	144	43
Mix E	630	90	180	900	948	403	140	43

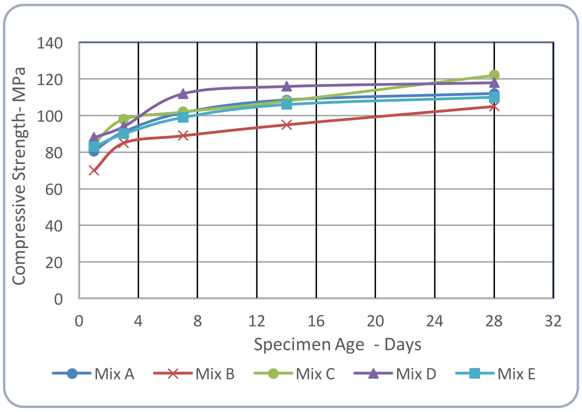

Fig. 4. Compressive strength results of HPC mixes.

2.3.2. Modulus of elasticity (E_c)

The modulus of elasticity (MoE) of concrete, known as static modulus or Young's modulus, is defined as the ratio of normal stress to axial compressive strain. The correct estimate of the MoE is essential for structural applications to calculate potential deflection. In precast/prestressed concrete applications, the MoE is used to estimate the initial prestress losses during fabrication of structural members. Hence, accurate calculation of MoE is required to estimate transfer and development length of prestress strands. Current codes and standard specifications provide equations to estimate the MoE of concrete as a function of concrete compressive strength. The ACI 318 calculates the MoE according to the following equation:

$$E_c = 0.043\ w_c^{1.5}\sqrt{f_c'}\ \text{(MPa)} \tag{1}$$

In this research, MoE was calculated by measuring the average MoE value for 3 (150 mms x 300 mms) cylinders at 28 day [26]. The value of MoE was calculated for different HPC mixes using ACI 318 equation and plotted versus the MoE measured lab value. The average MoE calculated through ACI empirical equation was over-estimated by 33% as compared to average lab value. Different calculated and measured MoE values are shown in Fig. 5.

2.3.3. Modulus of rupture (f_r)

The modulus of rupture is measured to estimate the tensile capacity of concrete. Concrete, as a brittle material has low tensile capacity as compared to its compressive strength. Current ACI 318 code and AASHTO LRFD specifications use the following equation to estimate the MoR as a function of the compressive strength:

$$f_r = 0.62\sqrt{f_c'}\ \text{(MPa)} \tag{5}$$

The MoR value was measured by testing short-span beams (150 mms x 150 mms x 500 mms) using two-point load test [27]. The MoR value was measured as the average of testing 3 specimens after 28 days of specimens' moisture-curing. Fig. 6

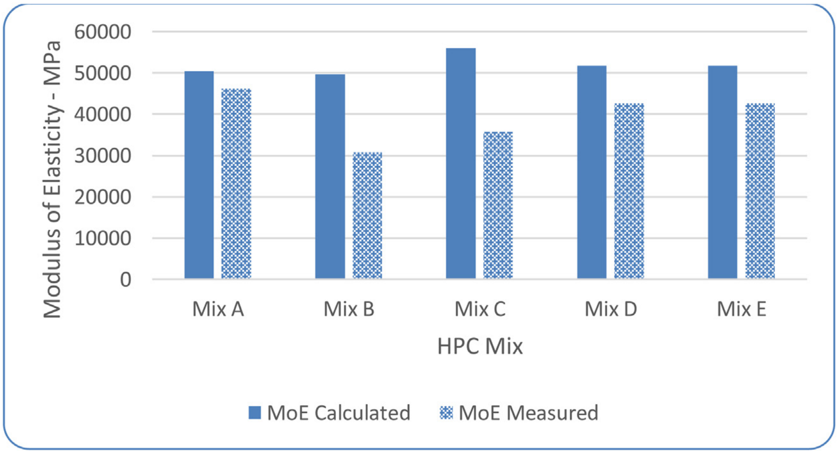

Fig. 5. Modulus of Elasticity (MoE) of HPC mixes.

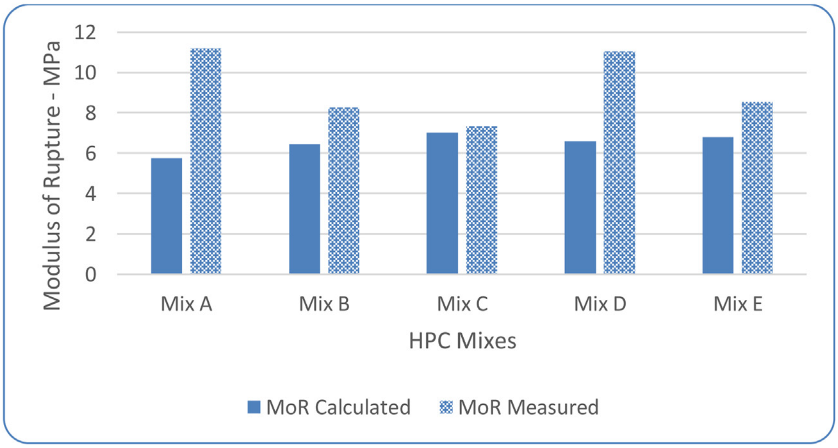

Fig. 6. Modulus of rupture (MoR) of HPC mixes.

displays the value of MoR calculated using code equations and through lab experimental investigation. The lab testing of MoR of HPC mixes showed that the current code equations under-estimates the MoR value of HPC mixes. The current code equation can successfully estimate MoR values for concrete mixes with compressive strength less than 100 MPa. Additional research is required to propose different empirical equation for accurate estimation of HPC mixes MoR.

2.4. Split cylinder cracking strength

Split cylinder cracking strength, also known as Brazilian tensile test or indirect tensile test, is used to evaluate the performance of concrete under tension. In this research, cylinders of dimensions 150 mms x 300 mms are tested in tension [28]. Measured values of split cylinder cracking strength are compared to the values calculated using current code equations.

The lab testing of split cylinder cracking strength of HPC mixes showed that the current code equations adequately estimates the crack strength of cylinders. Measured versus calculated values of crack strength of HPC is shown in Fig. 7.

2.5. Alkali-silica reactivity (ASR)

ASR destructive effect to hardened concrete and its contribution to the premature failure of concrete structures is highly dependent on the chemical reaction of aggregates with highly reaction silica content and the cement alkaline content in the presence of free moisture. The reaction results in the formation of white-colored expansive gel that applies internal pressure and cracks the concrete, as shown in Fig. 8.

It is hypothesized that the incorporation of micro-sized SCMs in concrete mix designs will result in improved particle gradation, and a lowered voids ratio [29]. The lower percentage of voids will prevent the moisture percolation into the hardened concrete, hence, the ASR reaction will be mitigated.

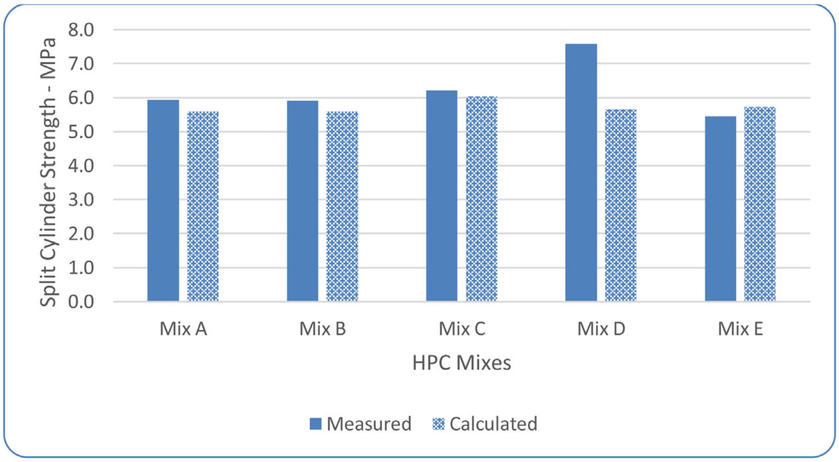

Fig. 7. Split cylinder cracking strength of HPC mixes.

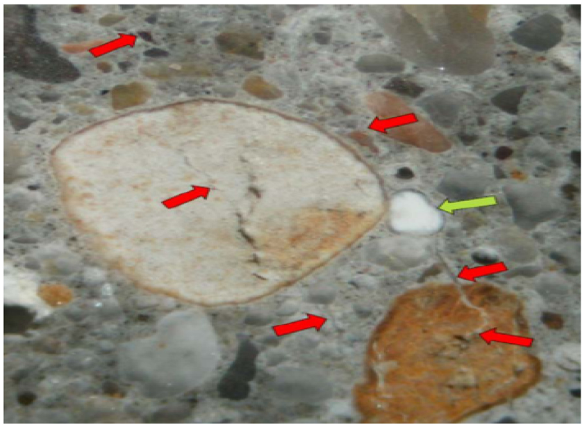

Fig. 8. ASR gel formation in hardened concrete.

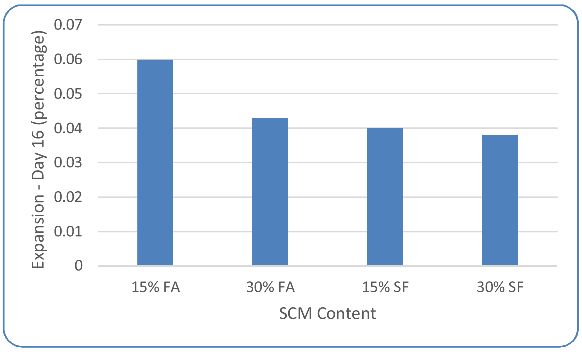

Fig. 9. Effect of class C fly ash (FA) and silica fume (SF) on ASR expansion.

Accelerated mortar bar test (AMBT) was conducted for mix designs with similar SCMs content as in the developed HPC mixes. Results of AMBT showed that the incorporation of 15% silica fume and/or 30% of class C fly ash was sufficient to substantially reduce the mortar bar length changes. A 15% silica fume content results in a 50% reduction of the potential expansion. Similar results are achieved when 30% class C fly ash content was used. The AMBT test results of mixes A through E displayed a final mortar bar expansion of less than 0.1% in 16 days, as shown in Fig. 9. The reduced AMBT displays the successful mitigation of ASR in HPC concrete.

3. Summary and conclusions

The main objective of this research is to develop HPC mixes with self-consolidating concrete properties using user-friendly mixing techniques. Developed mixes are required to attain a spread diameter ranging from 450 to 750 mms after a maximum mixing duration of 20 min. Early mix strength of 70 MPa should be reached at 24 -h compressive strength test, and a final strength of 105 MPa is to be attained at 28-day strength testing. Additional mechanical properties are investigated including modulus of elasticity, modulus of rupture, and split-cylinder cracking strength. Finally, the effect of SCMs on ASR mitigation is investigated as an indication to the long-term performance of developed mixes. Based on the research findings, the following conclusions are achieved:

Concrete mixing and workability: high energy paddle mixers are required to produce HPC mixes due to their high binder content and low water-to-powder ratio. Two-step mixing procedure is successfully used in HPX mixing in a total time period less than or equal 20 min. The successful mixing procedure includes a 2-min dry mixing to pre-blend dry granular material, followed by up-to 18 min of wet mixing after adding water and HRWR.

Produced HPC mixes had an average spread diameter ranging from 450 to 750 mms.

Compressive strength: developed HPC mixes had a minimum 24 -h compressive strength of 70 MPa and a 28-day compressive strength greater than or equal 105 MPa. The compressive strength is attributed to the high binder content, incorporation of silica fume and class C fly ash in the mix, in addition to the low water-to-powder ratio.

Modulus of elasticity: Current code equations over-predict the value of the MoE based on the actual 28-day compressive strength test results. Thus, actual testing for the MoE is required until a revised code equation is developed and adopted.

Modulus of rupture and Split cylinder cracking strength: The values calculated by code equations for indirect tensile strength of concrete (MoR and split cylinder cracking strength) are lower than results of experimental investigation. Thus, the lower values calculated can be conservatively used in case no lab experiments were conducted. Additional research is required to introduce a revised code equation for more-accurate estimation of concrete tensile strength.

Alkali-silica reactivity: The incorporation of SCMs in HPC mix designs results in a reduced potential of deleterious ASR. A minimum content of 15% of cement replacement is required to mitigate the ASR. The silica fume effect is mostly achieved when 15% of silica fume is added. Extra silica fume (up to 30%) doesn't result in significant improvement in concrete performance. On the other hand, incorporation of 30% of class C fly ash is advisable as it improves the concrete performance.

4. Future research

The lack of design guidelines for HPC mixes results in a trial-and-error approach when specific mechanical and long term characteristics are targeted for the concrete mix. Further research is required to develop performance-based criteria to provide general guidelines that could assist material engineers and batch plant personnel in developing economic HPC mixes. Further research is required to standardize quality control procedures for HPC including electrical resistivity methods. Finally, the reliability analysis of precast/prestressed I-girder [30] and environmental impact of high-performance concrete mixes [31] should be investigated to ensure the compliance of HPC girders to design codes reliability indexes and environmental regulations.

Declaration of Competing Interest

None.

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