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Developing Ultra-High Performance Concrete (HPC) with Locally Available Materials

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ABSTRACT: Ultra-High Performance Concrete (HPC) can enhance the durability and resilience of concrete structures. The use of local materials is a fundamental step to save energy and reduce the cost of concrete. The main focus of this research was to develop a HPC with compressive strength of 150 MPa using locally sources materials. In this study, the effect of fine materials, binder type and content, type of mixer, steel fibers and curing regimes on concrete's compressive strength were investigated. The relationship between compressive strength and elastic modulus was also studied. This study synthesizes all relevant experimental data in the literature to propose a new equation for predicting the modulus of elasticity (MOE) at different ages. A number of HPC mixtures were developed to verify the accuracy of the proposed equation. With an error of ±10%, the proposed equation provides a reasonable prediction for the HPC mixtures containing local materials. The final part of the dissertation focuses on developing economical HPC mixtures by reducing the amount of binder content by using of ash. Costs were compared with the HPC mixtures that are available in the market, indicating $283/m3 compared to approximately $200/m3 with current products.

KEY WORDS: HPC.UHPC, Compressive Strength

1. INTRODUCTION

Traditionally, high performance concrete (HPC) may be regarded as synonymous with high strength concrete (HSC). It is because lowering of water-to-cement ratio, which is needed to attain high strength, also generally improves other properties. However, it is now recognized that with the addition of mineral admixtures HPC can be achieved by further lowering water-to-cement ratio, but without its certain adverse effects on the properties of the material. Hence, it is important to understand how concrete performance is linked to its microstructure and composition. In fact, performance can be related to any properties of concrete. It can mean excellent workability in fresh concrete, or low heat of hydration in case of mass concrete, or very quick setting and hardening of concrete in case of spray concrete which is used to repair roads and airfields, or very low imperviousness of storage vessels. However, from a structural point of view, one understands usually that high strength, high ductility and high durability, which are regarded as the most favorable factors of being a construction material, are the key attributes to HPC. Decades ago, HSC was only tested in laboratory without real applications because there were still many uncertainties on the structural behavior of HSC at that time. Up to the present, HPC has been widely used in tall building.

Key Features of High Performance Concrete

HPC should have a better performance when compared to normal strength concrete. Three of the key attributes to HPC are discussed in this part. They are: strength, ductility and durability. We identify these three areas for discussion because they are the most important performance that a construction material should possess.

Strength

In practice, concrete with a compressive strength less than 50MPa is regarded as NSC, while high strength concrete (HSC) may be defined as that having a compressive strength of about 50MPa. Recently, concrete with the compressive strength of more than 200MPa has been achieved [12, 13]. Such concrete is defined as ultra high strength concrete. As the compressive strength of concrete has been steadily increasing with ample experimental validation, the commercial potential of high strength concrete became evident for columns of tall buildings in 1970s in the U.S. [14].

In general, the addition of admixture does not improve the concrete strength only. Usually, other aspects of performance, like ductility and durability, are also enhanced. Hence, the characteristics of HSC are very similar to those of HPC. Table 2 shows the characteristics of different type of HSC with various compositions. To illustrate the composition of the ultra high strength concrete, two examples are given in Table 3 [12, 13].

Table 1: Characteristics of High Strength Concretes

	Regular	High Strength		Very High Strength
Compressive Strength (MPa)	<50	50-100		100-150
Water-to-cement ratio Chemical admixtures	>0.45 Not required	0.45-0.30 Water-reducing	admixture	0.30-0.25 Superplasticizer
Mineral admixtures Permeability (m/s)	or superplasticizer Not required Fly ash Silica fume >10-12 10-13 <10-14			

Table 2: Composition (by weight) of Concrete with Compressive Strength of 200MPa

	Sauzeat et al. [12]	Aitcin and Richard [13]
Cement	1	1
Water	0.28	0.15
Superplasticizer	0.06	0.044
Silica fume	0.33	0.25
Fine sand	1.43	1.1
Quartz flour	0.3	N/A

II. LITERATURE SURVEY

A number of studies have developed the mixture proportions and evaluated the mechanical properties of HPC since 2000s. In the United States, the Federal Highway Administration is one of many organizations that have investigated the development and applications of HPC [1,13,15,16]. In the literature, there are two major trends in the HPC research. The first trend focuses on the enhanced HPC mechanical properties, typically including compressive strength, tensile strength, shear strength, and durability related properties. These improved properties are achieved by optimizing the HPC mixture proportion. The second trend concentrates on applications for HPC and aims at promoting its use in the design and construction of concrete structures. In the current state-of-the-art, HPC has shown unique advantages for long-span bridge applications [17]. The development of HPC using local materials can create additional opportunities for the HPC applications in building and underground structures. In the following paragraphs, the contribution of the constituent materials to the mechanical properties is discussed. This will lead to the development of simplified HPC mixture proportions as presented in the experimental program.

Table 3 shows a typical mixture proportion of HPC premix that is available [6,10,13]. A large amount of binder is necessary to produce HPC with a minimum compressive strength of 150 Mpa. For the mixture shown in Table 2-1, the binder accounts for almost 40% of the total mass of the mixture. Silica fume accounts for 25% of the binder, which could be as high as 30% of the binder according to Ma and Schneider [18]. The use of silica fume is required to achieve a high compressive strength and durability. Silica fume accelerates the pozzolanic reactions that produces additional calcium silicate hydrates (C-S-H) and fills the voids in the paste matrix [11]. However, the improved properties associated with the addition of silica fume do come with a

price; in the current market, silica fume is 4 –7 times more expensive than Portland cement. Wang et al. [19] stated that a HPC mixture with a minimum compressive strength of 138 Mpa at 28 days and 150 Mpa at 56 days can be produced with 10% of the binder replaced by silica fume. Likewise, El-Hadj Kadri et al. concluded that the effect of silica fume on the concrete’s compressive strength is minimal when used at a replacement rate greater than 10% of the binder. The concrete mixtures using silica fume at replacement rates of 20% and 30% had lower compressive strength when compared to the mixtures containing 10%. The effect of silica fume and any other pozzolanic materials can depend on

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the curing conditions. In this study, the authors determine the most effective silica fume content for developing HPC using the locally available materials, which not only provides an adequate compressive strength but also minimizes the cost of HPC. Ground quartz is another filler material that accounts for 8.4% of the total weight of the mixture shown in Table 2-1.

Table 3. Ground quartz is another filler material that accounts for 8.4%

Material	Amount (kg/m^3)	Percentage by weight	Average diameter (µm)
Binder (Portland cement and silica fume)	943	37.8	n/a
Portland cement	712	28.5	15
Silica fume	231	9.3	<10
Filler material (ground quartz and fine sand)	1,231	49.2	n/a
Ground quartz	211	8.4	10
Fine sand	1,020	40.8	150 to 600
Water	109	4.4	n/a
Superplasticizer	30.7	1.2	n/a
Accelerator	30	1.2	n/a
Steel fibers	156	6.2	200

Ground quartz has an average diameter slightly less than the diameter of portland cement, which enables this material to fill the possible voids between sand, unhydrated cement particles, and the hydration products which creates a denser paste matrix. A denser concrete matrix increases the compressive strength and decreases permeability. However, the use of ground quartz may not be necessary due to a substantial portion of unhydrated Portland cement which fills the voids and produces a dense paste matrix. Velez et al found that the stiffness of unhydrated cement particles is greater than the other components in the paste matrix. Therefore, the w/b can be decreased as long as there are enough hydration products to bind all concrete components into a solid matrix. This allows the quartz powder to be excluded from the mixture proportions for an additional reduction in the HPC cost.

The size of the filler materials generally influences the compressive strength of HPC. The Ductal® premix shown in Table 2-1 uses fine sand (150 – 600 µm) to ensure the homogeneity of the concrete and improve the strength. Park et al. evaluated the effect of sand gradation on the concrete's compressive strength. The first and second sand type had an average grain size of 300 – 500 µm and 170–300 µm, respectively. The experimental investigation showed that the mixture proportion in which the fine aggregate was composed of 70% of the 300 – 500 µm sand and 30% of the 170 – 300 µm produced the highest compressive strength. Gerlicher used sand that had grain sizes of 125 – 500 µm for the development of HPC that had 28-day compressive strength of up to 188 MPa. However, Ma concluded that the grain sizes of sand had no significant effect on the concrete's compressive strength. They used two types of sand that had different grain sizes to develop non-fiber reinforced, self-compacting HPC. The fine sand had grain sizes of 300 – 800 µm, and the coarse sand has grain sizes of 2 – 5 mm. The 28-day compressive strengths ranged from 150 to 165 MPa with water curing at 20°C and approximately 190 MPa with heat treatment at 90°C.

III. EXPERIMENTAL TESTING

Materials

For this research program, the binder consists of portland cement (Type I), densified micro-silica (silica fume), and Class C fly ash. The properties of cement, silica fume and fly ash are presented in Tables 4, 5, and 6. Three gradations of the Arkansas River sand were used for the development of HPC. Sand-1 had a natural gradation (Figure 2-1a) that was distributed from the No. 4 (4.75 mm) sieve to the No. 200 (75 µm) sieve. Sand-2 had a smaller particle size, which ranged from passing the No. 30 (600 µm) sieve and to being retained on that No. 50 (300 µm) sieve (Figure 2-1b). Another type of sand (Sand-3), which passed sieve No. 200 (75 µm), was used to evaluate the effect of curing regimens on the concrete's compressive strength (Figure 2-1c). The three types of sands are shown in Figure 2-2. The HRWR admixture was carboxylate-based, and the steel fibers had a diameter of 0.2 mm and a length of 12.7 mm. The steel fiber content was 3% by volume.

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Chemical	
SiO2	20.11 %
Al2O3	5.07%
Fe2O3	3.80%
CaO	64.15 %
MgO	0.98%
SO3	3.23%
Loss on ignition	2.39%
Na2O	0.18%
K2O	0.56%
Insoluble Residue	0.40%
CO2	1.09%
Limestone	2.80%
CaCO3	88.23 %
Potential compounds	
C3S	55%
C2S	14%
C3A	7%
C4AF	11%
C3S + 4.75 C3A	88%
Physical	
Air content of mortar (volume)	8%
Fineness	4.5 m^2/g
Autoclave expansion	-0.01%
Mortar Bar Expansion	0.00%

Item	Description
SiO_2	36.73%
Al_2O_3	21.49
Fe_2O_3	5.68%
CaO	22.70%
Na_2O	1.48%
K_2O	0.57%
MgO	4.30%
∑ Oxides	63.90%
∑ Alkalis	29.05%

Table 4 – Silica fume properties.

Item	Description
Chemical	
SiO_2	95.25%
SO_3	0.08%
CL^-	0.11%
Total Alkali	0.42%
Moisture Content	0.52%
Loss on Ignition	1.88%
pH	8.06%
Physical	
% retained on 45 μm sieve (wet sieved)	0.49%

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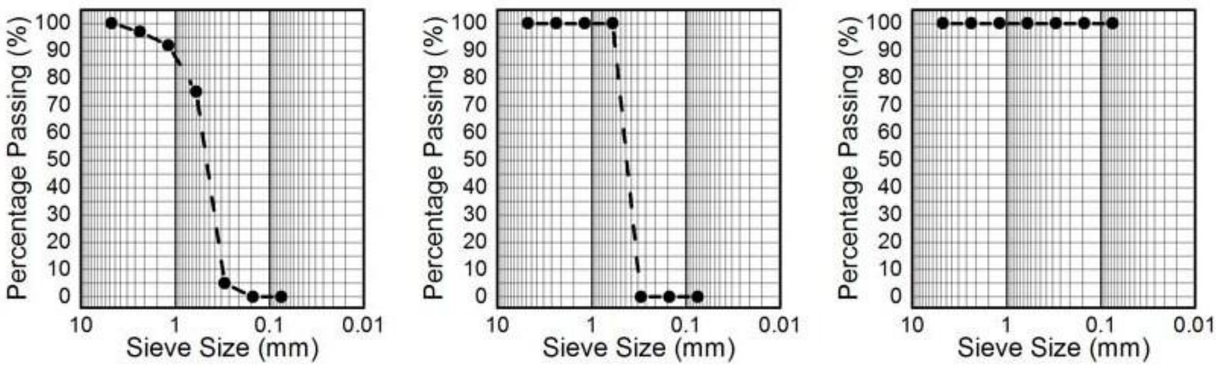
Density (specific gravity)	2.24
Bulk Density (per ASTM)	696.71 kg/m^3
Specific Surface Area	24.49 m^2/g
Accelerated Pozzolanic Activity Index - withPortland Cement	124.44 %



(a) (b) (c)

Figure1. Gradation of sands used

Figure 2. Three types of sand used in the experimental program

Testing procedure

Cube specimens, 50 x 50 mm, were cast to measure the concrete's compressive strength at 1 day of age and at 7, 28, 56, and 90 days of age. The compression test was conducted according to ASTM C109/C109M . The applied load rate was 1.0 MPa/s [10]. The concrete was mixed using a laboratory Hobart 19 L (20 quart) pan mixer. Cement, sand, silica fume, and/or fly ash were mixed for 10 min, and then water and HRWR admixture were added gradually. The mixing time was 15 – 20 mins for all mixtures due to the low w/b ratio and high binder content. The concrete was then placed in steel molds without vibration. The cubes were demolded after one day and then moist cured at of 21°C until testing. The flowchart shown in Figure 2-3 summarizes the mixing procedures. The rheology of the HPC mixtures was evaluated through the flowability of the fresh HPC mixtures. The flow test was conducted according to ASTM C1437 using a flow table test. This test is proposed for use with the mortar that presents plastic to flowable performance, and therefore, it is applicable for the fresh HPC mixtures [15]. The results are presented in Appendix 2A.

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The testing procedure of the cylinders was similar to that of the cube specimens .After demolding the samples at 1 day of age, the cylinders were placed into an end-grinder to remove any surface irregularities and to ensure a plane surface for compressive strength testing. **Figure 3** shows the end-grinder and the water bath used for the heat curing.

Figure 3. End-grinder and water bath used for heat curing

IV. RESULTS AND DISCUSSION

The compressive strengths for mixtures HPC-1 to HPC-15 are summarized in **Table 7**. Each compressive strength value presented in the table is an average of 3 samples. The compressive strengths at 1, 7, 28, 56, and 90 days of age are summarized in **Appendix 2B**. Since some of the mixtures contained supplementary cementitious materials, the compressive strength was measured up to 90 days of age. For the majority of the mixtures, the increase in strength from 56 to 90 days of age was minimal. The average increase is approximately 7%. Therefore, it is expected that the 90-day ompressive strength represents the ultimate compressive strength of the HPC mixtures.

Table 7 – Compressive strengths of the cube specimens at different ages.

Mixture	Concrete's compressive strength (MPa)					Standard deviation of 90-day strength
	1 day	7 days	28 days	56 days	90 days	
HPC-1	59.0	95.7	106.3	108.8	114.1	1.0
HPC-2	70.7	97.4	113.2	113.8	118.1	2.2
HPC-3	73.2	105.7	117.2	120.1	125.4	0.9
HPC-4	75.7	102.6	118.6	127.4	127.6	1.0
HPC-5	70.5	96.8	118.0	120.1	120.9	1.5
HPC-6	62.1	95.9	111.0	117.2	118.6	0.7
HPC-7	77.8	106.1	116.6	124.1	126.2	0.9
HPC-8	53.7	99.2	109.9	110.3	117.5	1.6
HPC-9	24.6	101.2	114.8	117.2	119.3	1.4
HPC-10	4.1	75.8	102.6	110.9	119.1	2.2
HPC-11	52.8	92.8	112.8	113.8	119.7	2.3
HPC-12	72.8	102.8	113.8	126.2	139.3	1.7
HPC-13	73.2	102.3	115.2	129.3	149.7	1.8
HPC-14	80.1	102.8	115.4	129.0	155.2	1.8
HPC-15	53.1	101.5	114.5	131.7	152.1	5.6

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Figure 3 presents the effect of silica fume on concrete's compressive strengths. This figure includes the test results of HPC-1 (0% of silica fume), HPC-3 (5% of silica fume), HPC-4 (10% of silica fume), HPC-5 (15% of silica fume), and HPC-6 (20% of silica fume). All of these mixtures contained Sand-1; therefore, the comparison is relevant. In general, the use of silica fume increased the strength at all ages, regardless of the replacement rate. Mixture HPC-4 had the greatest compressive strength at 1 day, and at 28, 56, and 90 days. The 90-day compressive strength of HPC-4 was higher than the strengths of HPC-1, HPC-3, HPC-5, and HPC-6 by 12, 2, 6, and 8%, respectively. However, the compressive strength of HPC-4 was slightly greater than the strength of HPC- 3 at 1, 28, 56, and 90 days. Since results showed a slight difference in the compressive strength of mixtures containing 5% or 10% silica fume, a silica fume content of 5% was chosen for this research program. By choosing 5%, the overall cost of the HPC would be less when compared to mixtures containing more silica fume; the cost of silica fume where the research was being conducted is in the range of $700–$800 per ton.

V. CONCLUSION

Based on the results of this experimental investigation, the following conclusions are drawn:

1. It is possible to develop HPC mixtures containing locally available materials. A 90-day compressive strength of 155 MPa was obtained with a total binder of 1,009 kg/m^3, 5% of silica fume, and Sand-1. For this mixture, the replacement of 20% fly ash had minimal effect on the 90-day compressive strength.
2. The use of finer sand increases the compressive strength when compared to natural gradation sand. However, this effect is minimal when silica fume is incorporated.
3. The use of more than 10% of silica fume had minimal effects on the compressive strength. The concrete mixtures containing 5% and 10% of silica fume had similar 90-day compressive strengths.
4. Regardless of the silica fume content and the types of sand, the compressive strength increases as the binder content increases. A binder content of 1,009 kg/m^3 is recommended to achieve a minimum compressive strength of 150 MPa at 90 days of age.
5. A fly ash content of more than 20% decreased the concrete's compressive strengths at early ages but increased the strengths at later ages. A fly ash content of 30% produced the highest 90-day compressive strength, while a content of 20% had minimal effect on the strengths at all ages.
6. The use of 3% by volume of steel fibers increased the compressive strength by 4% and 8% based on the test results of cylindrical and cube samples, respectively.

VI. FUTURE WORKS

Further experimental investigation may be considered for additional reduction in cost of HPC. This can be achieved by using supplementary cementitious materials rather than silica fume. Another idea is produced green HPC. Generally, mixture proportion of HPC contains a high amount of portland cement. Cement production is one of the main sources of energy consumption and CO2 emission. Therefore, future work may consider developing sustainable HPC mixtures. Cement content can be optimized by using Vitrified Calcium Aluminio-Silicate (VCAS) pozzolans. VCAS pozzolans are green construction materials from industrial by- products and can alternatively replace cement at a ratio of 1:1. Also, by-product glass powder can be used as micro-filler material in sustainable HPC mixtures. A complete testing matrix, with different percentages of glass powder, and VCAS, need to be considered for sustainable HPC mixtures

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