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Research Article

Properties of reactive powder concrete incorporating silica fume and rice husk ash

Mohamed Amin *

Deptartment of Civil Constructions, Faculty of Industrial Education, Suez University, Suez, Egypt

ABSTRACT

Reactive Powder Concrete (RPC) is composed of very fine powders (cement, sand, and pozzolanic materials), and superplasticizers. A very dense matrix is found, and this tightness provides RPC with ultra-high strength and durability. Recently, using supplementary cementing materials associates greatly with ultra-high strength and the mix design of ultra-high performance concrete (UHPC). These materials could be natural, by-products or industrial wastes. They could be also less energy consuming and little time produced materials. Silica fume (SF), rice husk ash (RHA) and granulated blast furnace slag (GBFS) etc. are among the major supplementary cementing materials utilized. The detailed experimental investigation done to study the impact of partial alteration of cement with SF, RHA, and GBFS on concrete properties. This study aims to a minor replacement of Portland cement by SF, RHA and GBFS to reach UHPC. Twenty-five different concrete mixes (f_c =150.1 to 188.2 MPa) with and without SF, RHA and GBFS were prepared with local materials in Egypt. Concrete mixes were cast with 0, 10, 15, 20, and 25% cement replaced by either SF or RHA, and another proportions taken combination between SF and RHA or SF and GBFS or RHA and GBFS about percentages from 10 to 15%. The mixes were tested for slump flow, air content, mechanical properties and water permeability. The findings of hardened properties indicate that optimum level for partial changing of cement by SF and RHA was 20% and it is observed that though the strengths of SF or RHA concrete goes on decreasing after the 20% addition of SF or RHA. Test results have indicated that RHA exhibits lower pozzolanic activity than SF.

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1. Introduction

Innovations in new concrete technology and the improvement of modern superplasticizers simplify new characteristics of unobtainable concrete. Ultra-high performance concrete (UHPC) is a novice type of concrete that has achieved a great concern in research and application recently, many researchers namely, Schmidt and Fehling (2005), Resplendino (2012), Schmidt (2012). The development of UHPC, known as reactive powder concrete (RPC), started in 1990s in France and Canada, Richard and Cheyrezy (1995). Components of UHPC generally is high amount of Portland cement, silica fume (SF) with fine grained aggregates and steel fibers for reinforcement. UHPC holds a small amount of water to binder ratio (w/b) with adding a high superplasticizer (SP) dosage, by previous researchers, Richard and Cheyrezy (1995), Park et al. (2008). Thus, UHPC accomplishes compressive strength between 150 and 800 MPa, modulus of elasticity of 50-60 MPa, high flexural strength and very high durability, many researchers namely, Schmidt and Fehling (2005), Richard and Cheyrezy (1995), Schmidt and Teichmann (2006). Ultra-high performance concrete (UHPC) gains compressive strength more than 150 MPa and developed durability. UHPC is considered a major concern in research and application, by previous researchers, Resplendino (2012), Schmidt (2012). The major objectives enhance compressive, ductility, microstructure and durability of concrete, and also develops workability, cost efficiency and sustainability, by Schmidt (2012).

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* *Corresponding author.* E-mail address: h_scc@yahoo.com (M. Amin)

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Applying pressure and post-set heat-treating improves the rendering of concrete. According to that, concrete displays compressive strength more than 150 MPa with normal temperature treatment, about 200-250 MPa with post-set heat treatment at 90°C, 450-650 MPa by the utilization of a high volume of steel fibers, high temperature treatments, pressurization of the fresh material while setting and hardening, and up to 800 MPa with steel aggregates, by previous researchers, Richard and Cheyrezy (1995), Dugat et al. (1996). With more content of Portland cement, SF and SP, the manufacture of UHPC is of a high cost than the cost of high performance concrete (HPC). Additionally, a high content of cement clinker makes UHPC not really sustainable, especially regarding CO_2 emission. However, the increased mechanical properties of UHPC helps in reducing the cross section of concrete structures while preserving similar or longer spans of structures , by Perry (2011). Because of the reduction of cross section of UHPC structure, sustainability is improved through raising the efficiency of using concrete and structure. Pros of UHPC is the enhanced durability of this concrete against freeze-thaw deterioration, corrosion of steel and chemical attack, by Schmidt and Teichmann (2006). Theoretically, a Portland cement or other cements are a reason of producing UHPC. It is clear that the amount of cement included in concrete affects its strengths and durability and also the w/b, especially in case of HPC and UHPC, by Neville (2006). The compatibility between cement and SP is necessary to choose cement for UHPC production to increase the efficiency of water reduction. Consequently, cement with low C_3A content is utilized to decrease SP demand, to raise fluidity and hence the packing density of UHPC, by previous researchers, Richard and Cheyrezy (1995), Sakai et al. (2008). Based on water content, cement minor changes by fine materials and utilized aggregates, Portland cement content in UHPC ranges between about 600 and 1000 kg/m^3 concrete, many researchers namely, Schmidt (2012), Richard and Cheyrezy (1995), Park et al. (2008), Ma et al. (2004). Silica fume (SF) is an industrial waste that is produced by silicon production or alloys including silicon. SF is a highly reactive pozzolanic material, normally with more than 85 wt.-% amorphous silica. The particles are spherical and extremely fine (0.1-0.3 μm). Pozzolanic admixture in the concrete industry has become the first choice. SF products are presented as undensified or densified powder or as slurry. The usage of undensified SF powder aims basically at achieving appropriate dispersion of SF in UHPC. The SF slurry should not be used as the quantity of water in the slurry may surpass the total quantity of water necessary for UHPC. Thus, SF greatly affects features of concrete, by previous researchers, Chung (2002), Chan and Chu. (2004). In a curtain Portland cement concrete with water cement ratio of 0.5, about 18.3% SF, showing the weight of cement, is enough to totally consume $Ca(OH)_2$ that is released from cement hydration ,by Papadakis (1999). However, the optimal content of SF in UHPC is normally about 20-30 wt.-% of cement to enhance the filler effect , many researchers namely, Richard and Cheyrezy (1995), Park et al. (2008), Long et al. (2002). Reactive rice husk ash is generated by burning rice husk, an agricultural waste, under convenient conditions. RHA has a high content of amorphous silica and a high particular surface area. RHA are highly reactive pozzolanic materials. RHA can also be a good replacement for SF in UHPC due to the clear impact of enhanced autogenous shrinkage and compressive strength, by previous researchers, Nguyen et al. (2011), Nguyen and van. (2012). However, because of the high specific surface area, porous structure, irregular particle shape and coarse grain size, UHPC including these pozzolans requires higher water content or/and SP dosage to protect the workability. Their mixing processes are also longer and harder than that of the mixture including SF, by Nguyen et al. (2011). Granulated blast furnace slag (GBFS) is a latent hydraulic material. GBFS is a by-product of the steel industry and always less expensive than Portland cement. When GBFS partially substitutes cement, it improves some features of concrete, like workability, heat release and durability. Moreover, using GBFS to partially replace cement makes concrete more environmentally. The partial alternation of cement by GBFS raises the degree of Portland cement clinker hydration and decreases portlandite content by reduced cement content in UHPC. It also improves the degree of SF hydration (shown by relative portlandite consumption). In UHPC, partial substitutions of cement by GBFS enhances workability and decreases superplasticizer demand, many researchers namely, Möser et al. (2010), Gerlicher et al. (2008), Yazıcı et al. (2010). After 28 days of hydration, compressive strength of UHPC with 15 vol.-%, by Moser et al. (2010), or about 20-35 wt.-%, by Yazıcı et al. (2010). GBFS replacing cement is similar or even higher than that of the reference mixture. The higher GBFS content will decrease the 28 day compressive strength of UHPC (both normal curing and heat treatments), many researchers namely, Möser et al. (2010), Yazıcı et al. (2010). UHPC that has a very high compacted density with optimized particle size distribution and a very low w/b gains a very high compressive strength. But its ductility is not enhanced from that of normal concrete. The inclusion of fibers develops tensile strength and compressive strength. Using fine aggregates, high homogeneity, good flowability and high ductility led that UHPC normally utilizes small-size fibers with 3 to 13 mm in length and 0.15 to 0.2 mm in diameter. The fiber content differs about 1 up to 8 vol.-% of mixture. Fibers can be made of steel or organic material. UHPC incorporating with carbon fibers is only utilized for the special durability demands. Polymer fibers are used in order to improve the fire resistance of UHPC, by previous researchers, Richard and Cheyrezy (1995), Boulet et al. (2000). The w/b used in UHPC differs from 0.15 to about 0.25 to make both the sufficient workability and the lowest porosity of hardened concrete. To reduce the excess water in UHPC, the low w/b usually does not supply sufficient workability to the mixture. SP is the obligatory ingredient to improve workability of UHPC. SP dosage in UHPC is almost at the saturation dosage to gain the highest workability of concrete at a very low w/b. Thanks to new generations of SP which support very high water reduction efficiency. The compatibility between SP and mixture is controlled by SP, by previous researchers, Hirschi and Wombacher (2008), Terzijski (2004); cement by previous researchers, Sakai et al. (2008), Terzijski (2004), and mineral admixture, by previous researchers, Plank et al. (2009), Hommer (2009).

2. Experimental Procedures

2.1. Materials

2.1.1. Cement

Ordinary Portland CEM I–52.5 N was used in all mixes. Testing of cement was carried out as the Egyptian Standard Specifications ESS ES4756/1 2013, ES (2013) and BSEN197/1 2011, BS (2011). The physical and chemical features of cement used represented in Table 1.

2.1.2. Aggregates

Fine aggregate used in this experimental work was quartz sand, clean and rounded fine aggregate with a specific gravity of 2.65, a bulk unit weight of 1670 kg/m^3 and fineness modulus of 2.80, according to the requirement of ECP 203-2017, ECP (2017).

2.1.3. Silica fume

In this paper, silica fume was locally produced in Egypt having a silica content of 97.5%, and a bulk unit weight of 391 kg/m^3 was used. The chemical composition and physical properties of SF shown in Table 1.

2.1.4. Rice husk ash

Rice husk ash obtained from burning the husk under temperature. The produced RHA having grey color. Experimental tests (EDX and TEM) were applied on produced RHA. EDX test investigated that produced ash contain 95.9% silica. TEM test indicate that particle size varying between (16 nm to 52 nm). The physical and chemical properties of RHA shown in Table 1.

2.1.5. Granulated blast furnace slag

Granulated blast furnace slag obtained from iron industry wastes. GBFS obtained from rapid cooling by water or quenching molten slag with specific gravity 2.63. The chemical composition and physical properties of GBFS shown in Table 1.

2.1.6. Superplasticizer

A high performance superplasticizer (SP) admixture of aqueous solution of modified polycarboxylate basis (Viscocrete- 3425) was used of all mixtures. Viscocrete-3425 complies with ASTM-C-494 types G and BS EN 934 Part 2: 2001, with a specific gravity of 1.12. The dosage ranged about 2 % for mixes of cementitious content 1000 kg/m^3.

2.1.7. Water

Portable water was utilized in the experimental work for both preparing and curing. The pH degree of water taken is not less than 7. As presented in Table 2, water to cementitious materials ratio (w/cm) was utilized as 0.18 for mixes of cementitious content 1000 kg/m^3.

2.1.8. Steel fiber

Stainless steel fibers are manufactured fibers composed of stainless steel. To improve the RPC ductility, some mixes were generated with fibers of straight steel wire, 12 mm length and 0.2 mm in diameter, with a minimum on-the-wire tensile strength of 2100 MPa.

Table 1. Properties of cementitious materials.

Properties	CEM I	Silica Fume	Rice Husk Ash	Granulated blast furnace slag
Physical				
Specific gravity	3.15	2.15	2.32	2.63
Specific area cm^2/gm	3200	20000	-	-
Colour	Grey	Light Grey	Light Grey	Hard Grey
Chemical compositions (%)				
Silicon dioxide (SiO_2)	20.31	97.5	95.9	13.26
Aluminum oxide (Al_2O_3)	5.89	0.23	0.28	5.52
Ferric oxide (Fe_2O_3)	3.45	0.52	0.51	37.23
Calcium oxide (CaO)	62.49	0.24	0.43	33.15
Magnesium oxide (MgO)	2.13	0.45	0.24	5.38
Sulphur trioxide (SO_3)	2.18	0.13	0.16	4.14
Potassium oxide (K_2O)	0.73	0.47	0.61	-
Sodium oxide (Na_2O)	0.87	0.18	0.17	-
Loss on Ignition (LOI)	1.62	0.60	1.10	1.35

Table 2. Proportions of concrete mixtures.

Group	Mix No.	CEM I kg/m^3	Quartz Sand %	SF %	RHA %	GBFS %	Steel Fiber %	SP %	W/Cm
G1- CEM I	M0	1000	100	0	0	0	0	2.0	0.18
G2 -SF	M1	900	100	10	0	0	0	2.0	0.18
	M2	850	100	15	0	0	0	2.0	0.18
	M3	800	100	20	0	0	0	2.0	0.18
	M4	750	100	25	0	0	0	2.0	0.18
	M5	800	100	10	10	0	0	2.0	0.18
	M6	750	100	10	15	0	0	2.0	0.18
	M7	800	100	10	0	10	0	2.0	0.18
	M8	750	100	10	0	15	0	2.0	0.18
	M9	750	100	15	10	0	0	2.0	0.18
	M10	700	100	15	15	0	0	2.0	0.18
	M11	750	100	15	0	10	0	2.0	0.18
	M12	700	100	15	0	15	0	2.0	0.18
	M13	800	100	20	0	0	1	2.0	0.18
	M14	800	100	20	0	0	2	2.0	0.18
G3-RHA	M15	900	100	0	10	0	0	2.0	0.18
	M16	850	100	0	15	0	0	2.0	0.18
	M17	800	100	0	20	0	0	2.0	0.18
	M18	750	100	0	25	0	0	2.0	0.18
	M19	800	100	0	10	10	0	2.0	0.18
	M20	750	100	0	10	15	0	2.0	0.18
	M21	750	100	0	15	10	0	2.0	0.18
	M22	700	100	0	15	15	0	2.0	0.18
	M23	800	100	0	20	0	1	2.0	0.18
	M24	800	100	0	20	0	2	2.0	0.18

2.2. Mix proportion

To achieve the objectives of this work, three groups of concrete with a total numbers of 25 mixtures were ready and investigated as presented in Table 2. The mixtures were divided into three groups representing the variables in the study. The first group (G1- CEM I) with 1000 kg/m^3 cement content was prepared without any replacement material as SF or RHA or BFSP (reference mix). Group two (G2-SF) with 1000 kg/m^3 cementitious content is contains partial replacement materials as SF only by (10, 15, 20, 25%) or combination from SF (10, 15%) and RHA (10, 15%) or combination from SF (10, 15%) and GBFS (10, 15%) or 20% SF and steel fiber (1, 2%), that mixes from M1 to M14. While the third group (G3-RHA) is contains RHA only (10, 15, 20, 25%) or combination from RHA (10, 15%) and GBFS (10, 15%) or 20% RHA and steel fiber (1, 2%), as replacement materials by weight of cement (M15-M24).

2.3. Test procedure

The consistency of concretes is estimated via slump terms and slump flow values according to ASTM C143/C143M-15a (ASTM C143/C143M-15a), and the air content values according to ASTM C231/C231M-17a (ASTM C231/C231M-17a) of the fresh concrete were tested. The compressive strength test of concrete was tested using cubes (150 mm) according to BS 1881: part 116 - 2004 (B.S.1881, Part 116, 1989). This test was conducted at the ages of 1, 7, 28, 56, and 91 days. The splitting tensile strength test at 28 days was carried out according to ASTM C496/C496M - 11 (ASTM C496/C496M–11). A cylindrical specimen of dimensions (150×300 mm) was used for this test. The flexural strength test at 28 days was performed in accordance with ASTM C78/C78M-16 (ASTM C78/C78M–16). The prism specimens of 100×100×500 mm for flexural strength were used. The bond strength between a reinforcing bar (16mm) and surrounding concrete (cyl. 150×300 mm) was determined by using the pull out test according to BS 1881: part 207:1992 (B.S.1881, Part 207, 1992). The average of three specimens was recorded for each testing age and all strengths. While the modulus of elasticity at 28 days was conducted on the cylinder specimens of dimensions (150×300 mm) according to ASTM C469/C469M-14 (ASTM C469/C469M –14). To evaluate the water permeability of concrete, the concrete specimens were subjected to a hydrostatic water pressure of 30 bars for about 24 hours. The test was carried out on cylindrical specimens of diameter 150 mm and 150 mm height. The Darcy permeability coefficient (K) was calculated using the following formula:

$$K = Q \cdot H + A \cdot t \cdot P \,, \tag{1}$$

where Q is volume of the permeated water (cm^3), H is height of the specimen (cm), A is cross sectional area of the specimen (cm^2), t is time in seconds, P is apparatus coefficient = 1019.72 g/cm^2.

3. Results and Discussion

The test results of slump, air content, compressive strength, splitting tensile strength, flexural strength, bond strength, modulus of elasticity and water Permeability are shown in Table 3.

3.1. Consistency

The slump flow of RPC mixes containing 1000 kg/m^3 at 2% SP, W/Cm of 0.18 and different partial replacement of cement contents by (SF, RHA and GBFS) are presented in Table 3 and Fig. 1. However the workability of the mix could be enhanced due to better high range water reducing admixtures. The use of superplasticizer was very essential in RPC containing pozzolanic fine materials as SF or RHA or GBFS to achieve well dispersion. Obviously, when the SF, RHA and GBFS content raises, the flowability of RPC increases. The slump flow of UHPC 25% SF equal 294mm and RPC 25% RHA equal 365 mm but RPC 10% SF+15% RHA equal 315 mm and RPC 15% RHA+10% GBFS equal 328mm. It can be seen that RHA offered a much better consistency than did SF for the given mixture proportions. When 2 vol.-% of steel fibers was used, slump flow of both the RPCs 25% SF and 25% RHA obtained 232 mm and 280 mm, respectively with the same condition. Therefore, 25% RHA to partially replace cement can be considered as the optimal content in RPC including SF or RHA or GBFS.

Table 3. Fresh and hardened properties of results.

Mix No.	Groups	Slump Flow (mm)	Air Content (%)	Compressive Strength (MPa)					Splitting Tensile Strength (MPa)	Flexural Strength (MPa)	Bond Strength (MPa)	Modulus of Elasticity (GPa)	Water Permea-bility x 10^{-11}
				1d	7d	28d	56d	91d	28d	28d	28d	28d	Cm / sec
M0	CEM I	220	1.40	70.6	114.1	150.1	160.6	167.9	9.7	13.4	27.1	49.50	2.85
M1	SF	245	1.10	78.1	122.7	160.8	172.2	180.3	10.3	13.3	29.4	51.49	-
M2		265	1.00	81.7	129.1	168.7	180.8	189.5	10.6	13.9	31.0	53.14	-
M3		280	0.90	88.3	136.9	179.2	192.1	201.3	11.0	14.5	33.1	55.54	1.45
M4		294	0.85	85.4	131.7	172.4	184.7	193.8	10.3	13.8	31.9	53.13	-
M5		305	1.00	85.6	133.8	175.1	187.6	196.5	10.9	14.3	32.3	54.62	1.63
M6		315	0.95	83.8	131.0	171.6	183.9	192.6	10.3	14.1	31.5	53.74	-
M7		285	1.10	76.0	120.9	158.5	169.7	177.7	10.1	13.1	28.9	50.72	1.89
M8		293	1.05	74.6	118.4	155.6	166.5	174.3	10.4	13.0	28.4	50.12	-
M9		302	0.95	83.3	129.8	170.2	182.4	190.9	10.6	13.9	31.4	53.25	-
M10		310	0.90	81.9	128.0	167.3	179.3	187.8	10.4	13.7	30.9	52.54	-
M11		297	1.00	79.8	126.3	165.5	177.2	185.4	10.3	13.6	30.4	51.98	-
M12		305	0.95	78.0	123.6	162.4	173.8	181.9	10.2	13.4	29.9	51.16	-
M13		257	1.10	91.7	141.7	185.5	198.7	208.3	17.4	29.5	34.4	57.50	1.57
M14		232	1.20	93.0	143.8	188.2	201.9	211.2	24.9	43.3	34.6	58.13	1.68
M15	RHA	290	1.15	75.3	119.2	156.6	167.7	175.6	10.1	13.2	28.4	51.68	-
M16		327	1.10	79.2	124.6	163.2	175.1	183.1	10.3	13.6	29.8	52.61	-
M17		345	1.10	84.8	131.4	171.8	184.4	193.2	10.6	14.1	31.6	54.36	1.75
M18		365	1.00	83.3	128.3	168.1	180.3	188.8	10.2	13.7	31.1	53.12	-
M19		280	1.20	73.4	117.2	153.8	164.8	172.3	10.0	12.8	28.1	49.21	1.96
M20		270	1.15	72.6	115.3	151.6	162.2	169.8	9.8	12.6	27.7	48.67	-
M21		328	1.10	76.8	121.5	159.4	170.6	178.7	10.1	13.2	29.2	50.68	-
M22		317	1.05	75.1	119.7	157.3	168.2	176.2	9.9	13.0	28.8	49.86	-
M23		310	1.15	87.3	135.6	177.6	190.5	199.4	16.7	28.6	32.8	55.05	1.84
M24		280	1.25	88.7	137.5	180.1	193.2	202.3	24.2	41.7	33.0	55.63	1.93

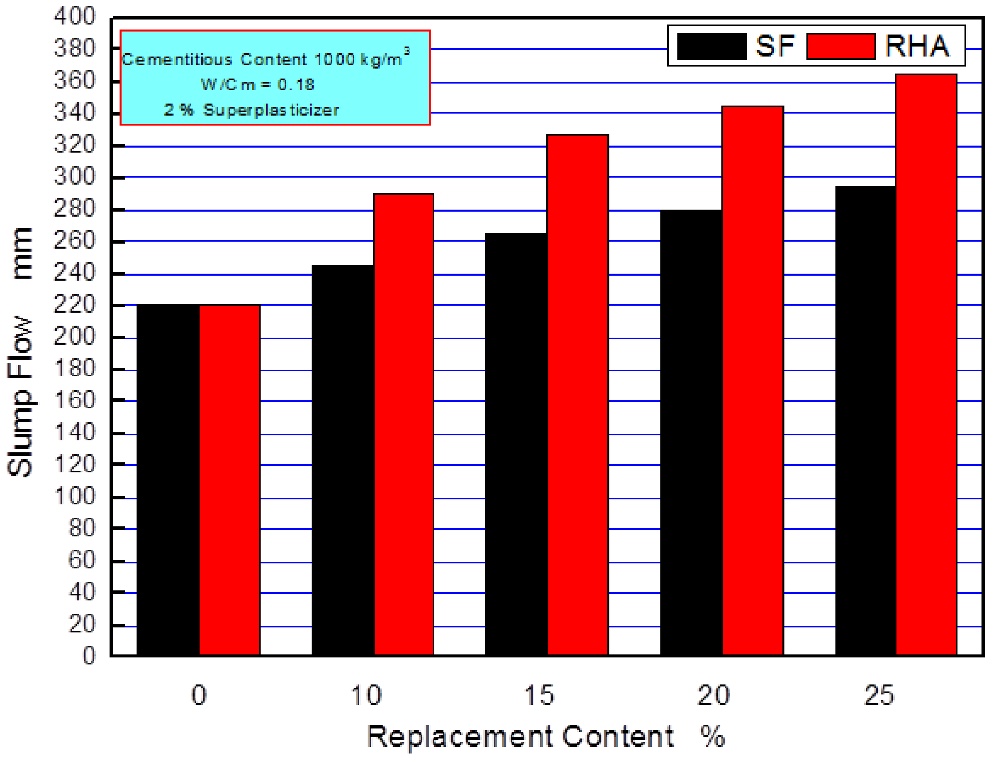


Fig. 1. Effect of replacement materials on the consistency.

3.2. Air content

Table 3 shows that the effect of SF, RHA, and GBFS as a replacement materials of cement on air content percentage. The RPC mixes containing SF or RHA or GBFS content up to 25% lead to significant reductions in air content, while when the content of SF or RHA increased from 0 to 25%, the air content decreased to about 39% and 29% for mixes with 1000 kg/m³ cementitious materials, respectively. The measured air contents were 1.4, 0.9, 1.0, 1.1, 1.2, 1.1, 1.2, and 1.25% for concrete mixes (1000 kg/m³ cementitious materials) containing 0, 20% SF, 10% SF+10% RHA, 10% SF+10% GBFS, 20% SF+2% steel fiber, 20% RHA, 10% RHA+10% GBFS, and 20% RHA+2% steel fiber, respectively.

3.3. Compressive strength

The compressive strength of RPC at different replacement of cement (SF, RHA, and GBFS) contents are presented in Table 3 and Fig. 2. The compressive strength at 1, 7, 28, 56, and 91 days are shown in Table 3 and Figs. 2-3. In general, the addition of SF or RHA as a replacement of cement up to a particular percentage resulted in a corresponding raise of the compressive strength. The test results indicate that the particular content of SF or RHA or combination of them and GBFS, which may be referred to as the optimum content, is about 20% as shown in Figs. 4-5. At the optimum content, SF, RHA and GBFS are sufficient to react with all liberated calcium hydroxide produced from the cement hydration process to produce calcium silicate hydrates.

In UHPC, RHA can also act as a good pozzolanic admixture to generate UHPC without considerable change in compressive strength compared with that of mixture including SF. The experimental findings reflected that mixing SF or RHA as partial alternation of cement enhances the compressive strength of concrete. Positive impact of SF or RHA on compressive strength is suggested to be because of the high pozzolanity of SF or RHA as a result of the large SSA and the high silica content. SF or RHA responds intensively with the water and the calcium hydroxide generated from the hydration of cement to generate more C–S–H. The additional C–S–H itself is the major strength-contributing compound, and also fills in the capillary pores to enhance the microstructure of the paste matrix and transition zone in concrete resulting in improving compressive strength. SF or RHA is supposed to enhance compressive strength because of the internal water curing and the lower effective w/b ratio of concrete. SF or RHA develops compressive strength improvement in two ways apart from its pozzolanic activity; it speeds up the hydration process in the wet phase by offering more nucleation sites for the operation to happen, while its pore-filling effect enhances the packing features of solid particles within the concrete matrix during later ages. The principle reasons for the excellent pozzolanic activity and raise in compressive strength are amorphous silica and the fine particle size of SF or RHA. The raising in compressive strength of SF or RHA concretes were basically because of the filler physical effect and by the pozzolanic chemical effect.

Findings reveal that at 20% SF as a replacement of cement enhanced the compressive strength, where 25.1, 20.0, 19.4, 19.6, and 19.9% improvement in compressive strength is regarded at 1, 7, 28, 56, and 91 days, respectively of mixes with 1000 kg/m³ cementitious materials. While, for concrete containing 20% RHA, the increase of compressive strength are 20.1, 15.2, 14.5, 14.8, and 15.1% for ages 1, 7, 28, 56, and 91 days respectively, but compressive strength of 10% SF+10% RHA mixes increase about 21.2, 17.3, 16.7, 16.8, and 17.0% for ages 1, 7, 28, 56, and 91 days respectively. In this study that the improvement of compressive strength is more significant at early age than the later ages. The early age strength raises could be because of finer particle size of SF and RHA, which quicken the hydration reaction and packs into cement particles gaps. On the contrary, the long term strength of concrete is raised through pozzolanic effect. But, with respect to mixes containing 10% GBFS+10% SF and 10% GBFS+10% RHA, the increase of compressive strength about 5.6% and 2.5% for 28 days respectively.

Figs. 4-5 demonstrate the effect of SF, RHA and GBFS on the 28-day compressive strength at different replacement levels. It is clear that SF increased compressive strength at 1000 kg/m^3 cementitious materials to almost about 7.1, 12.4, 19.4, and 14.9% at 10, 15, 20, and 25% respectively. The compressive strengths of the mixes at 10, 15, 20, and 25% of RHA were about 4.3, 8.7, 14.5, and 12% respectively higher than that of the control concrete at 28 days. The compressive strength of concrete incorporating SF are comparable and sometimes better than RHA concrete. The test results showed that the optimum replacement percentage for maximum compressive strength was 20% for concrete incorporating SF or RHA. Based on the results, it can be observed that concrete prepared with GBFS indicated reduced strengths compared to the mixes containing SF or RHA, while this mixes produce sustainable UHPC.

Reactive Powder Concrete shows a higher rate of strength gain at early ages as compared to normal strength concrete, but at later ages the difference is not significant. The higher rate of strength development of RPC at early ages may be caused by; an increase in the internal curing temperature in concrete specimens due to a higher heat of hydration, and shorter distance between hydrated particles in RPC due to low water-cementitious ratio. Table 3 and Fig. 6 show the results of compressive strength at different ages. The statically analysis of these results yields the following equations:

$$f_{c1} = 0.486 \cdot f_{c28} \, , \tag{2}$$

$$f_{c7} = 0.763 \cdot f_{c28} \, , \tag{3}$$

$$f_{c56} = 1.071 \cdot f_{c28} \, , \tag{4}$$

$$f_{c91} = 1.122 \cdot f_{c28} \, . \tag{5}$$

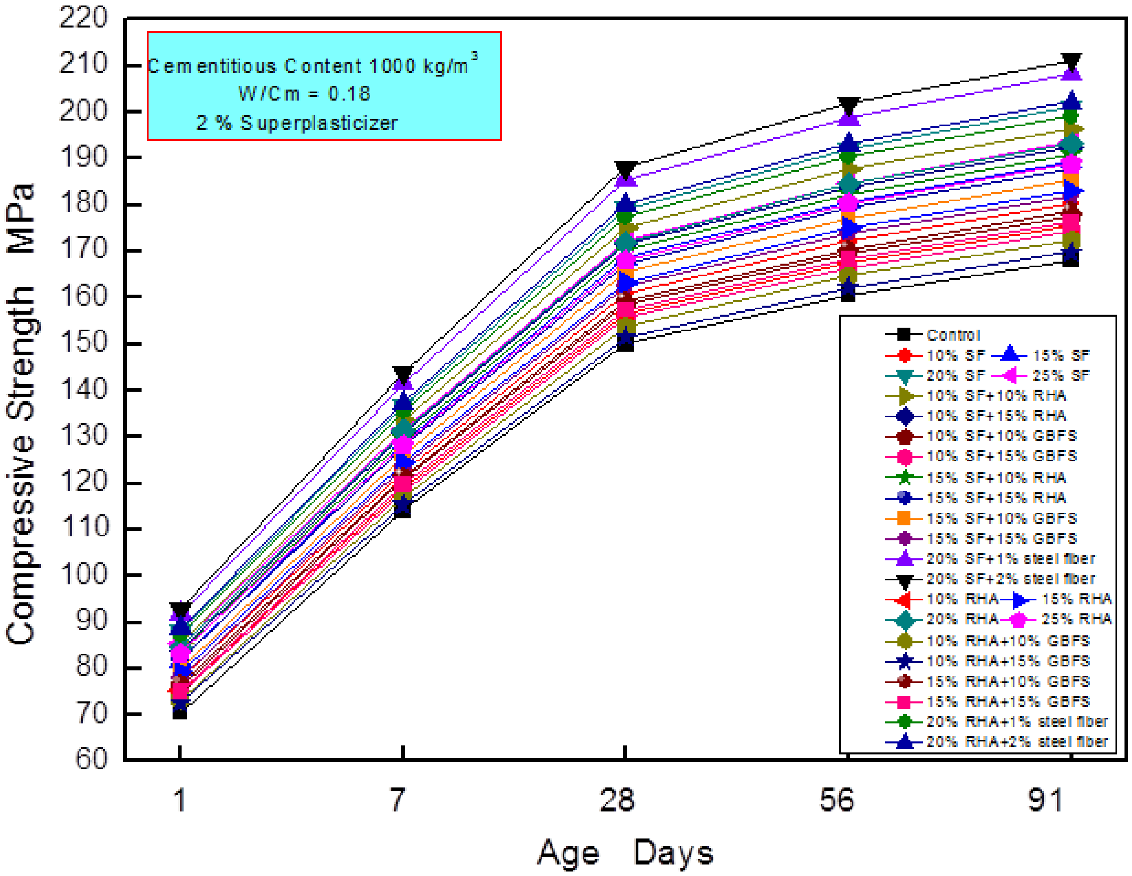


Fig. 2. The compressive strength of mixes with 1000 kg/m^3 cementitious content at different ages.

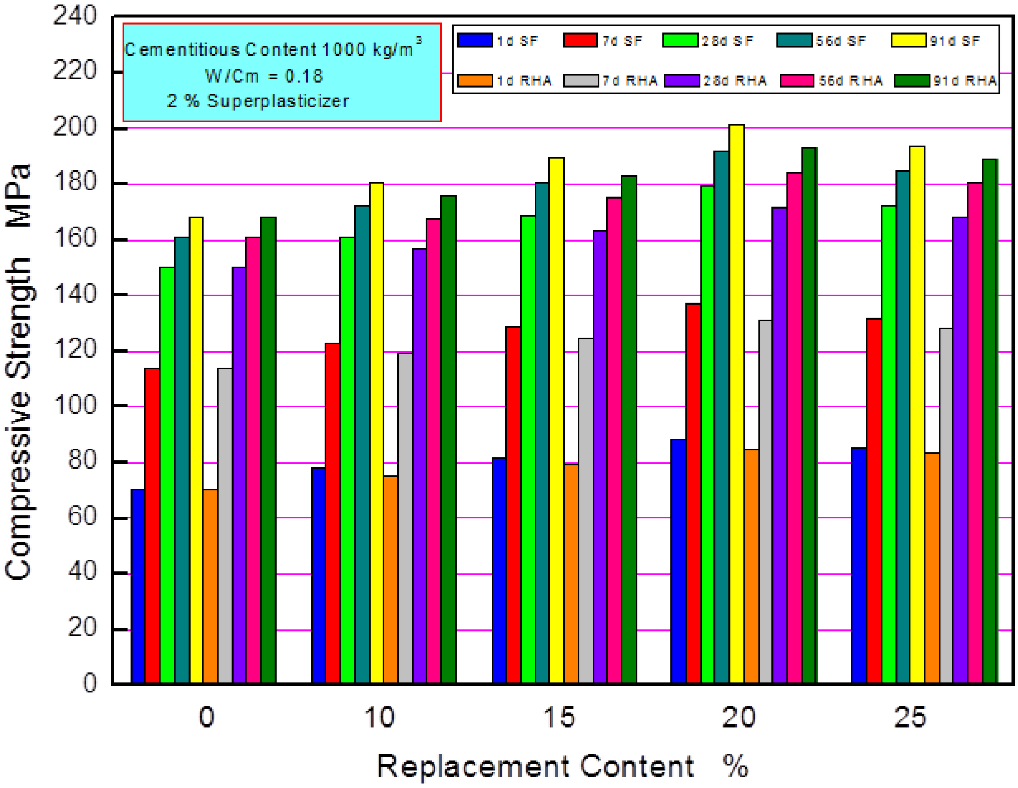


Fig. 3. Effect of replacement materials on the compressive strength at different ages.

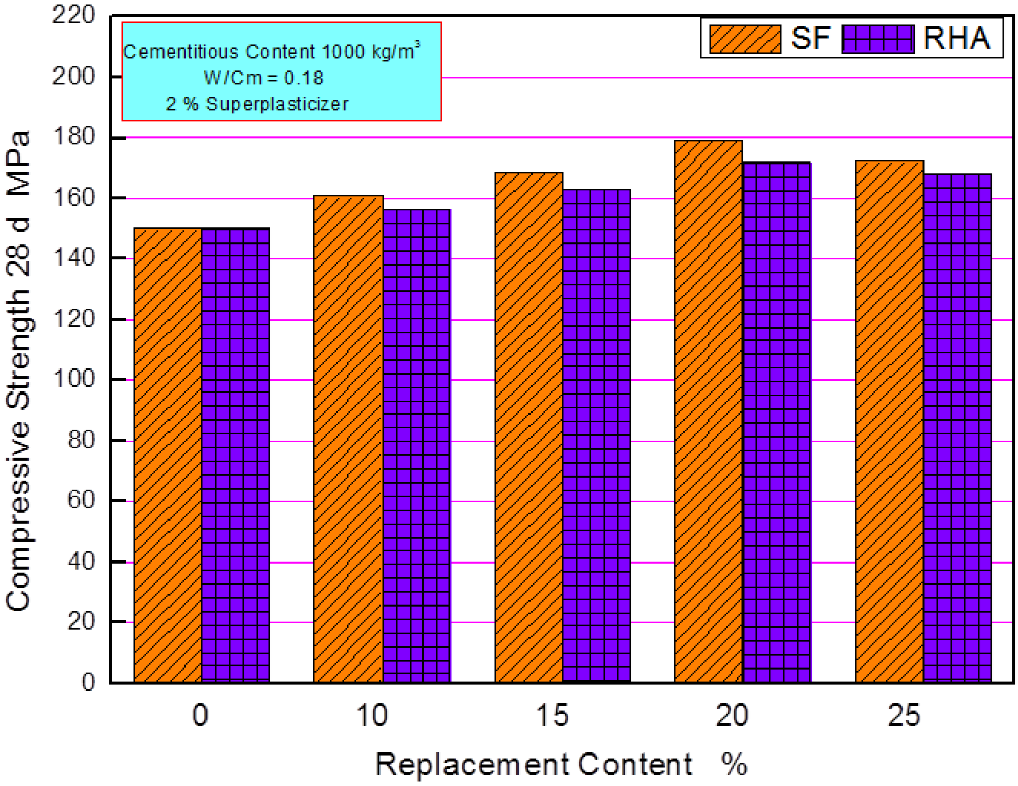


Fig. 4. Effect of replacement content on the compressive.

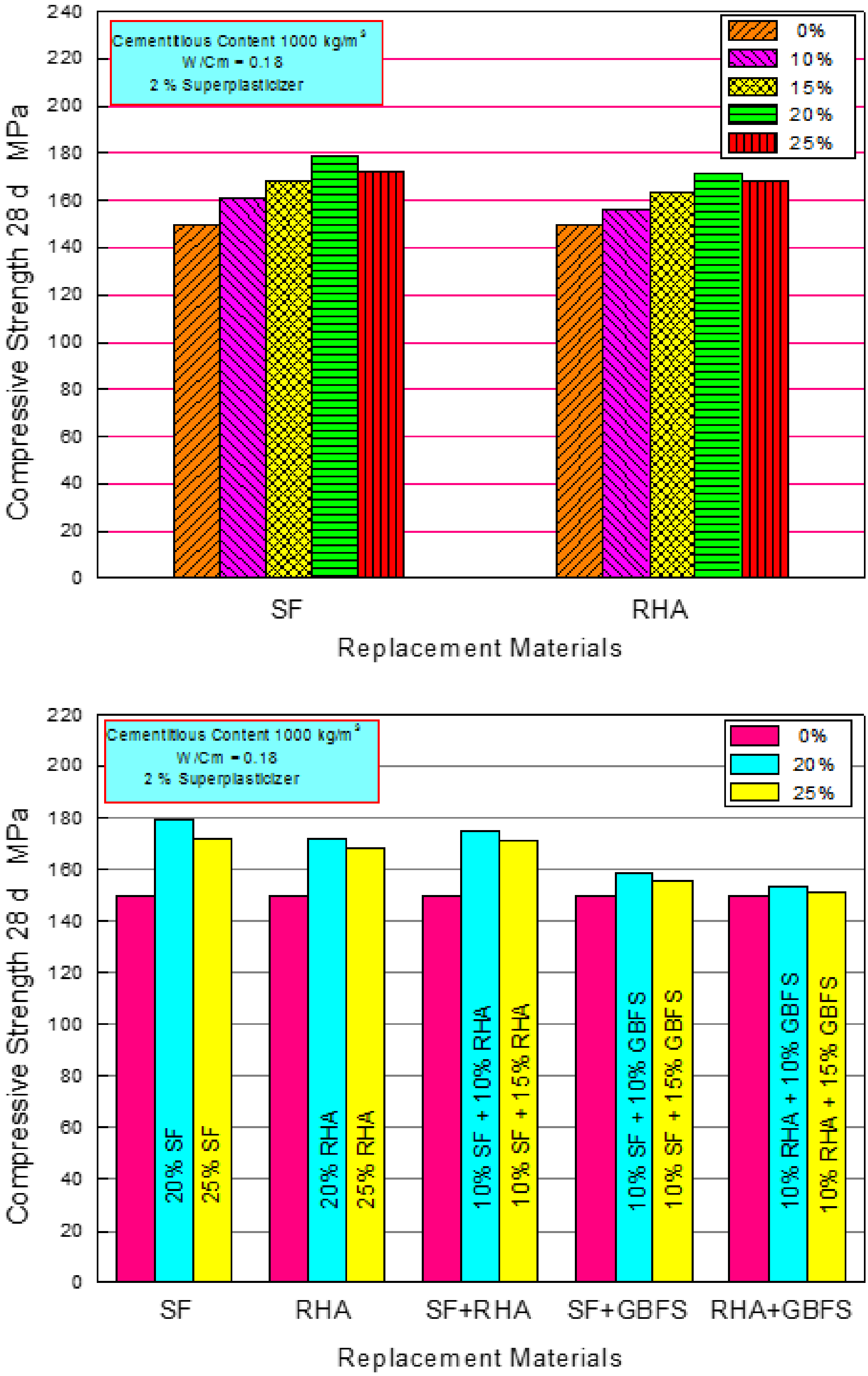


Fig. 5. Effect of replacement materials on the compressive strength at 28 days.

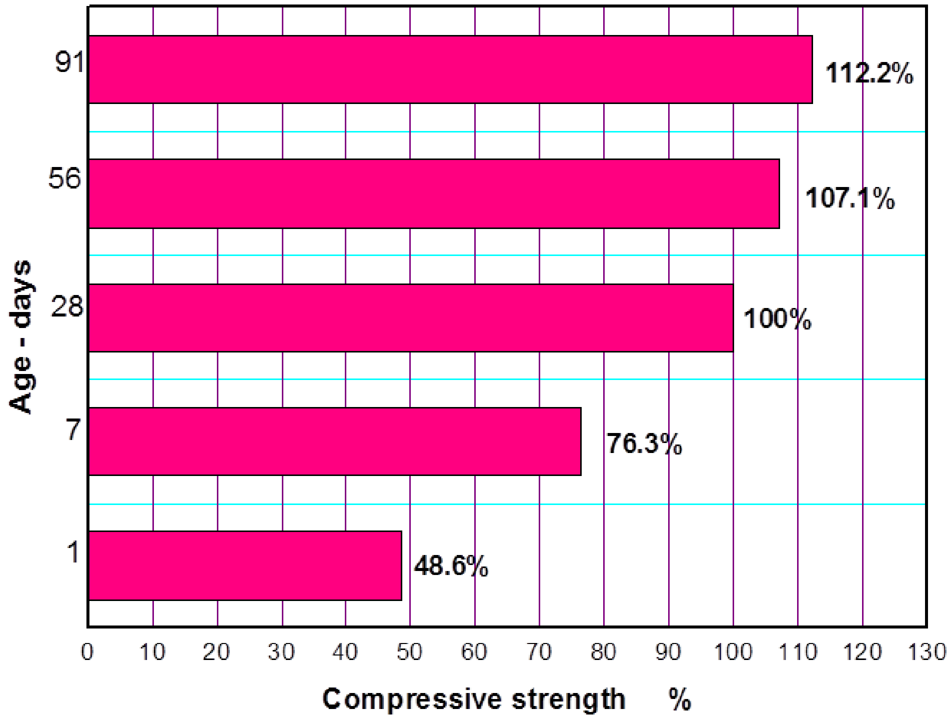


Fig. 6. Relative gain of compressive strength of HSC at different ages.

3.4. Splitting tensile strength

The effect of SF, RHA and GBFS on the splitting tensile strength for different replacement contents is shown in Table 3 and Fig. 7. The results of splitting tensile strength increases with the increase of SF or RHA content. For 20% replacement contents, the improvement of the tensile strength were 13.4, 9.3, 12.4, 4.1 and 3.1% for mixes containing 20% SF, 20% RHA, 10% SF+10% RHA, 10% SF+10% GBFS and 10% RHA+10% GBFS respectively. On the other hand, the splitting tensile strength results of mixes containing 20% SF+2% steel fiber and 20% RHA+2% steel fiber comparing to control mix were enhanced about 156.7 and 149.5% respectively. Splitting tensile strength for these mixes with 1 and 2% steel fibers equal about 9.4 and 13.4% from compressive strength respectively. With comparability of splitting tensile strength result of all mixes to compressive strength result, it is noticed that, splitting strength result represent about 6.3% nearly of compressive strength result of the same mixes as shown in Fig. 8. From above table we can notice that the average tensile strength of Reactive Powder Concrete are attain more than target strength at 20% of SF or RHA as a replacement with cement quantity.

3.5. Flexural strength

The flexural strength results are shown in Table 3 and are illustrated in Fig. 7. It shows that the flexural strength of concrete mix also increases with increase in SF or RHA replacement of cement. The flexural strength for the mixes with 20% SF or 20% RHA gain of 8.2 and 5.2% was obtained respectively in comparison with control mix. The maximum value of flexural strength was obtained for 20% from SF or RHA as a replacement of cement. The average value of flexural strength is about 8.27% of the 28-days compressive strength of the same mixes as shown in Table 3 and Fig. 8. The average flexural strength of Reactive Powder Concrete with 1 and 2% steel fibers increase about 117 and 217% respectively, comparing to control mix. Average of flexural strength for these mixes with 1 and 2% steel fibers equal about 16.0 and 23.1% respectively from compressive strength.

3.6. Bond strength

The bond behaviour is generally represented as the relation of bond stress versus slip, which means the difference between the displacement of the rebar and the concrete in cracked regions of reinforced concrete members. The bond stress-slip relationships are mostly determined on the basis of pull-out tests. The bond strength of different RPC mixes at 28 days age is represented in Table 3 and Fig. 7. As shown the bond strength for controlled mix protected 27.1 MPa. The mixes contain SF or RHA or GBFS achieve improvement in bond strength. It's noticed that bond strength increase to 33.1, 31.6, 32.3, 28.9 and 28.1 MPa in mixes with 20% SF, 20% RHA, 10% SF+10% RHA, 10% SF+10% GBFS and 10% RHA+10% GBFS respectively, with improvement of about 22.1, 16.6, 19.2, 6.6 and 3.7%. Also, the average bond strength results represent about 18.35% of compressive strength results of the same mixes as shown in Fig. 8. With respect to the above result replacing a small dosage of OPC by about of 20% from RHA or SF in the concrete mix had a great effect on the bond strength of concrete 33.1, 31.6, 32.3, 28.9 and 28.1 MPa in mixes with 20% SF, 20% RHA, 10% SF+10% RHA, 10%

SF+10% GBFS and 10% RHA+10% GBFS respectively, with improvement of about 22.1, 16.6, 19.2, 6.6 and 3.7%. Also, the average bond strength results represent about 18.35% of compressive strength results of the same mixes as shown in Fig. 8. With respect to the above result replacing a small dosage of OPC by about of 20% from RHA or SF in the concrete mix had a great effect on the bond strength of concrete.

3.7. Modulus of Elasticity

The test results of modulus of elasticity for RPC mixes at 1000 kg/m^3 cementitious content after 28 days are shown in Table 3. The modulus of elasticity for controlled mix equal 49.5 GPa. It's noticed that modulus of elasticity reached to 55.54, 54.36, 54.62 and 50.72 GPa in mixes with 20% SF, 20% RHA, 10% SF+10% RHA and 10% SF+10% GBFS respectively, with improvement of about 12.2, 9.8, 10.3, and 2.5%. The elasticity modulus for mixes contains SF by 10, 15, 20 and 25% of cement content increase about 4.0, 7.4, 12.2 and 7.3% compared to control mix, respectively. On the other side, modulus of elasticity for RHA mixes with 10, 15, 20 and 25% are improved about 4.4, 6.3, 9.8 and 7.3%, respectively. It is worthy of note that, the optimum value of modulus of elasticity was obtained for 20% SF or 20% RHA as a replacement of cement. Also, the average modulus of elasticity results represent about 316.2% of compressive strength results of the same mixes.

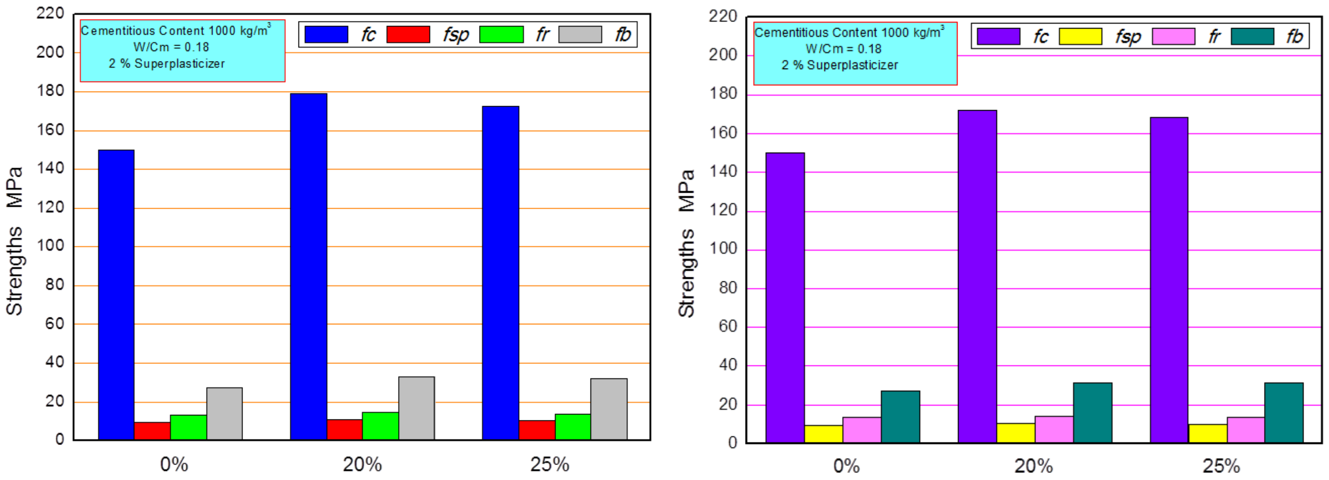
3.8. Permeability

Table 3 and Fig. 9 illustrate the results of the permeability coefficient, and the effect of SF, RHA, and GBFS on concrete permeability. The test results indicated that, concrete incorporating SF, RHA and GBFS are less permeable and thus, are more durable. The coefficient of permeability of RPC mixes containing 20% SF, 20% RHA, 10% SF+10% RHA, 10% SF+10% GBFS and 10% RHA+10% GBFS were about 50.9, 61.4, 57.2, 66.3 and 68.8% of the permeability coefficient of mix without replacement materials, respectively. However, this improvement of the permeability of concrete incorporating SF, RHA and GBFS may be ascribed to the difference in pore distribution. One cause of this difference in pore structures is the higher content of calcium silicate hydrate gel (CSH). Another cause that the relative decrease in capillary porosity is due to a difference precipitation of the CSH gel. In contrast to Portland cement, the CSH gel does not precipitate directly on the cement gain, but in the space between clinker grain and silica grain.

4. Conclusions

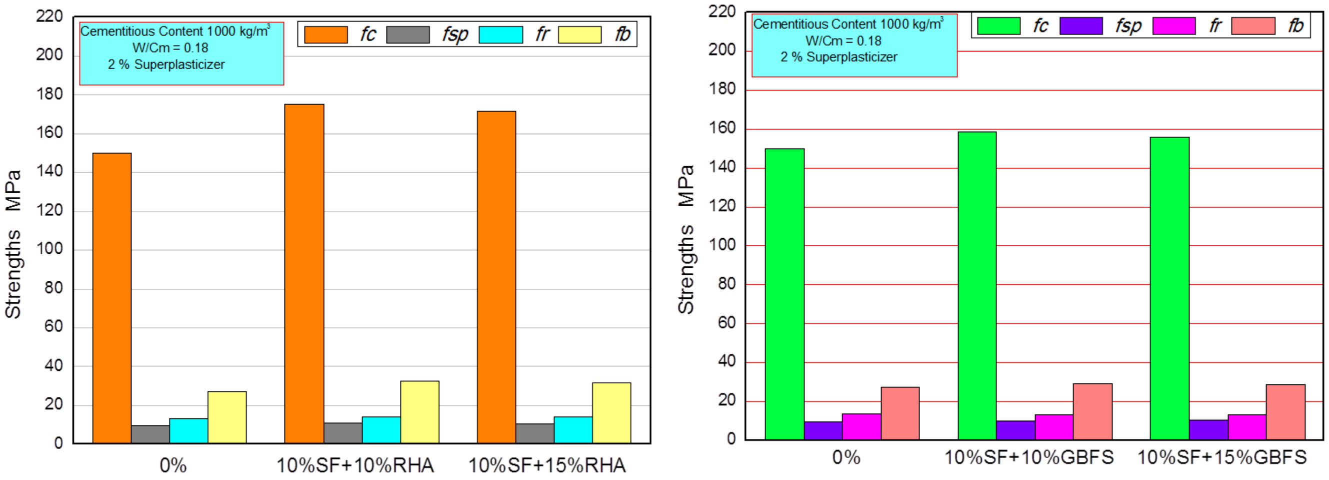
Based on the results presented above, the following conclusions can be drawn:

- When the SF, RHA and GBFS content increases, the flowability of RPC increases. The use of superplasticizer was very essential in concrete containing fine particles like SF or RHA or GBFS to achieve well dispersion and better results. In mixes with 2% superplasticizer, when the replacement level of SF or RHA was increased to 25%, the slump flow was increased by approximately 33.6% and 65.9% respectively.
- 2. When the content of SF or RHA increased from 0 to 25%, the air content decreased to about 39.3% and 28.6% for mixes with 1000 kg/m^3 cementitious materials, respectively.
- 3. For all replacement contents, the improvement of the compressive strength at 28 days were 7.1, 12.4, 19.4, and 14.9% for mixes containing 10, 15, 20 and 25% SF, and the improvement of the compressive strength were 4.3, 8.7, 14.5, and 12% for mixes with 10, 15, 20 and 25% RHA, respectively.
- For all RPC mixes, the average splitting strength result represent about 6.3% nearly of compressive strength result of the same mixes. The splitting tensile strength increase about 13.4 and 9.3% for mixes containing 20% SF and 20% RHA respectively. While, the splitting tensile strength results of mixes containing 20% SF+2% steel fiber and 20% RHA+2% steel fiber comparing to control mix were enhanced about 156.7 and 149.5% respectively.
- The average value of flexural strength is about 8.27% of the 28-days compressive strength of the same mixes. The flexural strength for the mixes with 20% SF or 20% RHA gain of 8.2 and 5.2% was obtained respectively in comparison with control mix. But, the average flexural strength of RPC with 1 and 2% steel fibers increase about 117 and 217% respectively, comparing to control mix.
- For RPC mixes with 20% SF and 20% RHA the bond strength increase about to 22.1 and 16.6% respectively, Also, the average bond strength results represent about 18.35% of compressive strength results.
- The elasticity modulus for mixes contains SF by 10, 15, 20 and 25% of cement content increase about 4.0, 7.4, 12.2 and 7.3% compared to control mix, respectively, on the other side, modulus of elasticity for RHA mixes with 10, 15, 20 and 25% are improved about 4.4, 6.3, 9.8 and 7.3%, respectively. Also, the average modulus of elasticity results represent about 316.2% of compressive strength results of the same mixes.
- The coefficient of permeability of RPC mixes containing 20% SF, 20% RHA, 10% SF+10% RHA, 10% SF+10% GBFS and 10% RHA+10% GBFS were about 50.9, 61.4, 57.2, 66.3 and 68.8% of the permeability coefficient of control mix, respectively.
- The test results indicate that the optimum replacement percentage for maximum compressive strength and other hardened properties was 20% for concrete incorporating SF or RHA or combination of them and GBFS. While, based on the results, it can be observed that concrete prepared with GBFS indicated reduced strengths compared to the mixes containing SF or RHA, while this mixes produce sustainable UHPC.



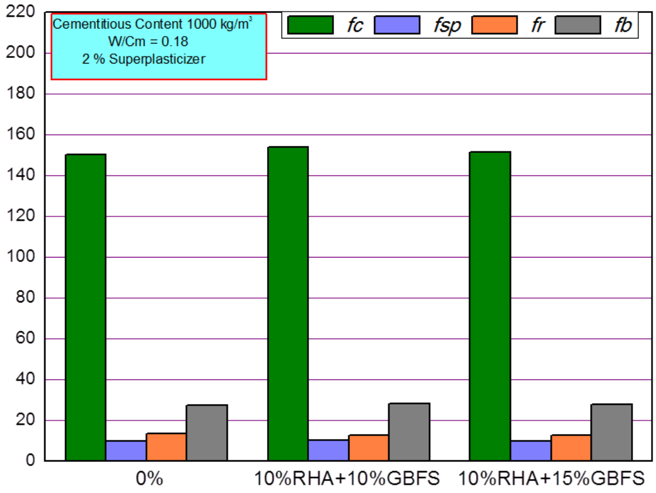
(a) Silica Fume

(b) Rice Hask Ash



(c) Silica Fume + Rice Hask Ash

(d) Silica Fume + Granulated Blast Furnace Slag



(e) Rice Husk Ash + Granulated Blast Furnace Slag

Fig. 7. Effect of replacement materials on different strengths of HSC: (a) Silica Fume; (b) Rice Husk Ash; (c) Silica Fume + Rice Husk Ash; (d) Silica Fume+ Granulated Blast Furnace Slag; (e) Rich Husk Ash +Granulated Blast Furnace Slag.

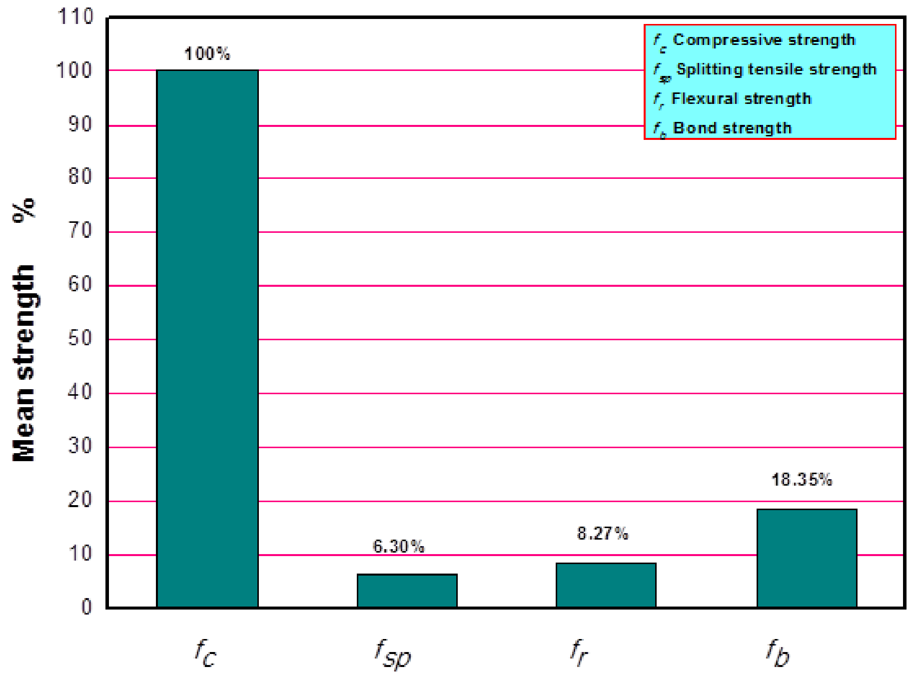


Fig. 8. Compressive strength of HSC in comparison to other strengths.

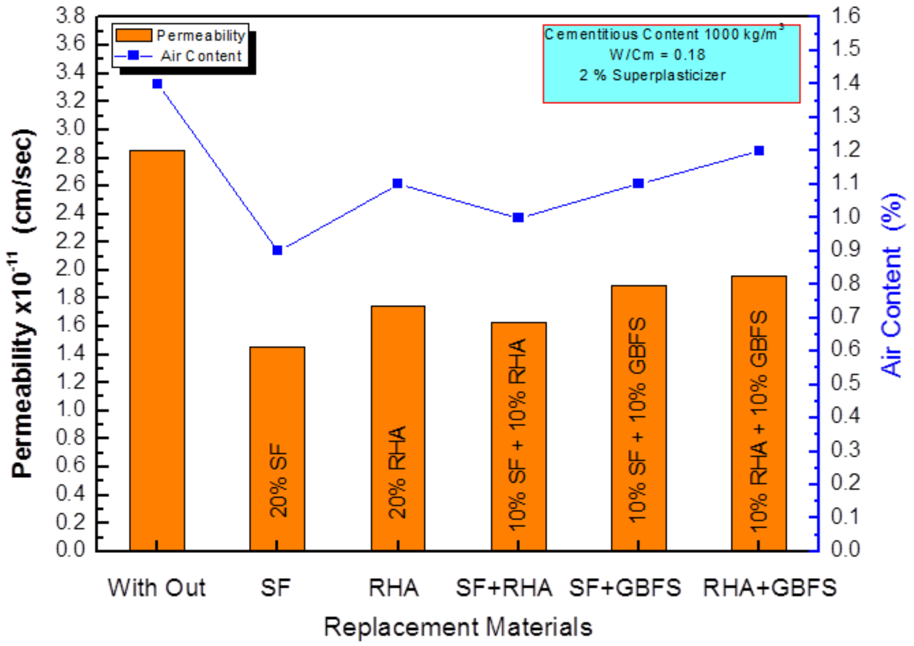


Fig. 9. Effect of replacement materials on the permeability of HSC mixes.

REFERENCES

ASTM C78/C78M - 16 (2016). Standard Test Method for Flexural Strength of Concrete. ASTM International, West Conshohocken, PA.

ASTM C143/C143M - 15a (2015). Standard Test Method for Slump of Hydraulic-Cement Concrete. ASTM International, West Conshohocken, PA.

ASTM C231/C231M - 17a (2017). Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method". ASTM International, West Conshohocken, PA.

ASTM C469/C469M - 14 (2014). Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression. ASTM International, West Conshohocken, PA.

ASTM C496/C496M - 11 (2011). Standard Test Method for Splitting Tensile of Cylindrical Concrete Specimens. ASTM International, West Conshohocken, PA.

B.S.1881, Part 116, (1989). Method for Determination of Compressive Strength of Concrete Cubes. British Standards Institution (BSI), UK.

B.S.1881, Part 207 (1992). Method for Determination of Bond Strength of Concrete Cylinders. British Standards Institution (BSI), UK.

BS EN 197-1 (2011). Cement. Composition, Specifications and Conformity Criteria for Common Cements. British Standards Institution (BSI), UK.

Chan YW, Chu SH (2004). Effect of silica fume on steel fiber bond characteristics in reactive powder concrete. *Cement and Concrete Research*, 34(7), 1167-1172.

Chung DDL (2002). Review: Improving cement-based materials by using silica fume. *Journal of Materials Science*, 37(4), 673–682.

Dugat J, Roux N, Bernier G (1996). Mechanical properties of reactive powder concretes. *Materials and structures*, 29(4), 233-240.

Egyptian Code of Practice: ECP 203-2017 (2017). Design and Construction for Reinforced Concrete Structures. Ministry of Building Construction, Research Center for Housing, Building and Physical Planning, Cairo, Egypt.

ES 4756-1 (2013). Cement Part: (1) Composition, Specifications and Conformity Criteria for Common Cements. Egyptian organization for Standardization and Quality (EOS), Egypt.

Gerlicher T, Heinz D, Urbonas L (2008). Effect of finely ground blast furnace slag on the properties of fresh and hardened UHPC. *In: Second International Symposium on Ultra High Performance Concrete*, 367-374.

Hirschi T, Wombacher F (2008). Influence of different superplasticizers on UHPC. *In: Proceedings of the Second International Symposium on Ultra High Performance Concrete, Kassel University Press, Kassel*, 77-84.

Hommer H (2009). Interaction of polycarboxylate ether with silica fume. *Journal of the European Ceramic Society*, 29(10), 1847-1853.

Kim DJ, Park SH, Ryu GS, Koh KT (2011). Comparative flexural behavior of hybrid ultra high performance fiber reinforced concrete with different macro fibers. *Construction and Building Materials*, 25(11), 4144-4155.

Long G, Wang X, Xie Y (2002). Very-high-performance concrete with ultrafine powders. *Cement and Concrete Research*, 32(4), 601-605.

Ma J, Orgass M, Dehn F, Schmidt D, Tue NV (2004). Comparative investigations on ultra-high performance concrete with and without coarse aggregates*. In: Proceedings of International Symposium on Ultra* High Performance Concrete, Germany, 205-212.

Möser B, Pfeifer C, Heinz D, Gerlicher T, Mechtcherine V, Dudziak L (2012). Investigations on the workability and microstructure development of UHPC–Part 2: influence of admixtures and curing on the microstructure of ultra-high strength concretes. *Cement International*, 8(6), 74-85.

Neville AM (2006). Concrete: Neville's Insights and Issues. Thomas Telford, London, UK.

Papadakis VG (1999). Experimental investigation and theoretical modeling of silica fume activity in concrete. *Cement and Concrete Research*, 29(1), 79-86.

Park JJ, Kang ST, Koh KT, Kim SW (2008). Influence of the ingredients on the compressive strength of UHPC as a fundamental study to optimize the mixing proportion. *In: Proceedings of the Second International Symposium on Ultra High Performance Concrete,* 105-112.

Perry V (2003). A revolutionary new material for new solutions. *In: Technical Forum*. Presentation, Lafarge North America.

Plank J, Schroefl C, Gruber M, Lesti M, Sieber R (2009). Effectiveness of polycarboxylate superplasticizers in ultra-high strength concrete: the importance of PCE compatibility with silica fume. *Journal of Advanced Concrete Technology*, 7(1), 5-12.

Resplendino J (2012). State of the art of design and construction of UHPFRC structures in France. *In: Proceedings of Hipermat-3rd International Symposium on UHPC and Nanotechnology for Construction Materials*, 27-41.

Richard P, Cheyrezy M (1995). Composition of reactive powder concretes. *Cement and Concrete Research*, 25(7), 1501-1511.

Sakai E, Akinori N, Daimon M, Aizawa K, Kato H (2008). Influence of superplasticizers on the fluidity of cements with different amount of aluminate phase. *In: Second International Symposium on Ultra High Performance Concrete,* 85-92.

Schmidt M (2012). Sustainable building with ultra-high-performance concrete (UHPC)—Coordinated research program in Germany. *In: Proceedings of Hipermat 2012, 3rd International Symposium on UHPC and Nanotechnology for High Performance Construction Materials*, Ed., Schmidt M, Fehling E, Glotzbach C, Fröhlich S, and Piotrowski S, Kassel University Press, Kassel, Germany, 17-25.

Schmidt M, Fehling E (2005). Ultra-high-performance concrete: research, development and application in Europe. *ACI Special Publication*, 228, 51-78.

Schmidt M, Teichmann T (2006). New developments in ultra high performance concrete–non corrosive PVA-fibres and gluing of structural elements. *In: Proceedings of the 2rd fib congress-Section*, 13, 1-11.

Terzijski I (2004). Compatibility of components of high and ultra high performance concrete. *In: Proceedings of the 1st International Symposium on Ultra High Performance Concrete*, Kassel, Germany, 175-186.

Tuan NV, Ye G, van Breugel K (2012). Mitigation of early age shrinkage of ultra high performance concrete by using rice husk ash. *In: 3rd International Symposium on UHPC and Nanotechnology for High Performance Construction Materials: Ultra-High Performance Concrete and Nanotechnology in Construction* (*HIPERMAT-2012*), 19, 341-348). Kasse University Press GmbH.

van Tuan N, Ye G, van Breugel K, Fraaij AL, Dai Bui D (2011). The study of using rice husk ash to produce ultra high performance concrete. *Construction and Building Materials*, 25(4), 2030-2035.

Yazıcı H, Yardımcı MY, Yiğiter H, Aydın S, Türkel S (2010). Mechanical properties of reactive powder concrete containing high volumes of ground granulated blast furnace slag. *Cement and Concrete Composites*, 32(8), 639-648.