Research Article

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Mechanical properties of sustainable reactive powder concrete made with low cement content and high amount of fly ash and silica fume

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Abstract: Reactive powder concrete (RPC) is one of the distinctive kinds of concrete whose benefits are high mechanical performance and durability. It contains a high content of cement, which means a high amount of carbon dioxide emitted during manufacturing. Scientists have tended to search for a way to reduce environmental damage, and one solution is to partially replace cement with mineral admixtures, waste from other industries, or by-products. There are restricted studies involving the use of high content of compounding mineral admixtures in the making of RPC. Therefore, this research aims to produce sustainable RPC with a low cement content (50%). The main objective of this research is to study the impact of substituting cement with 50% of silica fume (SF) + fly ash (FA) on the mechanical characteristics of RPC. Three mixtures containing various percentages of SF + FA were poured, in addition to the reference mixture. Flowability, flexural and compressive strengths, ultrasonic pulse velocity (UPV), and density were examined. The results showed that a sustainable RPC can be produced by substituting the cement with 10% SF and 40% FA with an improvement in workability and compressive strength and an insignificant reduction in other properties.

Keywords: fly ash, mechanical properties, reactive powder concrete, silica fume, sustainability

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1 Introduction

Reactive powder concrete (RPC) is a kind of concrete recognized by its high mechanical performance [1]. The enhancement of modern material RPC was dependent on improving the homogeneity of particle size, microstructures, and porosity [2]. RPC consists mainly of cement, silica fume (SF), sand, superplasticizer, and water [3]. The water/binder of RPC is low (maybe less than 0.2). One of the determinants of the widespread use of RPC is its high initial cost as a result of containing a large amount of cementitious materials that may exceed 800 kg/m^3 [4,5]. In addition to the fact that this high amount of cementitious materials increases the cost of RPC, the high content of cement has a negative influence on the environment as a result of high carbon dioxide emissions during cement manufacturing [6]. Therefore, to reduce this environmental damage, researchers have resorted to find out substitutions to cement, including the use of mineral additives (*i.e.*, metakaolin, slag, fly ash (FA) and SF) [7–9], industrial by-products [10], or waste [11].

SF is considered one of the significant ingredients of RPC. Due to the high fineness and amorphous silica content, it improves the microstructure of RPC because of the reaction with calcium hydroxide (pozzolanic reaction) [12]. However, as a result of the limited available resources and their high cost, especially in developing countries, they restrict their application in modern construction, which prompted researchers to seek for alternatives with similar functions to replace SF [13]. FA is one of the commonly used SF alternatives in RPC [14]. FA has a significant function in enhancing the microstructure of RPC [15].

The use of FA in conjunction with SF in RPC production has been previously conducted by several researchers. For example, Ahmad *et al.* [16] partially replaced SF (its content was about 20% of the weight of the binder) with FA in RPC production. The replacement rates for SF were 40, 60, and 80%. The results showed that it is possible to replace SF with FA, where sufficient flow and strength were achieved. The results also indicated that the best substitution rate was 60% (or 40% SF + 60% FA). Gamal *et al.* [17] investigated the impact of using different replacement ratios of SF and FA (separately or combined) on the fresh and hardened properties of RPC. For combined mixtures, the SF replacement rate was fixed (10% of the weight of the cementitious materials) and the proportions of FA were within the range of 15, 20, and 25%. Normal and hot-water curing were applied. Results showed that the best performance was achieved after using 25% of SF or (15% FA + 10% SF). Moreover, using FA alone recorded a decrease in RPC properties compared to FA + SF or SF mixtures. Muhsin and Fawzi [18] searched the influence of using different percentages of FA (8, 12, and 16% of the weight of cement) on the properties of RPC. SF was used at a fixed rate for all mixes (10% of cement weight). The results revealed that the FA improved the flowability of fresh RPC. Moreover, the compressive strength was increased in the presence of FA. The optimum replacement rate of FA was 8%, which was recorded, at the ages 7, 28, and 90 days, respectively, with compressive strength values of 75.7, 96.5, and 115 MPa. Moreover, at this percentage, the tensile strength of RPC increased by 48.8% at the age of 28 days compared to the control mixture.

According to the above, there are restricted studies involving the use of high content of compounding mineral admixtures in the making of RPC. Therefore, this research aims to produce sustainable RPC with a low cement content (50%) by replacing it with different percentages of SF + FA combinations. The fresh and hardening properties of concrete are taken into account. It is believed that the use of the high content of by-products in RPC will participate not only to change them from do-nothing substances to other worthy materials, but will also contribute to reduce greenhouse gas emissions resulting from the cement industry by reducing its content in the mixture, thus reducing environmental damage and producing green RPC.

2 Materials and methods

The main components of the RPC mix that were employed in the current study included cement, fine aggregate, mineral admixtures, superplasticizer, and water. The cement conforms to Iraqi Standard No. 5 [19], and its chemical composition is illustrated in Table 1. As for the fine aggregate, natural sand was used. Table 2 presents the sieve analysis results for sand. SF and FA were utilized as mineral admixtures, a partial substitution for cement. Table 1 displays the chemical composition of SF and FA. The fineness and specific gravity of cement, SF, and FA were, respectively, 370 m^2/kg and 3.1, 21,000 m^2/kg and 2.3, and 420 m^2/kg and 2.12). A superplasticizer (Glenium 54 purchased from BASF company) conforming to ASTM C494 [20] was used to adjust the flowability of the fresh RPC. Tap water was employed for mixing and curing all the RPC mixtures.

Four mixtures were made in this study, three of them included replacing the cement with SF and FA, where each material was used at rates ranging from 10 to

Table 1: The chemical composition of cement, SF, and FA

Oxide	Content, %		
	Cement	FA	SF
SiO_2	22.1	50.5	90.2
CaO	62.1	10.8	0.65
Fe_2O_3	3.9	9.3	2.4
Al_2O_3	4.2	22.7	0.24
SO_3	1.9	1.5	0.4
MgO	3.3	1.2	0.41
Na_2O	—	1	0.16
K_2O	—	0.8	1.26
Loss of ignition	3.1	1.2	—
Free lime	0.7	—	—

Table 2: Sieve analysis and fineness modulus (FM) of the fine aggregate

Sieve No. (mm)	Passing, %
8 (2.36)	100
16 (1.18)	100
30 (0.6)	78.8
50 (0.3)	71.7
100 (0.15)	1.5
200 (0.075)	0
FM	2.48

40%, so that the total substitution rate remained constant at 50% of the cement weight. The fourth mixture (the reference mixture) was without any replacement. The details of RPC mixtures can be seen in Table 3.

The mixing method (adopted from [21]) was done by adding dry materials to a planetary mixer and running it for 1 min at 140 rpm, then adding water and superplasticizer, and operating the mixer for another 2 min, thereafter stopping the mixer for 10 min. After that, the ingredients were mixed at a fast speed of 285 rpm for 1 min. Immediately after mixing, the mortar flow was measured as described in ASTM C1437 [22], and then RPC was poured into standard molds (prisms with dimensions of 40 mm^3 × 40 mm^3 × 160 mm^3). The specimens were removed from molds after about 24 h and placed in water until testing age. For sustainability purposes, standard curing was adopted for all specimens. For the hardened specimens, the compressive and flexural strengths, ultrasonic pulse velocity (UPV), and bulk density tests were executed at 91st day (cured in water for 90 days). The flexural and compressive strength were calculated as described in BS EN 196–1 [23] using a compression device with a capacity of 350 kN. While the bulk density was calculated by dividing the mass of the samples by their volume [24], the UPV was measured using prismatic specimens (40 mm^3 × 40 mm^3 × 160 mm^3) [25]. The frequency of the UPV device was 55 kHz.

3 Results and discussion

3.1 Flow rate

Results of the flow rate of RPC mixes are shown in Figure 1 and Table 4. Results revealed that the inclusion of mineral admixtures improved the flow rate of fresh RPC. The enhancement of flow was boosted with the growth of FA content in the mix. The enhancement rates were 22.2, 78.7, and 80.2% for 40SF:10FA, 15SF:35FA, and 10SF:40FA mixtures, respectively. The reason for this is due to the reduction in the water requirements of the mixture as a result of the spherical shape of the FA granules [26]. The smooth surface of the FA granules of different sizes helped to lubricate the RPC mixture and thus improved the workability [27].

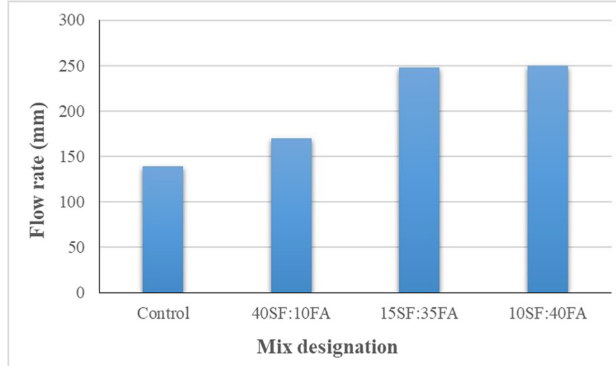

Figure 1: The flow rate results of fresh RPC.

3.2 Compressive strength

The compressive strength outcomes are displayed in Figure 2. It was observed from the figure that 40SF:10FA diminished the compressive strength slightly (2.2%) related to the control sample, while the strength declined by 17.7% for the 15SF:35FA mixture. The reason for compressive strength decreasing in these mixes may be that the pozzolanic activity and the filling impact could not recompense for the dilution influence resulting from reducing the cement content [28]. In contrary, the compressive strength was improved by 8% when the cement was replaced with 10% SF plus 40% FA. This enhancement for the mix containing high amount of FA can be attributed to those spherical granules of FA, which have densified the paste and improved the packing impact as a result of the balling effect [29].

Table 3: Mix proportion details of the RPC (kg/m^3)

Mix designation	Cement	SF	FA	Sand	Water	Superplasticizer
Control	1,125	0	0	1,125	214	28.125
40SF:10FA	563	450	112			
15SF:35FA	563	169	393			
10SF:40FA	563	112	450			

Table 4: The result values of all executed tests

Mix designation	Flow rate (mm)	Compressive strength (MPa)	Flexural strength (MPa)	Density (kg/m^3)	UPV (m/s)
Control	139	83.8	14.0	2410.2	4938.3
40SF:10FA	170	81.9	12.8	2259.1	4771.4
15SF:35FA	248	69.0	11.7	2279.9	4819.3
10SF:40FA	250	90.4	12.9	2276.0	4809.6

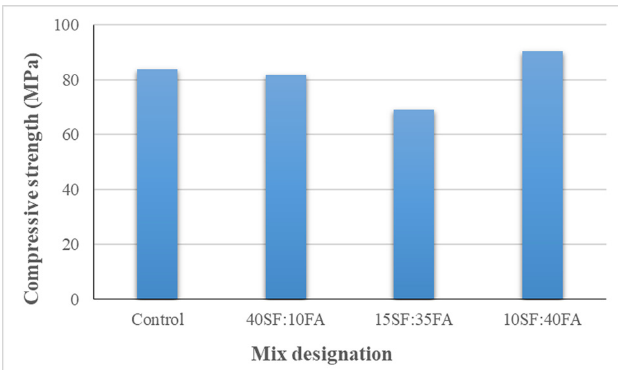

Figure 2: The results of compressive strength of RPC mixtures.

3.3 Flexural strength

The flexural strength is one of the important characteristics of concrete as it influences the structural design through its impact on shear resistance, deflection, and brittleness [30]. The results of flexural strength of RPC mixtures containing supplementary cementitious materials are illustrated in Figure 3. Results demonstrated that the high-volume FA and SF cause a reduction in flexural strength. The maximum reducing percentage was given by 15SF:35FA (which is also recorded as the lowest compressive strength). Otherwise, the 10SF:40FA indicated the minimum decline rate in flexural strength, which was lesser than the reference mix by 7.3%. When comparing the results of this mixture with the compressive strength test, it was noted that it enhanced the compressive strength, while it led to a decline in the flexural strength, although it recorded the lowest percentage of reduction compared to other mixtures. This may be because the flexural strength is more influenced by the structure of pores and the changes in the interfacial transitional zone than that for the compressive strength [31].

3.4 Bulk density

The results of bulk density test of RPC mixes are displayed in Figure 4. Results revealed that the replacement of cement with high volume faction of SF and FA causes a reduction in density values. The minimizing rates were 6.3, 5.4, and 5.6% for 40SF:10FA, 5SF:35FA, and 10SF:40FA, respectively. This decreasing in bulk density can be interpreted by the fact that the specific gravity of SF (2.3) and FA (2.12) is less than that of cement (3.1) as indicated in Section 2. Moreover, comparing with the UPV results, it is noticed that the largest decrease in the velocity was recorded in the mixture 40SF:10FA, while the least reduction was recorded in the mixture (15SF:35FA), which is similar to the behavior of the density results. This behavior is expected because the velocity is affected by the

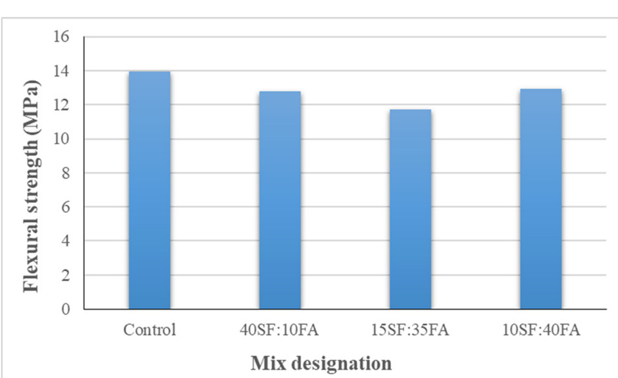

Figure 3: The flexural strength results of RPC mixes.

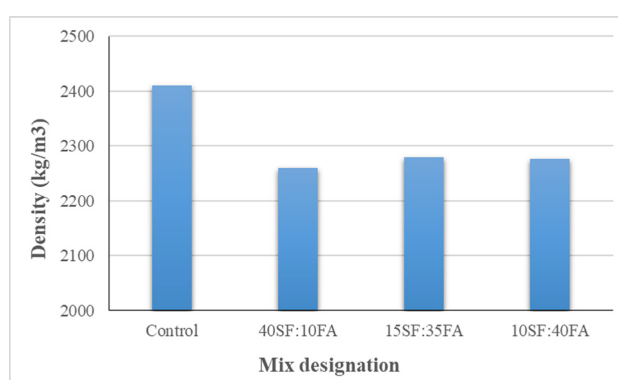

Figure 4: The bulk density results of RPC.

presence of voids within the sample, which in turn, also affects the density.

3.5 UPV

Ultrasound pulse velocity is one of the common non-detrimental mechanisms used to evaluate the homogeneity of concrete as well as to qualitatively assess the compressive strength of existent structures [32]. The UPV is affected by the density of the materials used and its elasticity modulus, in addition to the mechanical properties of concrete, so it can be used to monitor the uniformity and quality of concrete [32,33]. The UPV results are shown in Figure 5. It was found that the use of 50% mineral admixtures did not cause an important drooping in UPV compared to the reference sample. The maximum reducing percentage was recorded by 40SF:10FA which was lesser than the reference sample by 3.4%. The UPV decline rates of 5SF:35FA and 10SF:40FA mixes were, respectively, 2.4 and 2.6%. It has been stated in the previous work [34] that high-speed values indicate the good durability of concrete. The UPV values for RPC mixtures in the current study were within the range of 4,771–4,938 m/s which are higher than the limits (3,660–4,575 m/s) set by the literature [35] for the excellent quality concrete.

4 Conclusion

According to the findings gained in the current experimental study, the following conclusions are deduced:

1. The simultaneous use of SF and FA in a high amount improved the flowability of fresh RPC by about 22–80% compared to the free-replacement mix.

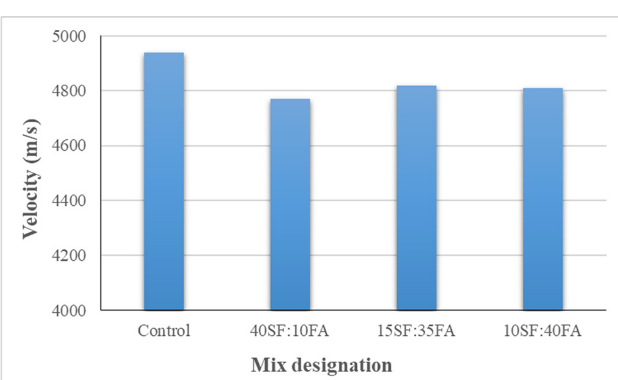

Figure 5: The UPV results of RPC mixes.

2. Replacing 50% of the cement with 10% SF and 40% FA can improve the compressive strength of the RPC by 8%. While the use of 40% SF + 10% FA and 15% SF + 35% FA caused a decline in the compressive strength by about 2 and 18%, respectively.
3. The combined use of SF + FA decreased the flexural strength by about 7% (for 10SF:40FA) to 16% (for 15SF:35FA) related to the control sample.
4. The replacement of cement with 50% SF and FA reduced the UPV values slightly, while the bulk density was reduced by no more than 6.3%.
5. In summary, green RPC made by replacing cement with 10% SF + 40% FA can be produced with an improvement in workability and compressive strength, and a slight decrease in other properties (flexural strength, density, and UPV).

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