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Utilization of High Volume Fraction of Binary Combinations of Supplementary Cementitious Materials in the Production of Reactive Powder Concrete

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Abstract

The reactive powder concrete (RPC) is one of the special concrete types that characteristics with high cement content which means high production cost and CO_2 emissions to the atmosphere. Therefore, to enhance the environment as well as to develop green RPC, alternatives to cement, such as supplementary cementitious materials (SCMs) were used. Limited studies addressed the use of a high volume fraction of SCMs as a binary combination in the production of RPC. Thus, this study aims to replace a high percentage of cement (50 %) with binary combinations of silica fume (SF), type F fly ash (FA) and metakaolin (MK). The experimental program included two phases. In phase one, two groups (SF + FA and MK + FA) were cast without steel fibers. Based on group performance in the first phase, one group was chosen to be used with steel fibers in the second phase. The flow rate, compressive and flexural strengths, density, ultrasonic pulse velocity and dynamic modulus of elasticity tests were conducted. The phase one results showed that SF + FA combination mixtures had better performance than MK + FA mixtures thus they were selected to be used in the second phase (with the addition of 1 % volumetric fraction micro steel fibers). Results indicated that it is possible to produce sustainable RPC in which the cement can be replaced with 30 % SF and 20 % FA (the total replacement is 50 %) in the presence of 1 % steel fibers with a remarkable enhancement in compressive strength and flexural strength reached up to 44 % and 10 %, respectively.

Keywords

reactive powder concrete, cement replacement, supplementary cementitious materials, sustainability

1 Introduction

Reactive powder concrete (RPC) is developed through the improvement of the cementitious materials microstructure and is considered as a new generation concrete [1]. The combining of very low water content with particle packing enhancement lead the RPC to have a dense microstructure [2]. The homogeneity between the RPC ingredients is enhanced as a result of the omitting of coarse aggregate [3].

The excellent mechanical properties, dense microstructure and low permeability realize the reactive powder concrete as ultra-high performance concrete (UHPC) [1]. In comparison to conventional concrete, many advantages are provided by the ultra-high performance of RPC such as very high compressive strength (about four times of normal concrete), excellent durability, ductility and energy absorption. However, it has appointed weaknesses, where, the cement content is 800 – 1000 kg/m^3 which mean high production cost, shrinkage problems and heat of hydration [4] as well as high CO_2 emissions into the atmosphere [5]. The emissions of carbon dioxide from the cement industry represent about 7 % of global production [6, 7]. Thus, to reduce this environmental impact, the supplementary cementitious materials (SCMs) are used in the manufacturing of RPC [8]. Some of the SCMs used in the literature to replace the cement in the production of RPC were silica fume, fly ash,

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slag, rice husk ash and metakaolin [9]. However, how to produce UHPC with a high efficiency, based on the materials view, still requires additional investigaion [8].

The using of SCMs in the making of RPC was discussed by many researchers. For instance, Yazıcı et al. [10] studied the combined effect of silica fume with fly ash (FA) and/or ground granulated blast furnace slag (GGBFS) on compressive strength of RPC under autoclaved curing. Silica fume content was fixed at 26 % of the total binder weight. Results indicated that the compressive strength of RPC was reduced with the increasing of FA or GGBSF replacement level in comparison to that for control mixture (0 % of FA and GGBSF). However, up to 40 % FA or 60 % GGBSF replacement, the compressive strength remained over 200 MPa. Tafraoui et al. [11] used the metakaolin instead of silica fume in the manufacturing of UHPC. It was found that the compressive strength was decreased by 6.7 % while the flexural strength was increased by 2.6 %.

Steel fibers can be used in the production of RPC to enhance the flexural strength as well as to transform the failure behavior from brittle to ductile one [12]. Other mechanical properties can also be enhanced by the inclusions of steel fibers [13].

Different curing systems were used in the production of RPC such as standard (normal curing at 20°C), steam, heat and autoclave curing systems [14]. However, except for normal curing, all other curing systems consume high cost and energy, and consequently high impact on the environment.

Based on the above, limited studies investigated the high volume combinations of SCMs in the production of RPC. Thus, to reduce environmental impact by reducing the cement content as well as to develop green RPC, this study was performed. The main aim of this study is to investigate the effect of binary additions of silica fume, fly ash and metakaolin as cement replacement on the properties of RPC such as flow rate, compressive and flexural strength, density, ultrasonic pulse velocity and dynamic modulus of elasticity. For sustainable purposes, the total replacement percentage was fixed at 50 % of cement weight for all combinations. Micro steel fibers were used in a proportion of 1 % (by volume) to improve the mechanical performance of the RPC produced. Additionally, to reduce the energy consumed, the only standard curing (at 20°C) was depended.

2 Materials and methods

The materials used in the manufacture of RPC were lime cement (CEM II/A-L 42.5R), sand, silica fume (SF), fly ash (FA), metakaolin (MK), micro steel fibers (St), superplasticizer and water. The cement is in conformity with Iraqi specification No. 5/1984 [15]. The chemical composition of cement is shown in Table 1. Natural sand within the range (0.15–1.18 mm) as shown in Table 2 was employed as fine aggregate. The SF was purchased from BASF Company while the FA was purchased from DCP company. The MK was prepared by burning the kaolin (brought from Anbar province, west of Iraq) in a controlled oven at 700°C for one hour [16]. The physical and chemical properties of SF (which is conformed to ASTM C1240 [17]), FA and MK (which are conformed to ASTM C618 [18]) are illustrated in Table 3. The properties of SF are adopted from [19]. Where the same materials were used in this study. Steel fibers with 15 mm length and 0.2 mm diameter were added for some of the RPC mixes. The properties of the steel fibers are illuminated in Table 4. Superplasticizer called Glenium 54 conforms to ASTM C494 Type A and F [20] was used as workability adjuster.

The experimental program of this study included two phases. In the first phase, two groups of RPC mixtures (without steel fibers) were poured as follows:

- First group: in which the cement was replaced with three combinations of (SF + FA).
- Second group: in which the cement was replaced with three combinations of (MK + FA).

Table 1 The chemical composition of cement

Oxides	Content, %	Iraqi specifications (IQS NO.5), %
CaO	62.1	-
SiO_2	22.1	-
Al_2O_3	4.2	-
Fe_2O_3	3.9	-
MgO	3.3	< 5
SO_3	1.9	< 2.5
Free lime	0.7	-
L.O.I.	3.1	< 4
L.S.F.	0.86	0.66 – 1.02
Insoluble residue	1.1	< 1.5

Table 2 The grading of fine aggregate

Sieve opening (mm)	Accumulative passing, %
2.36	100
1.18	100
0.6	78.8
0.3	71.7
0.15	1.5

Table 3 The physical and chemical composition of silica fume, fly ash and metakaolin

Oxides	Content, %		
	Silica fume	Fly ash	Metakaolin
SiO_2	90.2	50.5	51.59
Al_2O_3	0.24	22.7	38.11
Fe_2O_3	2.4	9.3	1.82
CaO	0.65	10.8	0.45
MgO	0.41	1.2	0.23
SO_3	0.4	1.5	0.14
K_2O	1.26	0.8	0.43
Na_2O	0.16	1	0.11
TiO_2	0.02	0.7	---
L.O.I.	3.33	1.2	6.12
The physical properties			
Fineness (m^2/kg)	21000	420	16500
Chloride content (%)	< 1%	-	-
Activity index (%)	123	85	85

Table 4 Properties of steel fibers used

Property	Value
Tensile strength (MPa)	2600
Density (kg/m^3)	7800
Length (mm)	15
Diameter (mm)	0.2
Aspect ratio	75

Depending on the groups' performance in the first stage, one of the two groups was chosen to use it with steel fibers as a third group, in which the cement was replaced with three combinations of (FA + SF + St). Additionally, a mix without any replacement was cast as a control. Thus, A total of ten mixes were cast for this study.

The steel fibers, which were used in the second stage (third group), were added at 1 % by volume of the RPC. The total replacement for all combinations was fixed at 50 % by weight of cement. Each replacing material (SF, FA or MK) was used in proportions of 20 % or 30 %. The details of all considered mixes can be seen in Table 5.

A planetary mixer with two speed rates: low (140 revolutions per minute) and moderate (285 revolutions per minute) rates were utilized for mixing the fresh RPC according to the following steps:

- The dry materials were mixed at a slow speed (140 revolutions per minute) for one minute.
- The mixer was stopped and the whole amount of water and superplasticizer (which were previously mixed) were added.
- Then, all materials were mixed at a slow speed for two minutes.
- After that, the mixer was stopped for one minute and the speed was changed to the moderate (285 revolutions per minute) rate.

Thereafter, the RPC ingredients were mixed (final mixing) for ten minutes.

The above-mentioned procedure was depended for all RPC mixes, except for some MK-based mixes. The final mixing for 25MK:25FA was five minute rather than ten minutes. While the 30MK:20FA mixes were mixed without final mixing period (ten minutes). These mixtures were quickly wet after the addition of water and superplasticizer but soon became very sticky, so the mixing time was modified for these mixes. This fluidity reduction of MK-based mixtures can be attributed to the angular shape of MK particles as well as to the gap-graded particle size distribution [21]. Moreover, the increase of water demand of MK and the large quantity of MK in these mixtures together with the low water content in the mix could have an important effect.

After the end of the mixing, the fresh RPC was poured into standard metal molds in two layers and compacted using an electric vibrator. After 20–24 hours, the molds were removed and the samples were placed in the water tank at 20°C until the time of the test.

The tests adopted in this study were flow rate, compressive strength, flexural strength, density, ultrasonic pulse velocity (UPV) and dynamic modulus of elasticity. Prisms with dimensions of 40 × 40 × 160 mm^3 were used to examine the flexural strength using the following equation [22]:

$$F = \frac{1.5PL}{b^3}, \tag{1}$$

where; P is the ultimate load (N), F is the flexural strength (MPa), b is the cross-section dimension of the prism and L is the distance between supports (mm).

The broken parts (halves) under the flexural machine were used to examine the compressive strength. Three prisms were cast for each mix. Before testing the flexural strength, the density and UPV test were measured. The density was determined by dividing the weight of specimens on the prism dimensions. The dynamic modulus of elasticity was calculated, based on UPV, using the flowing equation [23]:

$$Ed = \frac{(1+\mu)(1-2\mu)}{(1-\mu)}\rho V^2, \tag{2}$$

where *Ed* is the dynamic modulus of elasticity (MPa); μ is the dynamic poisons ratio (taken as 0.2 in this study); ρ is the density (kg/m^3); and V is the velocity (m/s).

The hardened tests were performed at 91 days (see Fig. 1). An average of three readings was considered for each result.

3 Results and discussions

3.1 Flow rate results

Flow rate results of the fresh RPC mixtures are presented in Fig. 2. It was found that the SF + FA combinations improved the flowability of the fresh RPC (the flow rates were 43 %–74 % more than that for control mixture). The increasing percentage arose with the increasing of FA (or decreasing of SF) in the mixture. This behavior can be attributed to the water demand reducing caused by FA that leads to increasing the workability at constant water to binder ratio [24]. Additionally, Shi et al. [25] stated that the SF could improve the flowability of the fresh UHPC when present in the range 0 % to 22 %. Results also indicated that the addition of 1 % micro steel fibers did not have a significant effect on the flowability trend of the plain SF + FA mixtures. The flow rates remained higher than that for the control mixture by 42 % to 71 %. In contrary, the MK + FA RPC mixtures revealed a significant decreasing in flow rates, about 11 %–28 % relating to that for control mixture. The higher the MK content in the mix, the lower is the flow rate value. At 30 % MK content (30MK:20FA mix), no flow was measured. These results were in agreement with Cassagnabère et al. [26]

(a)

(b)

(c)

Fig. 1 Specimen under: (a) compressive strength test; (b) flexural strength test; and (c) UPV test

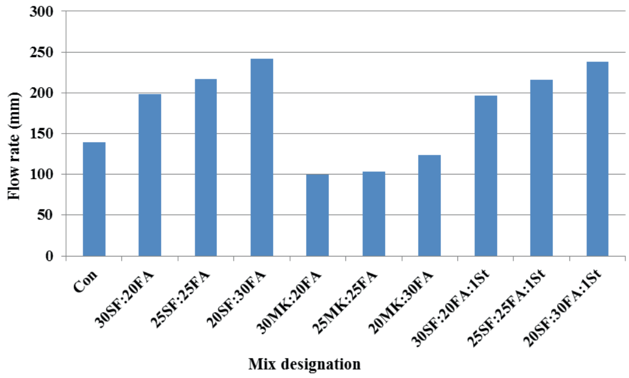

Fig. 2 Flow rate results of RPC mixtures

who recorded no slump for fresh mortar after 30 minutes of mixing when the cement is replaced with 25 % of MK. They attributed that behavior to the high surface area, high open porosity and irregular surface texture of the MK.

3.2 Compressive strength results

The compressive strength results of RPC are shown in Fig. 3. For control mixture, it can be seen that the compressive strength of the RPC produced was relatively low (< 90 MPa). This may be as a result of using only cement as a binder (without SCMs) in the mix, in addition to the using of normal curing for the hardened specimens (at 20°C). Similar results for the RPC were also recorded in the literature [14].

It can be seen from Fig. 3 that, for fibers-free mixtures, the compressive strength of RPC mixes containing cement replacements had lower values than conventional RPC. The reduction rates were 10 %, 18 % and 31 % for 30SF:20FA, 25SF:25FA and 20SF:30FA mixes, respectively. Similar results were also found in the literature [27]. For MK + FA combinations, the compressive strength values were diminished by 69 %, 62 % and 48 % for 30MK:20FA, 25MK:20FA and 20MK:30FA mixtures respectively. It can be observed that, for both combinations types (SF + FA and MK + FA), the reduction percentages were increased with the increasing of FA (or decreasing of SF and MK) in the mix. This diminishing can be attributed to the low pozzolanic activity and the dilution effect of FA [28]. Moreover, relating to the control mixture, it can be noticed that the average detraction rates of SF + FA combinations were much lesser than those for MK + FA combinations. This behavior is due to the higher pozzolanic activity index of SF (125 %) compared to MK (85 %), as shown in Table 3, together with the lower density of MK + FA mixtures compared with SF + FA mixtures as confirmed by the density results of the present study.

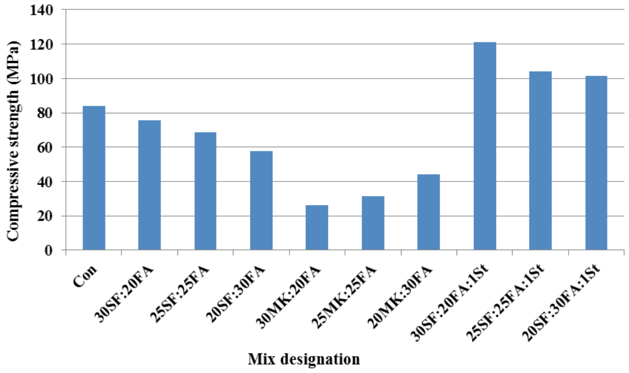

Fig. 3 Compressive strength of RPC mixtures at 91 day

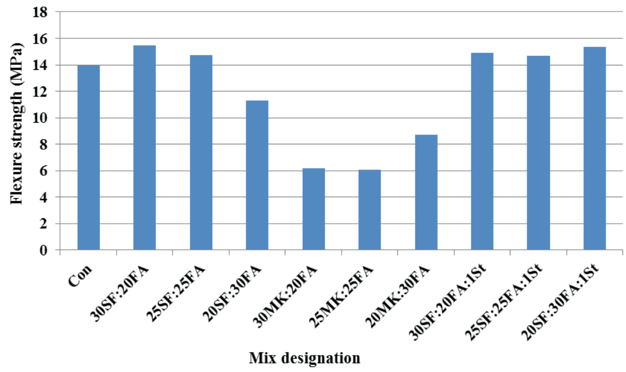

Fig. 4 Flexural strength of RPC mixtures at 91 days

According to above, it can be concluded that though those mixtures incorporated a high volume fraction of SCMs showed lower compressive strength than the control mixture, the SF + FA combinations mixtures revealed better performance than MK + FA mixtures. Therefore, the only SF+FA based mixtures were selected to be used with steel fibers in the second stage of this investigation.

Results of steel fiber containing mixtures indicated that the presence of 1 % micro steel fibers performed better compressive strength values than those for the control sample. It can be seen clearly from Fig. 3 that the 30SF:20FA:1St combination folded higher improvement in the presence of steel fibers. The enhancement rate was 44 % (or 121 MPa). This positive impact of steel fibers shows its ability to delaying the formation of micro-cracks [29]. These results are in agreement with Wu et al. work [30] who found that the presence of 1 % straight steel fibers increased the compressive strength of UHPC from 105 MPa (for plain concrete) to about 150 MPa (the enhancement rate was about 43 %) at 90 days.

3.3 Flexural strength results

Fig. 4 presents the flexural strength results of RPC mixtures. Results of SF + FA combinations revealed that the flexural strength was increased by 10 % and 5 % for 30SF:20FA and 25SF:25FA mixtures respectively. However, the 20SF:30FA mix decreased the flexural strength by 19 % compared to the reference mixture. As for compressive strength, the flexural strength declined with the increasing of FA in the mix. On the other hand, the flexural strength values of MK + FA combinations were reduced by 38 %–57 % relating to the conventional RPC. This reduction can be returned to the low binding properties of FA [31]. Comparable results for the FA concrete were obtained previously [32]. Atiş and Karahan [33] stated that the using of 15 % and 30 % FA as cement replacement decreased the flexural tensile strength of concrete by 10 % and 20 % respectively compared to plain concrete. Additionally, they recorded similar findings in the presence of steel fibers.

In the presence of steel fibers, results demonstrated that the flexural strength values were improved by 5 %–10 % for all SF + FA combinations compared to reference concrete. It can be noticed that for 20SF:30FA mix, the reduction in flexural strength was recovered after incorporating 1 % steel fibers. This improvement in flexural strength is attributed to the role of steel fibers in bridging the cracks and restricts their propagation which leads the flexural strength to be increased [34]. Furthermore, it can be observed that, in the presence of steel fibers, the improvements in compressive strength were more than that for flexural strength. It should be taken into account herein that the mechanism by which the steel fibers affect the concrete strengths is governed by several parameters such as fiber characteristics (i.e. fiber content, elastic modulus, volume percentage and fibers ponding properties) and concrete properties (i.e. strength and elastic modulus) [35]. Moreover, the flexural strength is greatly influenced by the fibers orientation (in the direction of tensile stress) and distribution within the matrix [36]. Therefore, according to the foregoing, and because the properties of the fibers, as well as their ratio, were fixed in the mixtures, it seems that the reason for the significant increase in the compressive strength compared to the flexural strength may be that the distribution and orientation of the fibers in the mixtures were not sufficient enough to raise the flexural strength by a high rate. However, other extensive studies must be done to better understand this situation.

3.4 Density results

Results of the density of RPC mixtures are shown in Fig. 5. In general, the density of all mixtures containing SCMs were lesser than that for the control sample. The reduction rates were within the range 4 %–5 % for SF + FA combinations and 6 %–7 % for MK+FA combinations. While in the presence of 1 % steel fibers, the density values were lower than the reference mix by 3 %–5 %. These results are supported by Demirboğa [37] work who reported that the concrete density is reduced as a function of mineral admixtures. It can be seen from Fig. 5, that MK based mixtures had the higher reduction rates among other combinations which may be due to the low plasticity of these mixes as a result of high percentage of MK (as confirmed in flow rate results) that led to low compactness of the fresh RPC and consequently high entrapped air.

3.5 UPV and dynamic modulus of elasticity results

The UPV is a non-destructive method can be used to evaluate the properties and the quality of concrete. It measures the time transmitted through the substance. Based on the sound transmission theory of solids, the velocity of the sound transfer is the function of the modulus of elasticity and density of the material [38]. The UPV results of RPC mixtures are illustrated in Fig. 6. It can be observed from the figure that for the control mixture and all other binary combinations, except for 30MK:20FA and 25MK:20FA, had UPV value higher than 4.5 km/s, the limit of good quality concrete [39]. However, results demonstrated that mixes incorporated binary combinations of SF, FA and MK had lower UPV values than that for reference specimens. A slight decline (2 %–5 %) was recorded for SF + FA combination mixtures even in the existence of steel fibers. However, the UPV values were reduced by 14 %, 10 % and 8 % for 30MK:20FA, 25MK:20FA and 20MK:30FA mixtures respectively. As obviously noticed, the velocity value increased as the MK content decreased in the mix. The lower density as a result of higher air voids of MK + FA mixtures (as proved in density results) can interpret this behavior.

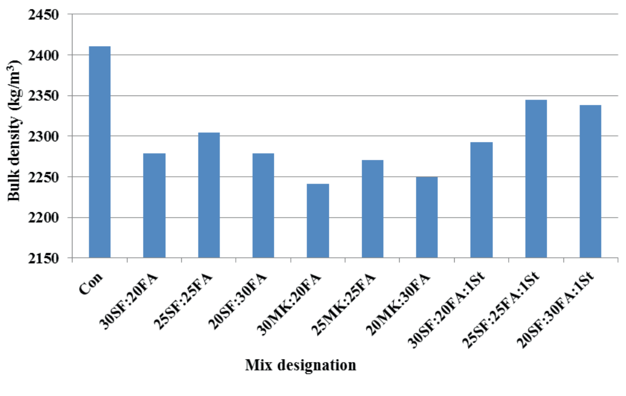

Fig. 5 Density of RPC mixtures at 91 days

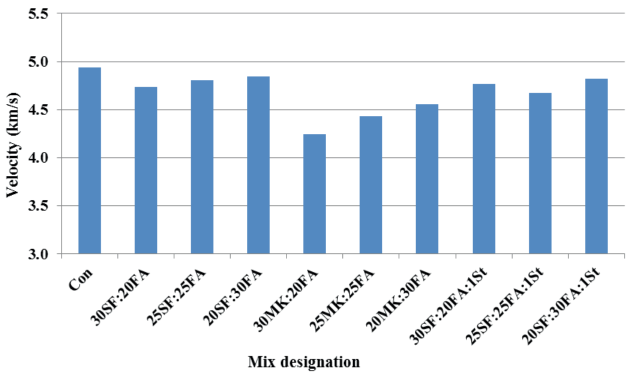

Fig. 6 Ultrasonic pulse velocity of RPC mixtures at 91 days

Results of dynamic modulus of elasticity (Ed) of RPC mixes are presented in Fig. 7. As for UPV results, all mineral admixtures mixes showed a reduction in *Ed* relating to that for reference specimens. The 30MK:20FA mix imparted 36.3 GPa (the minimum value) compared to 52.9 GPa for control mixture (31 % reduction rate). Moreover, for FA with MK mixes, the *Ed* was decreased with the increasing of MK percentage in the mix. For SF + FA mixtures, the *Ed* values were depressed by 9 %–13 % relating to the control mix. The *Ed* values in the subsistence of 1 % steel fibers seem to be equal to the corresponding values for plain SF + FA mixtures. This reduction in dynamic modulus of elasticity for different RPC mixtures compared to the reference mix can be interpreted according to the fact that *Ed* is a function of unit weight, UPV value, compressive strength, and porosity [40].

4 Conclusions

Based on the results obtained from this study, the following conclusions were drawn:

1. Replacement of cement with 50 % of SF + FA combination increased the flow rate of fresh RPC by 43 %–74 % compared to the reference mix. However, the MK + FA decreased it by 11 %–28 % with a reduction rate increased with the increase of MK content in the mix.

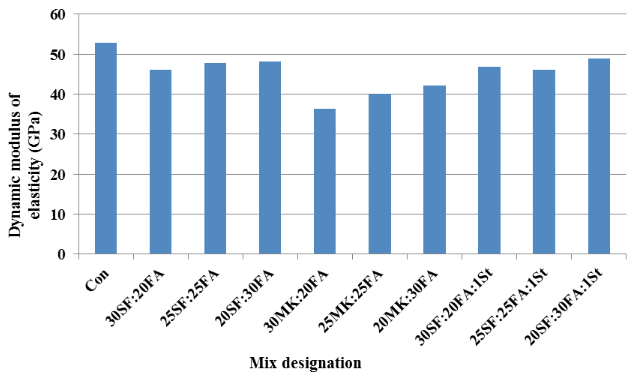

Fig. 7 Dynamic modulus of elasticity of RPC mixtures at 91 days

2. The plain RPC (without steel fibers) which containing SF + FA and MK + FA combinations as a cement replacement in the proportion of 50 % (by weight) led to decrease the compressive strength of RPC. The decreasing rate increased with the increase of FA amount in the mix. Minimum reduction percentage was found in the 30SF:20FA mixture, about 10 % lower than that for control specimens. The presence of 1 % micro steel fibers led to improve the compressive strength of all SF + FA combinations. The better enhancement (44 % more than the control sample) was found at 30SF + 20FA combination.
3. The flexural strength of RPC was improved by 10 % and 5 % for 30SF:20FA and 25SF:25FA combinations. Although it decreased the flexural strength by 19 % in the absence of steel fibers, the 20SF:30FA mixture increased the flexural strength by 10 % after incorporating 1 % micro steel fibers. On the other hand, MK + FA reduced the flexural strength by 38 %–57 %.
4. The substitution of cement with 50 % of SF + FA or MK + FA decreased the density of the RPC. The MK + FA combinations indicated higher decline percentages than SF + FA.
5. The control mixture showed higher UPV and dynamic modulus of elasticity than that for SCMs mixtures. Higher reduction rates were recorded for MK + FA mixes.
6. As a general conclusion from the present study, the 30SF:20FA combination performed better results than other combinations. Moreover, in the presence of 1 % micro steel fibers, it is possible to produce sustainable RPC in which the cement can be replaced with 30 % SF and 20 % FA (the total replacement is 50 %) with a significant improvement in the mechanical properties.

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