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The effect of Silica Fume and Fly Ash on the Properties of Reactive Powder Concrete and its comparison with High Strength Concrete

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Abstract

Reactive powder concrete (RPC) is a type of high-performance concrete. RPC eliminates the use of coarse aggregates in the mixture to increase compactness. RPC is composed by materials such as Portland cement (OPC), quartz sand, quartz powder, supplementary cementitious materials, water, superplasticizer, fiber (optional).

This research consists of two basic parts. The first part investigates the effects of many parameters on the fresh and mechanical properties of locally cast (RPC). The effective parameters are volume of binder content ratio, water-binder ratio, the type of supplementary cementitious material (silica fume (SF) and fly ash (FA)), and, also, their ratio. These parameters were examined experimentally to evaluate their effect on workability, compressive, tensile, and flexural strength. The second part was concerned with comparing the effects of both mentioned supplementary cementitious materials on (RPC) and high-strength concrete (HSC).

The results indicate an obvious decrease in RPC workability and an increase in strength by replacing part of the cement with silica fume. RPC can achieve high strength when the volume of binder content is 60% and silica fume replaces up to 20% of cementitious materials. The results also revealed that RPC workability is improved when a part cementitious material is substituting by fly ash. However, excessive replacement of cement with fly ash leads to a reduction in strength. Moreover, the results showed that substituting 10% of cementitious materials with fly ash and silica fume improved the compressive strength of RPC by 43% and 36%, respectively, higher than that of HSC.

Keywords: Reactive powder concrete, Silica fume, Fly ash, Workability, Compression, Flexural, High strength concrete

1. Introduction

1.1 Research background

A newly developed kind of ultra-high-performance cement-based composite material is called reactive powder concrete (RPC). The manufacture principle and production process of RPC were initially presented by Richard et al. [1], who also proposed the mix proportions of RPC200 and RPC800 [2]. After heat curing at 90 degrees Celsius and using quartz sand as the aggregate, the RPC200 with a compressive strength of 170–230 MPa was created. Successful preparation of the 490~650 MPa RPC was achieved through 50 MPa compression molding and autoclave curing at 250~400^{o}C. Through the addition of steel aggregate with a particle size of less than 0.8 mm, autoclaved curing and compression molding, an RPC800 with a compressive strength of 650–810 MPa was effectively created. Although RPC technology is relatively new, its exceptional performance has prompted its use in numerous structures globally. RPC's extremely high strength helps to produce slender elements and greatly lowers the structure's weight. In fact, the weight of RPC-built structures may reach one-third or half that of conventional structures [3]. Furthermore, RPC exceptional durability allows it to be a more sensible and affordable material for long-span constructions and high-rise buildings, particularly those that are subjected to harsh weather and deicing agents [4]. Sustainable development is thought to be possible through green development [5,6], and green concrete is quickly becoming a must-have trend in cement-based composite materials. RPC in general demands high cement content and fine quartz sand, which raises the cost of building and releases a large quantity of carbon dioxide (CO_2) into the atmosphere. RPC can be produced with less peak hydration heat, less construction cost, and less carbon emissions by replacing some of the cement with industrial by-products like fly ash, silica fume, slag powder, and other active mineral admixtures. In addition, it can be produced with enhanced microstructure, strength, impermeability, and corrosion resistance [7–9]. Yazcl et al. [10] investigated the fundamental mechanical characteristics of fly ash and granulated blast furnace slag RPC under various curing circumstances. The outcomes demonstrated that while autoclaved pressure and steam curing enhanced RPC's hydration process and compressive strength, they reduced the material's flexural strength and toughness. Additionally, adding more slag and fly ash can increase the RPC's toughness and compressive strength while lowering shrinkage and deformation. Al-Hassani et al. [11] examined the mechanical characteristics of RPC. These qualities included tensile strength, flexural strength, modulus of elasticity, and compressive strength. The primary research parameters included the use of various types of superplasticizers, steel fiber volume fraction, and silica fume content (SF) as a partial replacement of cement. These variables' impact on the RPC's characteristics was investigated. The experimental findings demonstrated that while tensile strength increased relatively less, compressive strength increased significantly when (SF) content increased from 0% to 30%. There is a noticeable increase in tensile strength but only a minor increase in compressive strength when steel fibers are implied. According to Kushartomo et al. [12], glass powder was a suitable substitute for quartz powder in RPC in this study. 136 MPa is the highest compressive strength value that can be obtained in this study for the RPC with a 20% glass powder content. By using various mix designs under different curing conditions, Mostofinejad et al. [13] investigates the compressive strength of non-steel microfiber reinforced RPC in an effort to identify the ideal practical conditions and parameters that would result in maximum RPC compressive strength. The specimens' compressive strength increased significantly by approximately 174% as a result of the eight-step procedure used in that study, as demonstrated by the increase from 85 MPa (28 days) to 233 MPa (13 days). Additionally, several curing treatment strategies were used. The combined curing treatment for three days of autoclave curing treatment at 125°C followed by seven days of heat cure treatment at 220°C-revealed superior mechanical properties at the shortest curing time and was found to be more effective. According to Ge et al. [14], when silica fume, slag powder or fly ash is used in place of up to 25% or 30% cement, respectively, RPC can achieve high strength, low water absorption, improved economy, and environmental protection.

1.2 Research significance

The properties of RPC that incorporate different industrial byproducts to lower construction costs and carbon emissions need to be thoroughly studied in order to achieve an affordable and sustainable development. This study looks into how various parameters affect the properties of locally cast reactive powder concrete (RPC). Workability, compressive strength, tensile strength, and flexural strength tests were examined to evaluate the effective parameters, which include the volume of binder content ratios (60, 55%, 50%, and 45%), water-binder ratio (20%,25%, and 30%), and replacement ratios of fly ash FA (0%,10%, 20%, and 30%) and silica fume SF (0%,10%, 20%, and 30%). The second part of the study compared the mechanical characteristics of high strength concrete (HSC) and reactive powder concrete (RPC).

2. Experimental programs

2.1. Raw Materials

In this study, cement, silica fume, fly ash, quartz sand, crushed quartz, superplasticizer, and water were the components employed to produce locally RPC mixtures.

2.1.1. Cement

The Suez factory supplied Ordinary Portland cement CEM.I 42.5 N, which was employed in this experiment to create the OPC concrete examples. There are no hard lumps in the cement, and its color is consistent. The typical physical and chemical characteristics meet Egyptian Standard Specification ES4756-1:2022.

2.1.2. Fly Ash

The most common additional cementitious material used in concrete is fly ash. It is produced as a byproduct of burning pulverized coal in power plants. The fly ash Type F utilized in this study was purchased in Egypt by the Sika Company. Table 1 shows the properties of fly ash according to manufacture data.

Table (1) Characteristics of Fly Ash

Composition	Alumina Silicate
Colour	Light grey colour
Specific density	≈ 2.13
Bulk density	300 kg/m^3
Particle shape	Spherical

2.1.3. Silica fume

Silica fume is a waste material utilized as a pozzolan. The silica fume utilized in this study was distributed in Egypt by the Sika Company. Table 2 shows the properties of silica fume.

Table (2) Characteristics of Silica Fume

Composition	A latently hydraulic blend of active ingredients
Colour	Grey colour
Specific density	≈ 2.20
Bulk density	320 kg/m^3
Particle shape	Spherical (extremely small particles)

2.1.4. Quartz Powder

The El-Hashem for Minerals & Quartz Materials Company in Egypt provided the quartz powder used in this study, which had a mean particle size of 10 to 15 μm and specific gravity of 2.65. Table 3 lists the chemical composition of quartz powder according to the supplier.

Table (3) Quartz Powder Chemical Analysis

Oxides	Min %	Max %
SiO_2	99.4	99.6
Al_2O_3	0.06	0.09
Na_2O	0.05	0.07
K_2O	0.01	0.02
CaO	0.02	0.09
MgO	0.03	0.03
Fe_2O_3	0.012	0.018
TiO_2	0.017	0.021
Cr_2O_3	2ppm	2ppm
L.O.1	0.15	0.25

2.1.5. Quartz Sand

The El-Hashem for Minerals & Quartz Materials Company in Egypt provided the quartz sand with particle sizes smaller than 2.36 mm, which is used to create RPC. There are three distinct gradations that range in size from 1.18 to 2.36 mm and a specific gravity of 2.65.

2.1.6. Superplasticizer

In the study, Sika ViscoCrete-3425 was used from Sika Company in Egypt. Sika ViscoCrete-3425 is a third-generation superplasticizer for homogenous concrete and mortar. It meets the requirements for superplasticizers according to ASTM-C 494 Types G and F and BS EN 934 Part 2: 2001. The properties of superplasticizer are given in Table 4 according to the manufacturer.

Table (4) Technical Data of Superplasticizer

Base	Aqueous solution of modified polycarboxylates
Appearance/Colour	Clear liquid
Density	1.08 kg/It (ASTM C494)
PH Value	4.0
Solid content	40% by weight.

2.1.7. Aggregate

In this study, high-strength concrete was set up to compare the difference in mechanical properties between RPC and HSC. Unlike RPC, HSC uses crushed, graded, hard dolomite as a source of coarse aggregate. The fine aggregate source of choice was river sand.

2.1.7.1. Fine aggregate

Natural silica sand was used as a fine aggregate in the high-strength concrete mixes. It was nearly pure and uncontaminated. Sand was first sieved through a 4.75-cm sieve to remove any particles larger than that size. The used sand has a fineness modulus of 3.00. The characteristics of the used sand are listed in Table 5.

Table (5) Characteristics of Fine Aggregate

Property	Test Result
Specific gravity	2.65
Volumetric weight (kg/m3)	1660
Voids ratio	35%
Fineness modulus	3.00
Clay, silt and fine dust (by weight)	1.4%

2.1.7.2. Coarse aggregate

Crushed-grade hard dolomite was used in the concrete mix through the experimental study. The maximum size of dolomite is 3/4" (1.9 cm). The overall form was sub-angular and angular, with a uniformly rough surface free of unwanted impurities. Table 6 presents the properties of the used crushed dolomite.

Table (6) Coarse Aggregate Characteristics

Property	Test Result
Type	Crushed
Specific gravity	2.65
Volumetric weight (kg/m3)	1500
Total water absorption	1.6%
Fineness modulus	6.90

2.1.8. Water

For mixing and curing, pure drinking water that was free of contaminants was used. There were no pollutants, organic materials, silt, oils, sugars, or acidic materials in the water.

2.2. Mixture Proportion

Mixtures with a total of 19 mixtures (17 RPC mixtures and 2 HSC mixtures) were examined in order to fulfill the objectives of the present study. RPC mixture proportions are shown in Table 7, while HSC mixture proportions are shown in Table 8. The first group contains a mixture prepared with silica fume as supplementary cementitious material, while the second group contains a mixture prepared with fly ash as supplementary cementitious material. Mix design parameters were gradually altered in order to assess the impact of mixture content on RPC properties. The effective parameters are the volume of binder content ratio (60%, 55%, 50%, and 45%), water-binder ratio (20%, 25%, and 30%), replacement ratios of fly ash FA (0%, 10%, 20%, and 30%), and silica fume SF (0%, 10%, 20%, and 30%). In all the mix proportions, the quartz powder to quartz sand ratio was 0.2 and the water reducer content ratio was 2% of the binder content. The water reducer kept constant for all RPC to be able to check the effect of the water ratio on the properties of the RPC mixtures and eliminate its effect on the workability of mixtures. The ID abbreviations in Table 7 show the volume of binder content, the water-to-binder ratio, the types of admixtures, and the proportion of cement substitution. For example, the specimen that has 60% volume of binder, a 0.25 water-binder ratio, and 20% silica fume as supplementary material is expressed as 0.60BC-0.25W-0.20SF. Mixture No. 5 and Mixture No. 15 are the same as their supplementary content is 0% (plain RPC mixture without SF or FA). The amount of each component in the mixture was calculated using the absolute volume method.

2.3. Mixing, Casting and Curing Procedures

A mixer with a 120-liter capacity, spinning at roughly 50 revolutions per minute as presented in Figure 1, was used to carry out the mixing procedure. After the mixture's components were carefully weighted, cement and sand were mixed together to form a homogenous mixture. Fly ash or silica fume was added to the mixture. The water and the superplasticizer mixed together. The dry contents in the mixer are combined with the water and superplasticizer, and the mixture is mixed until it reaches the proper consistency to be cast (mixing times vary depending on the components of the mixture).

The specimen molds were thoroughly cleaned, well-assembled, and checked for dimensional accuracy before being placed. The molds are shown in Figure 2. Before casting, the forms were lightly coated with oil to facilitate the specimens' easy removal from the mold. Three layers of casting were used for the specimens. Following the process of compaction, the extra concrete was removed; Figure 3 shows the specimens after casting. After casting, specimens were demolded 24 hours later, and the specimens underwent standard curing in water at a temperature of approximately 25 °C. The specimens were removed from the water at the time of testing. Every specimen was cured in the same curing tanks to ensure uniform curing.

Fig. (1) Mixing Machine.

Fig. (2) Specimen Molds.

Fig. (3) Specimen after casting.

Table (7) RPC Mixtures Proportion.

Group	Mix No.	ID	W / B	Volume of Binder Content (C+SF or FA+W) %	Cement (Kg/m3)	SF / Cementitious material %	FA / Cementitious material %	Volume of Quartz Ratio (QS & QP) %	QP / QS %	Superplasticizer / Binder %
G1-SF	01	0.60BC-0.25W-0.20SF	0.25	60	782.6	20	0	40	20	2
	02	0.55BC-0.25W-0.20SF	0.25	55	717.4	20	0	45	20	2
	03	0.50BC-0.25W-0.20SF	0.25	50	652.2	20	0	50	20	2
	04	0.45BC-0.25W-0.20SF	0.25	45	586.9	20	0	55	20	2
	05	0.60BC-0.25W-0.00SF	0.25	60	1024	0	0	40	20	2
	06	0.60BC-0.25W-0.10SF	0.25	60	900.5	10	0	40	20	2
	07	0.60BC-0.25W-0.30SF	0.25	60	669.8	30	0	40	20	2
	08	0.60BC-0.20W-0.20SF	0.2	60	852	20	0	40	20	2
	09	0.60BC-0.30W-0.20SF	0.3	60	723.6	20	0	40	20	2
G1-SF	11	0.60BC-0.25W-0.20FA	0.25	60	782.6	0	20	40	20	2
	12	0.55BC-0.25W-0.20FA	0.25	55	717.4	0	20	45	20	2
	13	0.50BC-0.25W-0.20FA	0.25	50	652.2	0	20	50	20	2
	14	0.45BC-0.25W-0.20FA	0.25	45	586.9	0	20	55	20	2
	15	0.60BC-0.25W-0.00FA	0.25	60	1024	0	0	40	20	2
	16	0.60BC-0.25W-0.10FA	0.25	60	900.5	0	10	40	20	2
	17	0.60BC-0.25W-0.30FA	0.25	60	669.8	0	30	40	20	2
	18	0.60BC-0.20W-0.20FA	0.2	60	852	0	20	40	20	2
	19	0.60BC-0.30W-0.20FA	0.3	60	723.6	0	20	40	20	2

Table (8) HSC Mixtures Proportions

Group	Mix No.	ID	w/b	Cement (Kg/m3)	SF / C %	FA / C %	Coarse Aggregate (Kg/m3)	Fine Aggregate (Kg/m3)	Superplasticizer/ Binder%
HSC	10	HSC-SF	0.3	475	10	0	1290	485	2
	20	HSC-FA	0.3	475	0	10	1290	485	2

2.4. Testing methods

2.4.1. Fresh concrete test

The flow test (T500), according to BS-EN-12350-8, is a method for measuring the workability and fluidity of fresh concrete. It is particularly useful for reactive powder concrete. The test involves placing a concrete sample in a slump cone and then measuring the time it takes for the concrete to spread out to a diameter of 500 mm. The flow test (T500) value indicates the concrete's workability. The procedure for the test is shown in Figure 4. For high strength concrete mixtures, a slump test was executed according to ECP-203 to measure the consistency of the high strength concrete.

Fig. (4) Flow Test (T500) Procedures.

2.4.2. Test of mechanical properties

2.4.2.1. Compressive strength test

The compressive strength test was carried out to determine the compressive strength of specimens of concrete cubes. A 2000 KN capacity compression testing machine was used. The compressive strength of RPC was tested using cube specimens (70x70x70 mm). This test was conducted according to ECP-203 at the ages of 7 and 28 days, and for each age, three specimens were prepared. Figure 5 (a) shows the compression test setup.

2.4.2.2. Tensile strength test

Using cylindrical RPC specimens, an indirect tension test (splitting method) was used to determine the tensile strength of concrete mixes according to ECP-203. A compression testing machine with a 2000 KN capacity had been used. The three prepared cylindrical specimens (150 mm in diameter and 100 mm in height) were tested for 28 days. Figure 5 (b) shows the tensile test setup.

2.4.2.3. Flexural strength test

This test method uses a flexure testing machine with a 50 KN capacity to determine the flexural strength of the prismatic specimens. The flexural strength at age of 28 days was measured using three prism specimens (70 x 70 x 500 mm). The flexural test setup according to ECP-203 is shown in Figure 5 (c).

(a) Compression Test (b) Tensile Test (c) Flexural Test

Fig. (5) Test Devices for Mechanical Properties.

3. Result and Discussion

The experimental results for workability, compressive, tensile, and flexural strength were covered in this section. The RPC results of flow test T500, compressive strength, tensile strength, and flexural strength are shown in Table 9, while HSC mixture results are shown in Table 10.

Table (9) RPC Mixtures Results.

Group	Mix No.	ID	Flow Test T500 (sec)	Compressive Strength (MPa)		Tensile Strength (MPa)	Flexural Strength (MPa)
				7 Days	28 Days		
G1-SF	01	0.60BC-0.25W-0.20SF	10.5	69.4	102.1	8.5	14.7
	02	0.55BC-0.25W-0.20SF	11.0	63.8	93.6	7.7	12.7
	03	0.50BC-0.25W-0.20SF	11.5	60.2	89.8	7.2	11.6
	04	0.45BC-0.25W-0.20SF	13.0	55.6	80.9	6.6	10.9
	05	0.60BC-0.25W-0.00SF	9.0	55.7	86.5	7.1	13.7
	06	0.60BC-0.25W-0.10SF	9.5	59.2	91.2	7.8	14.0
	07	0.60BC-0.25W-0.30SF	13.0	57.9	86.8	7.3	13.0
	08	0.60BC-0.20W-0.20SF	12.5	72.6	94.3	7.7	13.9
	09	0.60BC-0.30W-0.20SF	9.0	54.8	82.8	6.8	11.4
G2-FA	11	0.60BC-0.25W-0.20FA	7.0	48.2	80.8	6.3	11.0
	12	0.55BC-0.25W-0.20FA	8.0	45.5	77.5	5.7	10.4
	13	0.50BC-0.25W-0.20FA	8.5	44.1	72.3	5.6	9.7
	14	0.45BC-0.25W-0.20FA	9.0	40.7	68.9	5.3	9.5
	15	0.60BC-0.25W-0.00FA	9.0	55.7	86.5	7.1	13.7
	16	0.60BC-0.25W-0.10FA	8.5	51.3	82.9	6.7	11. 8
	17	0.60BC-0.25W-0.30FA	6.5	43.2	71.1	5.6	10.0
	18	0.60BC-0.20W-0.20FA	8.0	52.7	85.4	6.9	12.9
	19	0.60BC-0.30W-0.20FA	5.5	41.7	70.4	5.8	9.9

Table (10) HSC Mixtures Results.

Group	Mix No.	ID	Slump Test (mm)	Compressive Strength (MPa)		Tensile Strength (MPa)	Flexural Strength (MPa)
				7 Days	28 Days		
HSC	10	HSC-SF	100.0	46.9	67.1	6.0	8.8
	20	HSC-FA	110.0	37.1	58.1	5.3	8.3

To determine the impact of the factors taken into consideration in this study, comparisons between the results of various mixes were made.

3.1. Effect of volume of binder content ratio

Figure 6 shows the effect of volume of binder content ratio on the workability of RPC for mixtures with silica fume and fly ash. As can be seen in Figure 6, when the volume of binder content ratio increases from 45% to 60%, the fluidity of the paste containing silica fume increases by 23.8%, compared to 28.6% for the mixture containing fly ash. This can be illustrated as an increase in paste volume means that there is more cement paste in the mix, this paste acts as a lubricant helping to coat and suspend the aggregate particles in the mix. More paste means more lubrication, which makes the mix easier to flow and fill voids while improving the fluidity of the paste.

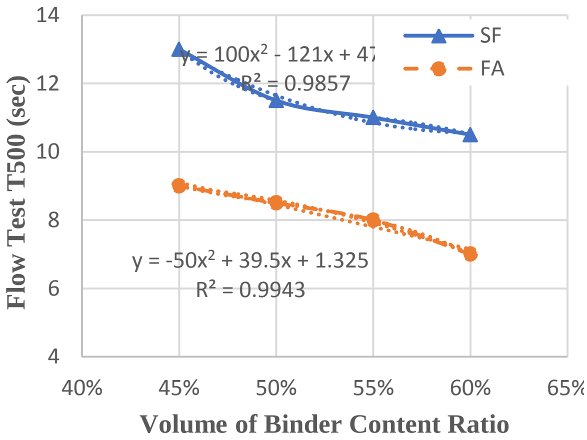

Fig. (6) Effect of Volume of Binder Content Ratio on the Workability of RPC.

Figure 7 shows the results of compressive strength at ages 7 and 28, flexural strength, and tensile strength for two groups (SF and FA), where each group has four mixtures with a volume of binder content ratio of 45, 50, 55, and 60%. In this case, the total water-binder ratio and the supplementary material ratio were kept constant. As shown in Figure 7 for the mixture containing silica fume, when the volume of binder content ratio increases from 45% to 60%, the compressive strength increases by 30.56% and 26.23% at age 7 and 28 days, respectively, and for the mixture containing fly ash, the compressive strength increases by 18.5% and 17.2% at 7 and 28 days, respectively. The flexural strength increases by 34.5% and the tensile strength increases by 28.42% for the mixture containing silica fume, while for the mixture containing fly ash the flexure and tensile strength increase by 16.12% and 17.26%, respectively. This means that regardless of the type of supplementary material used, the compressive, tensile, and flexural strengths are enhanced as the volume of the binder ratio increases. Also, the influence of silica fume on this enhancement is greater than that for fly ash.

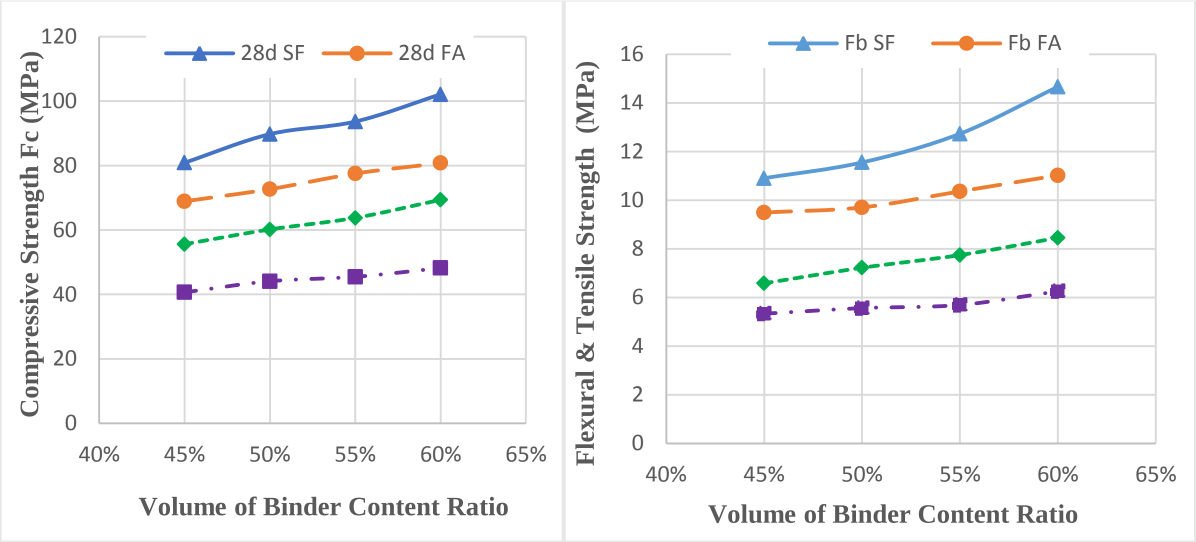

Fig. (7) Effect of Volume of Binder Content Ratio on Strengths of RPC.

3.2. Effect of water- binder ratio

Figure 8 shows how the water-binder ratio affects the fluidity of RPC for mixtures containing fly ash and silica fume. Figure 7 illustrates how the fluidity of the paste containing silica fume increases by 38.9% when the water-binder ratio rises from 20% to 30%, while it increases by 45.4% for the mixture containing fly ash. Water in RPC causes a water film to form on the cement particles, which helps to disperse the particles. Consequently, as the water-binder ratio increases, so does the thickness of the water film, which lowers particle friction and increases paste fluidity.

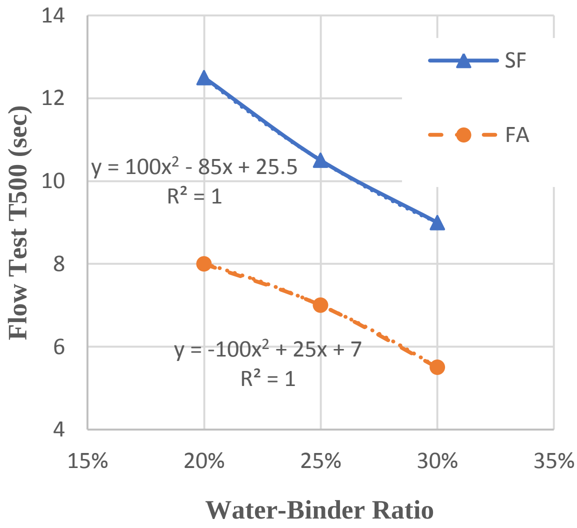

Fig. (8) Effect of Water- Binder Ratio on the Workability of RPC.

Figure 9 shows the results of compressive strength at ages 7 and 28, flexural strength, and tensile strength for two groups (SF and FA), where each group has three mixtures with a water-binder ratio of 20, 25, and 30%. In this case, the total volume of binder content and the supplementary material ratio were kept constant. As shown in Figure 9 for the mixture containing silica fume, it is seen that, with the increase of the water-binder ratio, the compressive strength at 7 days decreases, which is well known. However, the highest compressive strength, which is 102.1 MPa, was achieved with a water-binder ratio of 25% at 28 days, not a ratio of 20%. The maximum values of flexural and tensile strengths are 14.66 and 8.45 MPa, respectively, also found at a water-binder ratio of 25%. When the water-binder ratio increases from 25% to 30%, the flexural and tensile strengths decrease by 22.53% and 19.29%, respectively. This can be illustrated as the hydrated material's structure was negatively impacted by the unhydrated cement and silica in a low water-binder ratio of 20%. For the mixture containing fly ash the increase in the water-binder ratio led to a decrease in the compressive strength for the two ages 7 and 28 by 20.9% and 17.64%, respectively. Also, the flexural and tensile strengths decreased with the increases in the water-binder ratio, as the flexural and tensile strengths decreased by 23.29% and 16.21%, respectively, when the water-binder ratio increased from 20% to 30%. This can be illustrated as the fly ash has a lower water demand than that for the silica fume.

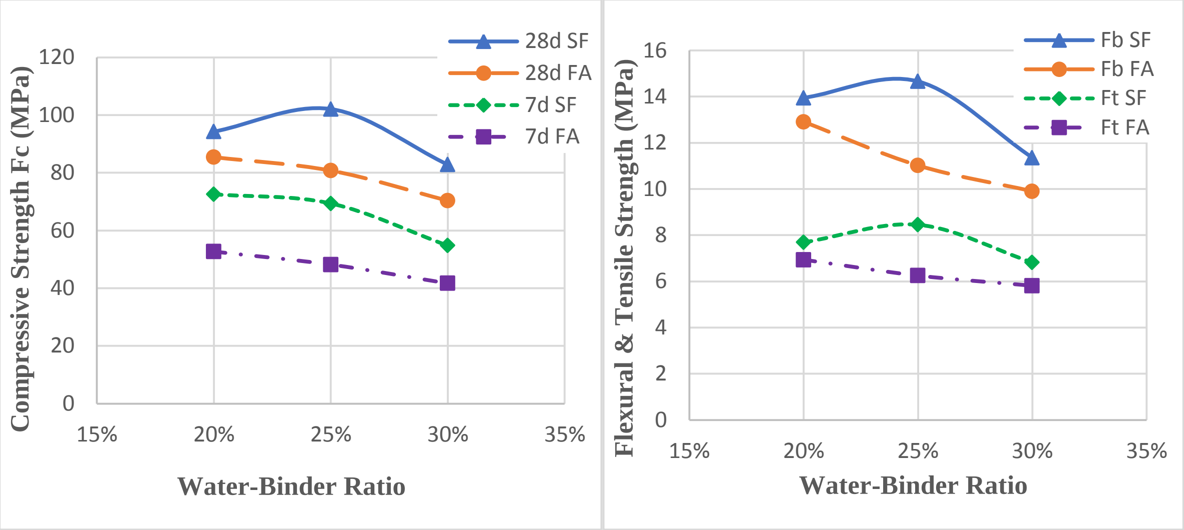

Fig. (9) Effect of Water- Binder Ratio on Strengths of RPC.

3.3. Effect of supplementary cementitious material type and ratio

Figure 10 shows how the supplementary cementitious material type and ratio affect the fluidity of RPC mixture. Figure 10 illustrates how the fluidity of the paste containing silica fume decreases by 45.5% when the silica fume replacement ratio increases from 0% to 30%, while it increases by 27.8% as the fly ash replacement ratio improves from 0% to 30%. Because silica fume particles are light and small, and because their specific surface area is larger than that of cement particles of the same mass, the excessive replacement of silica fumes with cement reduces the workability of RPC paste and raises the water demands for cementitious materials. Fly ash has a positive effect on workability; this is due to the spherical shape and smoother surface of fly ash particles, which require less water for lubrication and dispersing. Also, the spherical shape of fly ash particles can act as miniature ball bearings within the concrete mix, improving its flowability [15].

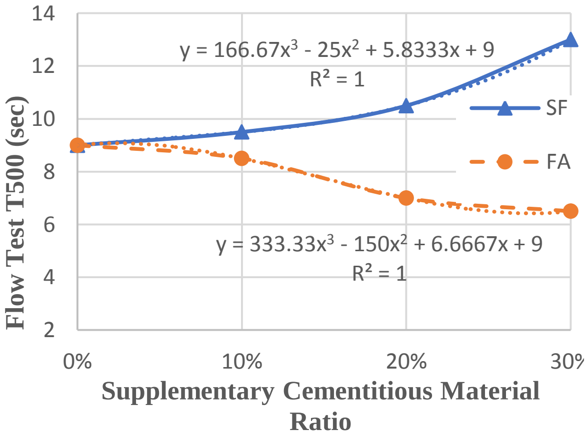

Fig. (10) Effect of Supplementary Cementitious Material Ratio on the Workability of RPC.

Figure 11 shows the results of compressive strength at ages 7 and 28, flexural strength, and tensile strength for two groups (SF and FA), where each group has four mixtures with a supplementary material ratio of 0, 10, 20, and 30%. In this case, the total volume of binder content and the water-binder ratio were kept constant. As shown in Figure 13 for the mixture containing silica fume, it is seen that the strength of RPC increases at first and then decreases with the increasing in replacement ratio. With the increase in the silica fume ratio, the strength reaches its maximum value when the replacement ratio is 20%. Comparing the strengths of specimens at 7 and 28 days, the compressive strength increased by 24.5% and 18.1%, respectively, when the replacement ratio increased from 0% to 20%. Also, the flexural and tensile strengths increased by 6.93% and 19.35%, respectively. The strength of RPC decreases when the replacement ratio increases from 20% to 30%. This is because, compared to cement with the same mass, silica fume has a larger specific surface area. Since the more specific surface area-to-volume of the components, the more water is required, using too much silica fume results in some of the components remaining unreacted, which increases the heterogeneity of the RPC content and weakens the microstructure, degrading the mechanical properties [13]. For the mixture containing fly ash the increase in the fly ash ratio from 0% to 30% led to a decrease in the compressive strength for the two ages 7 and 28 by 22.5% and 17.7%, respectively. Also, the flexural and tensile strengths decreased when the ratio of fly ash increased by 27.06% and 20.62%, respectively. This can be illustrated by the fact that, compared to cement, fly ash contributes less strength. Concrete containing FA hydrates slowly, leading to low compressive strength [16]. Fly ash mixes are slower in strength gain than concrete mixes; this indicated behavior may change if we study the strength after 56 or 90 days.

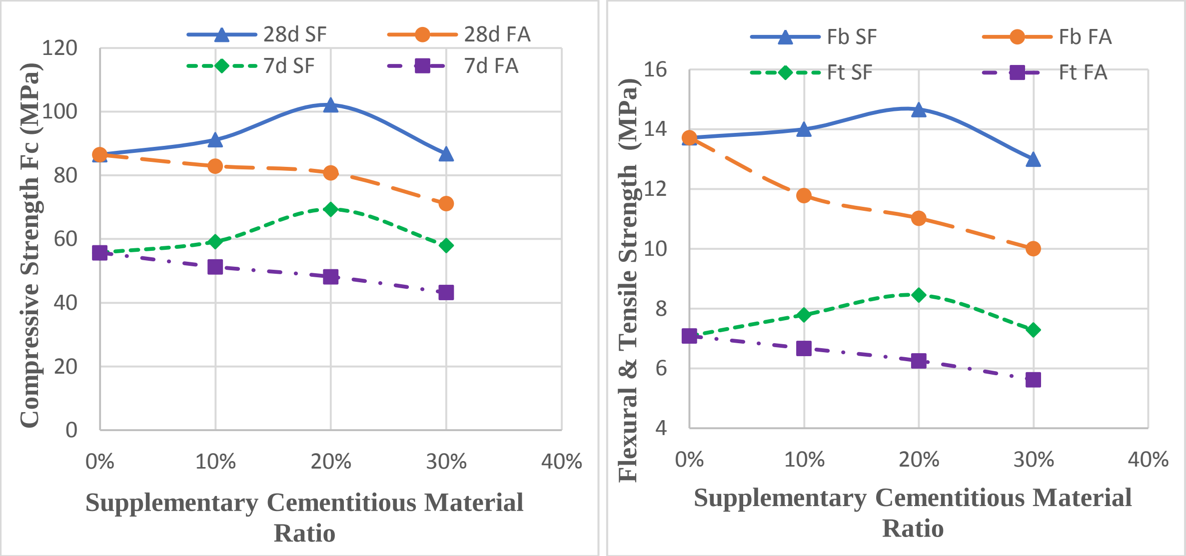

Fig. (11) Effect of Supplementary Cementitious Material Ratio on Strengths of RPC.

3.4. Effect of Silica Fume and Fly Ash on each of RPC and HSC

In order to compare the mechanical properties of RPC and HSC, two mixtures will be selected: mixture No. 06 (0.60 BC-0.25 W-0.10 SF) from the first group, which used silica fume as the supplementary cementitious material, and mixture No. 16 (0.60 BC-0.25 W-0.10 FA) from the second group, which used fly ash. Both mixtures have the same supplementary cementitious ratio of 10%, which is also used in HSC mixtures. The impact of applying fly ash and silica fume on the mechanical properties of RPC and HSC can be seen in Figure 12.

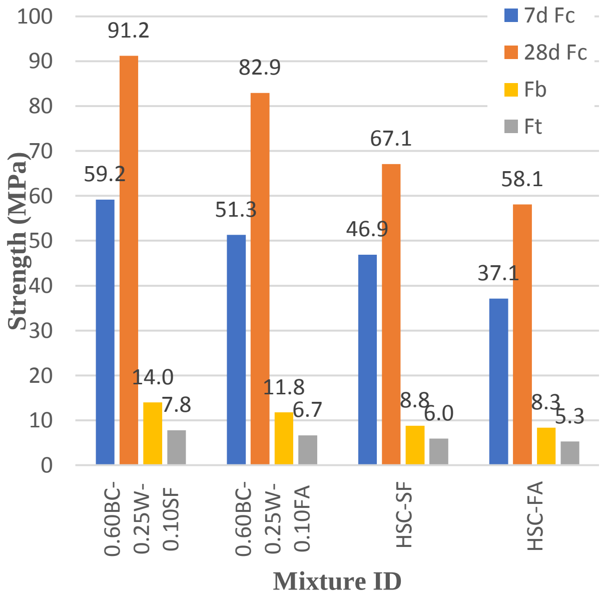

Fig. (12) Comparison of the results of the mechanical properties of RPC and HSC.

First, a comparison was made between the mixtures containing silica fume as cement replacement, as shown in Figure 12. The compressive strength of RPC at 7 and 28 days was 59.2 and 91.2 MPa, respectively, compared to 46.9 and 67.1 MPa for HSC. The compressive strength of RPC is greater than that of HSC by 26.23% and 35.92% for 7 and 28 days, respectively. Also, the flexural and tensile strengths of reactive powder concrete were 14.0 and 7.8 MPa, respectively, while those of HSC were equal to 8.8 and 6.0 MPa, respectively, which is much higher than the high-strength concrete by 59.1% and 30%, respectively. As shown in Figure 12, where the fly ash used as cement replacement had a compressive strength of 7 and 28 days, the flexural and tensile strengths of reactive powder concrete were higher than those of high-strength concrete by 38.3%, 42.7%, 42.2%, and 26.4%, respectively.

The mechanical properties of both HSC and RPC are improved by using silica fume in place of fly ash, as Figure 12 illustrates. For example, in the HSC mixture, the compressive strength increased by 26.4% and 15.5% for 7 and 28 days, respectively, and the tensile and flexural strength increased by 13.5% and 5.6%, respectively. Also, in the RPC mixture, the compressive strength increased by 15.4% and 9.9% for 7 and 28 days, respectively, and the tensile and flexural strength increased by 16.8% and 18.8%, respectively. While the use of silica fume in place of fly ash has a greater impact on compressive strength in the HSC mixture than the RPC mixture, it has a greater impact on tensile strength and flexural strength in the RPC mixture.

Conclusions

Based on the discussion above, the following conclusions can be made.

1. Increasing the volume of binder content and water-binder ratio improve the fluidity of RPC paste; fly ash contributes more to this improvement than silica fume does.
2. The strength of RPC is positively impacted by the volume of binder content, irrespective of the type of supplementary cementitious material used.
3. It is apparent that the water-binder ratio affects the mechanical characteristics of RPC, supporting the idea that a high water-binder ratio lowers RPC strength. The ideal water-binder ratio for a mixture that replaces cement with silica fume is 25%, while the ideal ratio for mixture with fly ash is 20%.
4. The 28-day strength of RPC decreased as the fly ash ratio increased from 0% to 30%, but the strength increased as the silica fume ratio increased up to a ratio of 20%.
5. The analysis of compressive strength results reveals that, when compared to mixtures containing fly ash and silica fume, respectively, RPC has a compressive strength that is 42.7% and 35.92% higher than HSC.

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