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MECHANICAL BEHAVIOUR OF ULTRA-HIGH PERFORMANCE CONCRETE OBTAINED WITH DIFFERENT CONCRETE CONSTITUENTS AND MIX DESIGNS

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ABSTRACT

This research investigates the mechanical behaviour for the Ultra-High Performance Concrete (UHPC) and Ultra-High Performance Fiber Reinforced Concrete (UHPFRC). UHPC and UHPFRC are designed to be self-consolidated concrete that level itself without mechanical vibration due to its highly flowability and moderate viscosity. UHPFRC is used as joint-fill cementitious materials for the connections of prefabricated bride elements and systems used for the Accelerated Bridge Construction and rapid bridge replacement. The main concrete constituents of such materials consist from: binders (cement), powders (fillers), liquids (additives), water, and fibers. Hence, the mixture proportion design should follow a densified mixture design algorithm to densify the particle packing that reduces the amount of pores and reduces the water/binder ratio to attain the design criteria. The concrete mix design has two approaches, namely: classical mixture including the response surface methodology and factorial-based central composite design, also known as the mathematically independent variable. Experimental work is conducted to determine the optimum particle size distribution and to identify the chemical effects followed by parametric experimental tests on different concrete constituents to develop series of UHPC/UHPFRC products and monitor there rheological behavior.

Keywords: Ultra-High Performance Fiber Reinforced Concrete, UHPFRC, UHPC, Bridges, Concrete Mix Design, Mechanical Performance

1. INTRODUCTION

The need of very high-early (HE) strength concrete increases with the use of the accelerated bridge construction and rapid bridge replacement techniques that allow bridges to be assembled or replaced with minimum disruption to traffic. Prefabricated bridge elements and systems are structural components of bridge elements that are built offsite, and assembled onsite with cast-in-place reinforced-concrete connections, i.e. used for the precast full-depth deck panels (FDDPs) in accelerated bridge construction and other structural elements. Concrete is a composite material composed of ordinary Portland cement (OPC), supplementary cementing materials (SCM), coarse, medium and fine aggregates, admixtures and water. The OPC and SCM react chemically with water and admixtures to bind all mixed aggregates and to form hard matrix with increasing strength over time. There are many types of concrete classes created by varying the proportion of the ingredients, application with varying strength, density, chemical and thermal resistance properties, and desired strength age.

Concrete is classified based on its range of compressive strength value or different mechanical behavior. Normal strength concrete (NSC), high strength concrete (HSC) has compressive strength range of 8 - 69 MPa in 28 days and 69 - 100 MPa in 56 - 91 days, respectively. Ultra-high performance concrete (UHPC) has compressive strength of 100 - 140 MPa after 28 days. Steel fibers (SF) can be added in percentage of the concrete volume to produce ultra-high performance fiber reinforced concrete (UHPFRC). The presence of SF changes the failure mode of concrete from brittle failure to ductile mode. UHPC is designed to have initial compressive strength of 69 MPa (10 Ksi) after 48 hours, to allow for surface grinding, and 145 MPa (21 Ksi) at 28 days, and cured by maintaining the ambient temperature above 15.56 ºC (60°F). UHPC is used as field-cast joint fill solutions for precast deck bridge panels. The bridge can be opened to traffic when strength of 104 MPa (15 Ksi) is achieved. The flow diameter of the mortar-type concrete is measured per ASTM C109 standard test method using flow table constructed according to ASTM C230 standard test method. The measured diameter of concrete after 20 table drops shall be within the range of minimum 177.8 mm (7 inches) and maximum of 215.9 mm (8.5 inches). The air content according to ASTM C231 standard test method shall be limited to a maximum of 5%.

The development of UHPC is based on the densified packing of cement particles corresponding to water/cement (w/c) ratio of 0.20, instead of a w/c ratio of 0.3 or 0.45, and to produce low cement / high amount of fine aggregate mixes. By making a very dense packing of the cement particles and fill the spaces between the much finer particles i.e. using micro-silica particles, there will be a little space to fill with water. During mixing, water will surround each particle in a thin layer and works like lubrication. The w/b ratio, also known as w/cm ratio, is 0.18 to 0.25, resulting in an ultra-strong and very dense binder with a very low porosity, compared to other grouts, mortars and concrete (Buitelaar, 2004). The use of high concentration of strong aggregate will increase the strength and the fracture energy. The additional of steel fibers will enable the brittle matrix of UHPC to strain under tensile loading (approx. 0.2 mm/m).

The main constituents of UHPC are composed of cement, water, sand, silica fume, superplasticizer and fibers. Cement used in production of UHPC should be ordinary Portland cement type V due to its low Tricalcium Aluminate content (C_3A), not more than 5 or 8%, which provides a high sulfate resistance and lower water demand. Silica Sand with less than 1 mm of particle size should be used to achieve adequate homogeneity in the mix. It is important that Silica Sand (Quartz) exhibit high strength and low absorption. Silica fume increases the mechanical strengths and gains the compactness and microstructure of the UHPC. The optimum ratio between silica fume to cement is 25%. Silica fume has three main functions in the UHPC, namely:

- Filling the voids between cement grains (100 um) since silica fume particles are smaller than 8 um.
- Improvement of rheological characteristics due its perfect sphericity of the particles that produce lubrication effect.
- Formation of hydration products by Puzzolanic activity with lime, producing an increase of the final strength.

Superplasticizer (SP) is indispensable solution, added to obtain adequate workability helping the fine particles to fill the void spaces and decrease the amount of water in the mix. In most cases, SP is based on Polycarboxylate. Fibers are added to concrete to increase ductility and mechanical properties. The amount of fibers influences the workability. Fibers are added from 1% to 4% in volume and maybe more up to 11% for heavy-reinforced UHPC. The mixing procedures and time were different from product to another; usually mixing time is set between 18 to 30 minutes. Figure 1 depicts the common mixing procedure, which suggests adding all the solid dry content to the shear mixer, rotate it for 1 min, then add all the HRWR with 90% of the water. Depends on the shear mixer and its speed, the higher speed, the shorter the time to reach to the turning point from hard mixture to soft mixture, at which the remaining percentage of the water is added or not.

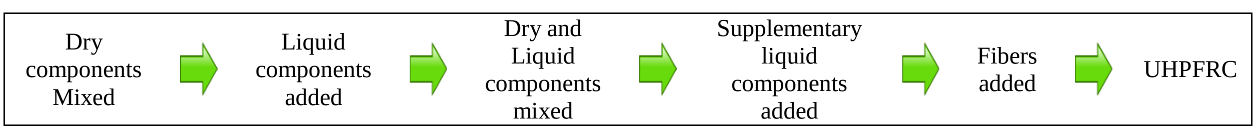


Figure 1: Typical sequence of mixing UHPFRC

The objective of this research is to design UHPC mixture that has air content less than 5%, flow diameter of 180 mm without drops, and to achieve compressive strength up to 140 MPa in 28 days. The mixture proportion design should follow the densified mixture design algorithm (DMDA) to densify the particle packing that reduces the amount of pores and reduces the water/binder ratio to attain the design criteria. The concrete mix design (CMD) has two approaches, namely: classical mixture including the response surface methodology (RSM), and factorial-based central composite design, also known as the mathematically independent variable (MIV). Experimental work is conducted to determine particle sizes and to identify the chemical effects followed with parametric experimental tests on different concrete constituents to develop series of UHPFRC products and monitor there rheological behavior.

2. CONCRETE MIX DESIGN

The ACI Recommended Practice 211.1 outlines number of steps to arrive at the proportions for the concrete mix design, CMD (ACI Committee 211, 1991). The first step is to determine the properties of the mixed materials, do sieve analysis, find the unit weight, and find the bulk specific gravity, absorption capacities of the aggregates. The second step is defining the required workability by the flow diameter; the ratio of water to cement plus Pozzolanic materials w / (c + p) needed to fulfil the required strength. Analyzed data from the CMD can be classified by (i) weight, (ii) weight to relative cement, and (iii) percentage by weight using the following procedure.

1. Consider target Mean Strength = Mean ± 3 times the standard deviation.
2. Calculate the cement content.
3. Select the water cement ratio (w/c) and its conversion of water to cement plus Pozzolanic materials w / (c + p) by weight equivalency.
4. Estimate the bulk Saturated-Surface-Dry (SSD) aggregate content, per Equation 1.

[1] $$U_M = 10\, G_a\, (100 - A) + C_M\, (1 - G_a/G_c) - W_M(G_a - 1)$$

Where U_M = unit mass of fresh concrete, kg/m^3; G_a = weighted average specific gravity of combined fine and coarse aggregate, bulk, SSD; G_c = specific gravity of cement (generally 3.15); A = Air content, percent; W_M = mixing water requirement, kg/m^3; C_M = cement requirement, kg/m3

[2] $$V_{concrete} = V_{gross} - V_{air\ content} = 100\% - A$$

[3] $$V_{concrete} = \left[w + \frac{Adm}{SG_{Adm}} + \frac{CM}{SG_{CM}} + \frac{FA}{SG_{FA}} \right] \frac{1}{1000}$$

The air or void content of the UHPC/UHPFRC mortar shall be calculated from Equations 4.1 and 4.2, based on Clause 6.1 of CSA A3000-C4 Test Method for the determination of air content (CSA A3000-13, 2013).

[4.1] $$D = \frac{\sum_{i=1}^{n} B_{g,i} + \sum_{i=1}^{n} P_{g,i} + \sum_{i=1}^{n} A_{g,i} + w_g}{\frac{B_{g,i}}{D_{B,i}} + \frac{Pg_{,i}}{D_{P,i}} + \frac{A_{g,i}}{D_{A,i}} + \frac{w_g}{D_w}}$$

Where D= density of the air-free mortar; $D_{B,i}$= density of the binder, g; $D_{P,i}$= density of the powder, g; $D_{A,i}$= density of the additives, g; D_w= density of the distilled water equal to 1.00 g/cm^3; $B_{g,i}$= binder mass
$P_{g,i}$= powder mass; $A_{g,i}$= additive mass; w_g= distilled water mass at 20 ~ 23˚C. The air or void content shall be expressed to the nearest 1.0%, using the following formula.

[4.2] $$A = 100 - \frac{M}{4D}$$

Where A = percentage of air content, by volume; M = mass of 400 mL of UHPC, kg

3. DENSIFIED MIXTURE DESIGN ALGORITHM

The packing of an aggregate for concrete is the degree of how good the solid particles of the aggregate measured in terms of "packing density", which is defined as the ratio of the solid volume of the aggregate particles to the bulk volume occupied by the aggregate as given in Equations 5 and 6 (Mangulkar & Jamkar, 2013).

[5] $$Packing\ Density\ (\text{Ø}) = \frac{Solid\ Vloume}{Total\ Volume}$$

[6] $$\text{Ø} = \frac{V_s}{V_t} = \frac{V_s}{V_s + V_v} = 1 - e$$

Where V_s = volume of solids; V_t = total volume= volume of solids plus volume of voids; e = voids = volume of voids over total volume

Concrete mixtures produced with a well-graded particle combination tend to reduce the need for water, provide and maintain adequate workability, require minimal finishing, and consolidate with segregation. These characteristics tend to enhance placement properties as well as strength and long-term performance. Concrete mixtures produced with a gap graded particles combination tend to segregate easily, contain higher amounts of fines, require more water, and increase susceptibility to shrinkage. These characteristics tend to limit placement properties as well as strength and long term performance. Achieving a uniform gradation may require the use of two, three or more different aggregate sizes. When using the coarseness/workability chart, it is assumed that particles are rounded or cubical in shape. Rounded or cubically-shaped particles typically enhance workability and finishing characteristics. Flat and elongated particles typically limit workability and finishing characteristics.

- Coarseness Factor and workability factor (not applicable for UHPC)
- The 0.45 Power
- Percent Retained (limitation must be developed)

In the 1960s, the Federal Highway Administration (FHWA) came up with the '0.45 power' gradation chart for aggregates in concrete mix design. This was designed to give straight lines for maximum density gradations after Andreasen and Andersen's Model (Andreasen & Andersen, 1930).

[7] $$CPFT = \left(\frac{d}{D}\right)^n \times 100$$

Where CPFT is the cumulative percent of particles finers than nominal/maximum particle size; d is the particular sieve size opening diameter; D is the maximum size aggregate; n is the parameter which adjusts curve for fineness or coarseness (distribution modulus), for maximum particle density n ≈ 0.5 according to FHWA, for maximum particle density n ≈ 0.5 according to (Fuller & Thompson, 1907).

4. RESPONSE SURFACE METHODOLOGY

The classical case for the response surface methodology (RSM) is the run of random independent variables using generalized linear models, also known as mathematically independent variable (MIV) to identify the reasons for changes in the output responses as shown in Equation 8. The MIV can be linear or nonlinear to n-degree depends on the experimental data analyzed statically.

[8] $$y = \beta_o + \sum_{i=1}^{k} \beta_i x_i + \epsilon$$

Where y is the combined percent passing (PP); x_i is the Percent Passing of fine particles; β_i is the relative percent of aggregate, β_o is the experimental coefficient and ϵ is the error. Both β_o and ϵ are set to zero for basic assumptions.

5. EXPERIMENTAL PROGRAM

The constituents of UHPC are cement, silica fume, quartz powder, superplasticizer, water with a low water-cementitious materials ratio. The basic philosophy lies in using course fine aggregate (CFA), medium fine aggregate (MFA), and very fine aggregate (VFA) with maximum particle size of 2.36 mm. The concrete mix design (CMD) developed herein follows the ACI Recommended Practice 211.1. Also, the mixture proportion design should follow the densified mixture design algorithm (DMDA) to densify the particle packing that reduces the amount of pores and reduces the water/binder ratio to attain the design criteria.

The High Early (HE) Type 30 Ordinary Portland Cement (OPC) is used for the development of this UHPC series. Its specific gravity and maximum particle size are 3.15 and 0.025 mm, respectively. Dry densified microsilica (silica fume) powder to be used to increase the concrete compressive and flexural strengths, increases durability, reduces permeability and improves hydraulic abrasion-erosion resistance. The very fine particles of Microsilica are able to fill the microscopic voids between the cement particles, creating a less permeable concrete microstructure. Silica fume used conforms to ASTM C1240-97b. Its specific gravity is 2.20, percent passing through 50 μm in dry laser diffraction analyzer (LDA) is 99.6% and particle size range lies between 50 μm – 0.4 μm. CemPlus (Slag) Type S is produced by finely grinding granulated blast furnace slag (GGBFS), a glass by-product of iron production that has cementitious properties similar to the OPC. Slag has seven advantages when mixed with OPC, gives: higher 28-day compressive and flexural strengths, reduces permeability and increases resistance to chlorides and other aggressive chemicals, improves workability / finishability / pumpability, increases resistance to alkali-silica reactions (ASR), increases resistance to sulphate attack, reduces heat of hydration, and a whiter brighter finished appearance. Its specific gravity is 2.92, and percent passing through 73 µm in dry laser diffraction analyzer (LDA) is 99.91% and particle size range lies between 73 µm – 0.9 µm.

The Quartz Powder has specific gravity of 2.65 as three types were used in this study. The course fine aggregate (CFA) has percentage passing through 2.36 mm wet sieve analysis of 50% and the particle size lies between 2.36 mm – 0.3 mm. The medium fine aggregate (MFA) has percentage passing through 0.3 mm wet sieve analysis of 98.8% and the particle size lies between 0.3 mm – 0.075 mm. The very fine aggregate (VFA) has percentage passing through 0.075 mm wet sieve analysis of 67.1% and the particle size lies between 0.075 mm – 0.0005 mm. The High Range Water Reducer (HRWR) is an admixture based on PolyCarboxylates (PCE) including Esters and Ethers and other copolymer derivatives and to conform to ASTM Specs C494 Type F and G and Type 1 and 2 into (ASTM C1017/C1017M-13e1, 2013) with solid content of 29% or more. Table 1 shows the specific gravity for the used material in terms of g/cm^3. Table 2 provide the logarithmic model for the percent passing versus the particle size distribution (PSD) for the mixture dry contents.

Table 1: Saturated Surface Dry (SSD) Specific Gravity at H2O = 1.0

Name of Materials	Specific Gravity	Max. Particle Size	Solid Content	Absorption %
Cement: GU, GUL, HE	3.15	0.025 mm		
Cemplus (Slag)	2.92	0.053 mm		
Force 10,000 D (Silica Fume)	2.20	0.075 mm		
B&M#12ST	2.65	2.360 mm		
B&M#730 Silica Sand	2.65	0.300 mm		
SIL-CO-SIL#106	2.65	0.075 mm		
Chryso Fluid Premia 150	1.06 ± 0.010	Liquid Base	0.29	

Table 2: Modeling of Cementitious and Filler Materials

Name	Modeling*	Coefficient of determination	Constraints
HE (Type 30) Cement	$P\,\% = 25.862\ln(D) + 184.88$	0.9072	D = 0.051 – 0.0009 mm D > 0.061 mm, P% = 100%
Cemplus (slag)	$P\,\% = 24.089\ln(D) + 169.24$	0.9781	D = 0.073 – 0.0009 mm
Force 10,000 D (Silica Fume)	$P\,\% = 19.388\ln(D) + 39.135$	0.9079	D = 0.05 – 0.0004 mm D > 0.1 mm, P% = 100%
BM 12ST	$P\% = -6.9032 D^2 + 58.242 D - 18.666$	0.9663	0.15 < D < 4.75 mm
BM# 730	$P\% = -697.93 D^2 + 653.38 D - 40.045$	0.9856	0.053 < D < 0.6 mm
Sil-Co-Sil# 106	$P\% = -3165.9 D^2 + 1075.3 D + 8.6938$	0.9816	0.0005 < D < 0.15 mm

* P is percent passing and D is the particle size into millimetres

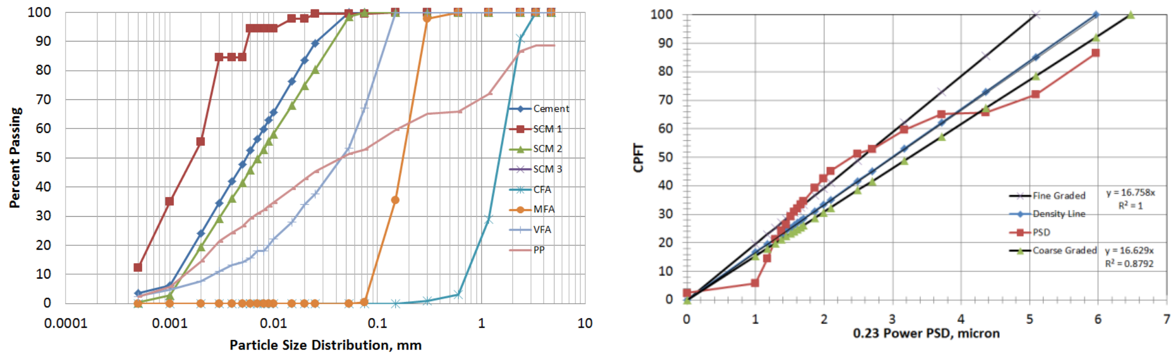
A planetary shear mixer Hobert Model HL300-3ST was used to mix the UHPC mixes. The mixer has 3 speeds of rotations. The dry content composed of cement, silica fume, with/without slag, quartz were poured into the mixer and spin for 1 minute at lower speed. HRWR is added with 90% of water as the same lower speed for 10 to 15 minutes. After the creation of small balls, the shear mixer is placed to the second speed until the mixture becomes homogeneously liquid, and remaining water may be added to reduce the mixing time to 5 minutes and to enhance the workability of the mix. UHPC mixes were casted into 50x100 mm plastic cylindrical molds with plastic caps. Sealed cylinders were kept into room temperature until day of testing.

The 0.45-power model, Equation 7, is used to obtain the optimized aggregate gradation for improving the strength of the UHPC and set the upper and lower limits for the gradation. The combined percent passing in Equation 8 is used in connection with Nonlinear Regression Analysis (NLREG) using the least squares to determine the relative percentage of the aggregate that results into high coefficient of determination that falls between $0 < R^2 < 1$. The mathematical process resulted into relative percentage of the CFA: MFA: VFA as 55: 20: 25 that results into gap-graded aggregates with R^2 equals to 0.9659. The nominal maximum particle size is set to be 2360 micron as obtained from the 12ST. The top limit represents one smaller sieve size of 1180 micron for the fine graded particles. The lower limit represents one bigger sieve size of 3360 micron coarse graded particles.

The Job Mix Formula (JMF) IDs of the developed mixes were named HE19C, HE20A, HE20B, HE21, HE22, and HE23. These mix designs have been design to account for the change of the cementitious materials including (i) cement to silica fume ratio, (ii) cement to slag to silica fume ratio, and (iii) the cementitious materials to powder quartz ratio, as shown in Table 3. The NLREG set of parameters for the dry contents are re-optimized while fixing the relative percentage of the aggregate using the proposed 0.23 power of Equation 7. Figures 2 through 7 depict two groups of data per each mix, namely: (a) the conventional particle size distribution (PSD) on semi-logarithmic graphs, and (b) the 0.23-Power PSD representing the optimized particle packing. The conventional PSD graphs depict the mix ratio of the dry contents. The PSD depicts the arrangement of finer-to-coarse particles from left to right as of: the Silica Fume (SCM1), Cement, Slag (SCM2), VFA, MFA, CFA, and the combined Particle Passing (PP, Equation 8) in connection with mix design listed into Table 3. The 0.23-Power PSD represents the use of Equations 7 and 8 to represent the 0.23-Power PSD in micron in the x-axis, and the CFPT in the y-axis, respectively. The density line that represents the optimum particle packing is said to be the relationship between the sieve size to the 0.23-power and to the CFPT - Equation 7 set to the used maximum particle size, D. The upper and lower lines represent the finer and coarse limits. The PSD obtained from Table 3 is then plotted, where the optimum mixes should be aligned to the density line. It can be seen from all graphs that mixtures are gad-graded ones.

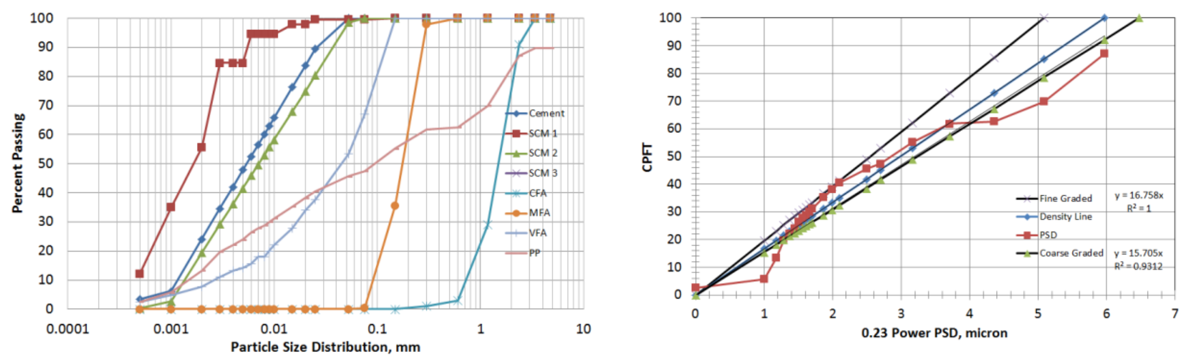
Table 3: Concrete Batch Design in cubic meter per ACI 211.1

Material	Job Mix Formula (JMF), and weight in kg					
	HE19C	HE20A	HE20B	HE21	HE22	HE23
HE (OPC Cement Type 30)	677.5567	689.0074	672.0224	622.2725	789.1367	667.131
Force 10,000 D (Silica Fume)	219.5415	223.2517	224.0075	207.3596	157.8273	333.5655
Cemplus (Slag)	169.3892	--	--	165.9264	197.4298	--
BM#12ST (Quartz)	551.4022	655.1309	640.6614	593.2306	503.1838	580.5893
B&M#730 (Quartz)	315.4762	315.4427	310.6237	345.0692	265.1953	316.6093
SIL-CO-SIL#106 (Quartz)	250.6705	297.8541	291.2097	269.7031	229.4611	263.8874
Added Water	262.1646	187.097	220.8745	49.75857	48.92065	64.85996
CHRYSO Fluid Premia 150 (HRWR)	49.33312	64.79114	46.59356	208.8594	323.0224	229.9718
Density, kg/m^3	2495.534	2432.575	2405.993	2462.179	2514.177	2456.614
Dry Content	2198.343	2199.476	2152.037	2217.991	2156.421	2180.592
Total Water	297.1911	233.0987	253.9559	244.1879	357.756	276.0223
Total Water/Dry Content, %	0.135189	0.105979	0.118007	0.110094	0.165903	0.126581
Mixing Time, minutes	14.5	20	22	16	26	20
Air Content	2.32	2.19	2.15	3.09	3.91	2.27
Flow Diameter, mm	160	230	180	185	155	230
Curing Age	Mean compressive strength, MPa					
1 days	57.63	14.85	57.80	54.93	69.22	34.63
3 days	75.62	76.32	70.12	79.37	89.10	71.18
4 days	81.64	82.25	74.25	83.91	92.84	85.14
7 days	81.26	89.38	74.45	76.59	82.80	85.34
14 days	98.08	105.89	81.61	91.96	80.65	96.40
28 days	112.16	123.65	100.02	115.37	119.07	134.87
56 days	119.42	126.43	114.56	118.68	129.33	120.14



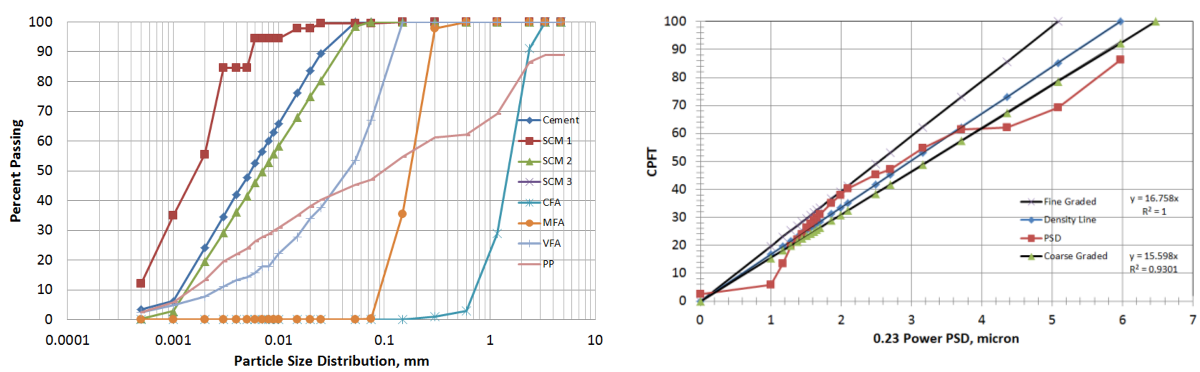
a. The Conventional PSD b. The 0.23-Power PSD

Figure 2: JMF – HE19C



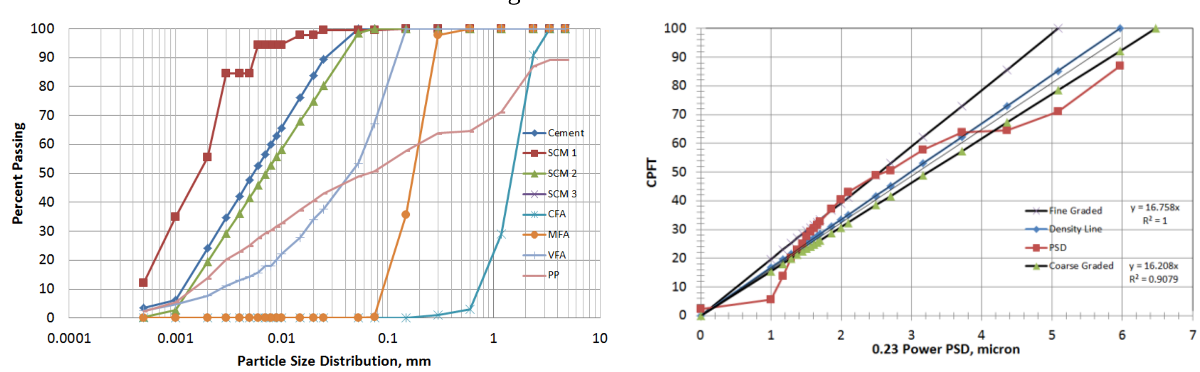
a. The Conventional PSD b. The 0.23-Power PSD

Figure 3: JMF – HE20A



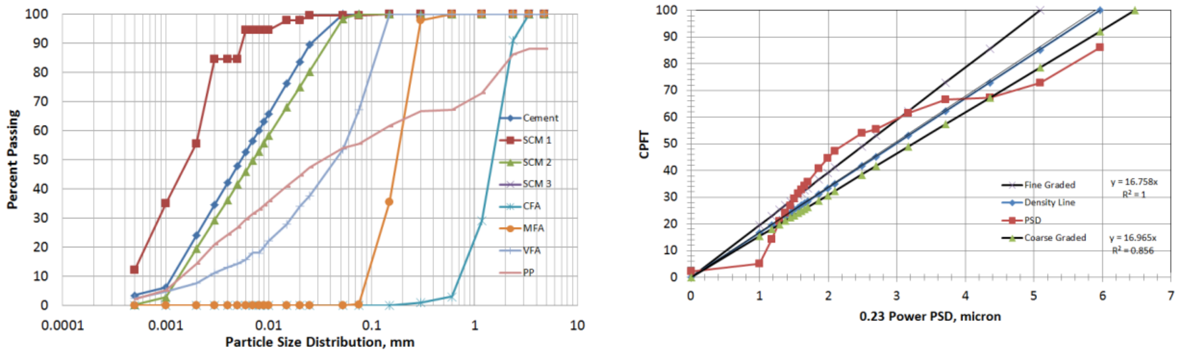
a. The Conventional PSD b. The 0.23-Power PSD

Figure 4: JMF – HE20B



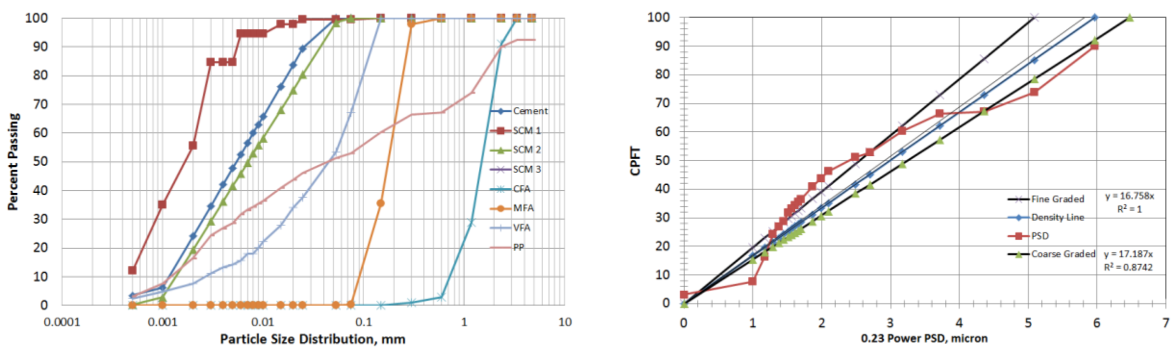
a. The Conventional PSD b. The 0.23-Power PSD

Figure 5: JMF – HE21



a. The Conventional PSD b. The 0.23-Power PSD

Figure 6: JMF – HE22



a. The Conventional PSD b. The 0.23-Power PSD

Figure 7: JMF – HE23

6. EXPERIMENTAL RESULTS

Experimental data includes measuring the air content using the 400 ml measure, mixing time, and record the mean value for the compressive strength over time. The air voids ranged from 2.15 to 3.91% which is less than 5%. Distribution of the air voids across the cross-sectional area of the concrete cylinder may reduce the targeted compressive strength. The flow diameter without drops for HE19C, HE20B, HE21 and HE22 is considered to be stiff mixture that has flow diameter < 200 mm. The flow diameters without drops for the mixes HE20A and H23 are considered to be fluid mixture that has flow diameter falls between 200 and 250 mm. According to ASTM C109, compression test on UHPC was carried on 50x100 mm cylindrical specimens (ASTM C109/C109M-16a, 2016). The strength was recorded at 1, 3, 4, 7, 28, and 56 days. The average reading of 3 cylinders was recorded as the strength at respective curing age. Compression test was carried out at the rate of 0.2 kN/sec. The ultimate strength, per Equation 9, was recorded after the specimen fails to resist any more loads. Table 4 provide the compressive strength versus the curing age for the series of mixes. It can be seen that the logarithmic model was good in determine strength behavior.

Table 4: Modeling for the compressive strength versus curing age

Mix ID	Curing Regime	Compressive Strength versus Curing Aging (d = number of days from casting)	Coefficient of determination
H19C	Ambient Temperature	$f_c' = 15.736\ln(d) + 57.252$	0.9802
H20A	Ambient Temperature	$f_c' = 25.758\ln(d) + 37.053$	0.8893
	60ºC + 100% Humidity	$f_c' = 18.862\ln(d) + 94.631$	1
H20B	Ambient Temperature	$f_c' = 14.105\ln(d) + 53.75$	0.9198
H21	Ambient Temperature	$f_c' = 15.857\ln(d) + 56.576$	0.9196
H22	Ambient Temperature	$f_c' = 13.274\ln(d) + 67.43$	0.7308
H23	Ambient Temperature	$f_c' = 21.94\ln(d) + 43.633$	0.8924
	60ºC + 100% Humidity	$f_c' = 23.553\ln(d) + 86.041$	1

$$[9] \quad Compressive\ Strength\ (f_c') = Load\ (P)/Cross\ Sectional\ Area\ (A)$$

The behavior of the compressive strength versus curing age can be expressed by the logarithmic expression with good agreement with respect to the coefficient of determination, as shown in Table 4. Heat curing regime was investigated for two mixes named H20A and H23. Concrete cylinders were stripped after 24 hours from casting, placed into sealed container with inside elevated base to allow for water storage, where the concrete cylinders placed on the top of the elevated base. The sealed container is placed into special oven, and cylinders cooled for 30 minutes before testing. The H20A mix has compressive strength value of 94.39 and 98.82 MPa under conventional curing regime and 128.43 and 139.86 MPa under heating regime after 6 and 11 days, respectively. The HE23 mix has compressive strength value of 85.14 and 85.34 MPa under conventional curing regime and 118.69 and 135.02 MPa under heating regime after 4 and 8 days, respectively. Concrete cylinders passed 60˚C heat and 100% humidity of curing exhibit higher compressive strength in few days.

7. SPHINX MIXING INSTRUCTIONS

The optimum mix design was found when the ratio of the Ordinary Portland Cement (OPC) to the Silica Fume (SF) is 1:0.5 where their weight percentage is about 45% from the total weight of the mix. This ratio produces very workable mix, with delay of setting time for extra few minutes compared to other mixes. The proposed instruction for mixing ingredients, mixing procedures, placing and curing are listed below.

7.1 Ingredients

Table 5: Composition of Sphinx Premix ingredients

Component	Percent (By Weight)
Ordinary Portland Cement (HE Type 30)	28 – 40
Silica Fume (Amorphous Silica)	< 8 - 14
Ground Granulated Blast-Furnace Slag (GGBFS)	< 8.5
Crystalline Silica	30 – 75

- Modified particle packing will determine the weight ratio of the ingredients.
- Weight out the dry content.
- Multiply the total dry content by 7% to 10.5% to find the maximum weight of total water (including water in the admixtures) in the system. Use PCE - HRWR with solid content above 29%.
- Add steel reinforcement fiber as of 7.1% from the dry content mixed weight (for high impact application, the use of 4% to 10% of dry content weight is common). Note that PVA fiber may be added with steel fibers.

Mixing Procedure

- Place all the dry content into the shear mixer and spin them for a minute.
- Slowly add all water, the high range water reducer, and accelerator. Keep spinning until different-sized balls are formed.
- Increase the speed of the shear mixer until the mix becomes homogeneously fluid.
- Slowly add the steel reinforcement fiber to the slowed shear mixer.
- Keep mixing, turn off the shear mixer to see if the mix is quickly self-levelled and air escaping. This mixing phase will take from 15 to 30 minutes of mixing.

Placing and Curing

- After placing, roller-compact the surface of the concrete.
- Spray water on the top surface of the placed fresh concrete.
- Cover the fresh concrete by plastic sheets for 48 hours at room temperature.

8. CONCLUSIONS

This research presents the mix design and properties as well as the assessment of the UHPC. The design of concrete mixture is based on (i) the ACI Recommended Practice 211.1, and (ii) the response surface methodology (RSM) in connection with the densified mixture design algorithm (DMDA) to densify the particle packing and the Nonlinear Regression Analysis (NLREG) to obtain the required parameters.

- The Andreasen and Andersen particle packing model to the 0.45-power was used to optimize the aggregate particle size distribution.
- The whole dry content that includes the cementitious materials and the aggregates was re-optimized to the 0.23-power model
- Concrete cylinders passed 60˚C heat and 100% humidity of curing exhibit higher compressive strength in few days.
- The Mathematical Independent variable is the key element in development better UHPC mix consistent with less air voids.
- Gap-graded mixes sustained high compressive strength. Further work is needed to fully densify the mixture to increase the sustained loads.

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