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ANALYSIS OF COMPRESSIVE STRENGTH OF STANDARD POURED MICROSILICA ADDED REACTIVE POWDER CONCRETE

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Abstract: Reactive powder concretes (RPC) are new-generation concretes with superior properties that have been continuously developed since 1995. They are the most important concretes that are candidates to be the concrete of the future. In this study, reactive powder concretes were produced by using silica fume and micro silica instead of cement. 5x5x5 cm cube samples were used as samples, and these samples were produced in steel molds. Silica fume was used at 20%, 25%, and 30% rates. Microsilica was used instead of cement at 5%, 10%, and 15% rates. These produced samples were cured under autoclave conditions at 160^{0}C 10 Atm for 4 hours, 175^{0}C 15 Atm for 4 hours, 160^{0}C 10 Atm for 8 hours, and 175^{0}C 15 Atm for 8 hours. The cured samples were broken in an automatically controlled test press loaded at 90 kg/s, and the compressive strengths of these samples were measured. According to the compressive strength results, an increase in compressive strength was detected when the proportions of silica fume samples were increased from 20% to 25%. When the silica fume samples were increased from 25% to 30%, a minimal decrease in compressive strength occurred. When the compressive strengths of microsilica samples were increased from 5% to 10% and 15%, a decrease in compressive strength was observed. As a result, the compressive strengths of microsilica samples were generally found to be higher than those of silica fume samples.

Keywords: Reactive concretes, Silica fume, Micro silica, Compressive strength
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1. Introduction

RPCs are ultra-high-strength cement-based composites with superior mechanical and physical properties, excellent ductility, and very low permeability (Walraven, 1999; Alaee, 2020; Bajpai et al., 2020). These materials were first developed in the early 1990s by researchers at the Bouygues laboratories in Paris. Reactive powder concretes represent a new generation of concretes with compressive strengths ranging between 200 and 960 MPa, tensile strengths between 25 and 150 MPa, fracture energies of approximately 30000 J/m^2, and unit weights ranging between 2500 and 3000 kg/m^2 (Bayrak, 2024). The internal structure of reactive powder concrete has a tighter grain arrangement, and its microstructure is strengthened by the presence of the strongest cementitious hydrated products compared to high-performance concretes. This remarkable performance is achieved through the following stages:

1. Fine adjustment of the distribution of all grains in the mixture to reach the optimum density matrix,
2. Reduction of the largest size of the aggregate grains for homogeneity of the concrete,
3. Reduction of the water content in the concrete,
4. Effective use of the pozzolanic properties of high-fineness silica fume,
5. Optimum composition of all components,
6. Use of short-cut steel wires for ductility,
7. Hardening under pressure and elevated temperature conditions to reach very high strengths permeability (Walraven, 1999; Richard Cheyrezy, 1994).

RPC owes its superior mechanical and durability properties to its tight microstructure. In order to achieve this tight microstructure, many measures are taken during its production, unlike traditional concrete, and a different design approach is adopted. These can be listed as follows:

1. The maximum aggregate diameter is kept at very small levels (Generally<1 mm) to increase the homogeneity in the matrix.
2. The amount of material to be used for the matrix to reach optimum density should be investigated experimentally, and the aggregate grain distribution should be adjusted appropriately.
3. The water/binder ratio is generally kept between 0.10 and 0.22.

4. Hyperplasticizer additives are used in high dosages.
5. Mixers that can mix at high speeds are preferred in its preparation.
6. An effective vibration should be used.
7. Ductility is increased with short-cut wires (mostly steel).
8. Mechanical properties are improved with high-fineness silica fume additive. In addition, mineral additives with high pozzolanic activity are used to reduce cement dosage.
9. In order to increase mechanical performance, in addition to water curing, steam curing and autoclave curing (steam curing under pressure) applications are performed.
10. In addition, if it is kept under pressure in the mold during the production phase, mechanical properties can be increased even more.

Basically, with the production of new generation strong plasticizers, the production of cementitious composites with such low water/cement ratios has become possible. In addition, thanks to the developing microscope and microstructure research technologies, designs are supported by microstructure examinations. In this way, it has become possible to produce strong composites such as RPC with considerably reduced defects (Yazıcı and Yalçınkaya, 2011; Jalal et al., 2012; Ghafari et al., 2014).

When the durability properties of RPCs are examined according to the studies in the literature, it is seen that they are incomparably high with normal concretes. The application of compression pressure increases the unit volume weight of RPC. The increase in unit volume weight means the decrease of the voids in the concrete. For this reason, the already high durability properties will increase even more with the application of compression pressure. For this reason, it can be used in facilities where industrial and nuclear wastes are stored where high durability properties are needed. With the application of compression pressure, thin-walled elements can be produced, as well as the thickness of the existing produced elements or the amount of fiber used in them, which constitutes the biggest cost, can be reduced (İpek and Yılmaz, 2009).

2. Materials and Methods

2.1. Materials

The construction sector is undergoing a major transformation today, where technology is rapidly developing. The transition from traditional methods to innovative and sustainable solutions is reshaping the dynamics of the sector (Cakir and Sofyanli, 2015; Carrasco Vasques and Fernandez Herrera, 2019; Cengiz, 2023a; Cengiz, 2023b). Environmentally friendly and sustainable construction solutions are becoming increasingly important in the sector. Applications such as the use of recyclable materials, high-energy-efficient buildings, and green roof systems aim to minimise environmental impacts (Chithra et al., 2016; Cengiz and Cengiz, 2018; Onur and Efe, 2020; Özer et al., 2021; Cengiz, 2024). In fact, many statistical models are applied to determine the ratio of these materials, aiming to reach the optimum solution (Cengiz and Karakaş, 2015; Cengiz and Aydoğdu, 2015; Cengiz, 2019). In this context, efficiency-based studies continue in today's world.

The materials used in this experimental study, which will serve the purpose of sustainability, are as follows:

a. Crushed Quartz Sand

The crushed quartz sand used in the experimental study is 600–150 μm in size and was supplied by Ankara Sika. Crushed quartz sand is seen in Figure 1.

Figure 1. Crushed quartz sand.

b. Quartz Powder

The quartz powder used in the study is 4 μm in size. Quartz Powder is seen in Figure 2.

Figure 2. Quartz powder.

c. Silica Fume

The silica fume used in the study is 0.1 μm in size. Silica fume at 0.1 μm scale is seen in Figure 3.

Figure 3. Silica fume at 0.1 µm scale.

d. Micro Silica
The microsilica used in the experiments is 0.05 µm in size. Microsilica at a 0.05 µm scale is seen in Figure 4.

Figure 4. Microsilica at a 0.05 µm scale.

e. Hiper Liquefier
The hyperliquefier used is polymer-based. The hyperliquefier used is shown in Figure 5.

Figure 5. The hyperliquefier used.

f. Cement
The cement used is CEM 1 42.5R.

2.2. Tools

The tools used in this experimental study are as follows:
a. Concrete Sample Molds
The concrete sample moulds used in the experiments are made of steel and have dimensions of 5x5x5 cm. The concrete sample moulds are shown in Figure 6.

Figure 6. Concrete sample molds.

b. High-Capacity Concrete Mixer
The high-capacity concrete mixer used to mix the concrete samples is shown in Figure 7.

Figure 7. High-capacity concrete mixer.

c. Autoclave
An autoclave was used to cure the test samples. The samples were cured under the curing conditions of 160 °C at 10 Atm pressure for 4 hours, 175 °C at 15 Atm pressure for 4 hours, 160 °C at 10 Atm pressure for 8 hours, and 175 °C at 15 Atm pressure for 8 hours. The autoclave used in the experiments is shown in Figure 8.

Figure 8. Autoclave.

d. Concrete Press
A concrete press with a crushing capacity of 300 tonnes and a loading of 90 kg/s was used to measure the compressive strength of the test samples. The concrete press is shown in Figure 9.

Figure 9. Concrete press.

2.3. Method

2.3.1. General mixing ratios of RPCs

According to the research conducted within the scope of this study, no local or foreign standards were

encountered for the mixture design of RPCs. Different mixing theories were used to proportion the granular materials forming the mixture to form a tight structure. These theories were derived from Mooney's suspension viscosity model reduced (Larrard and Sedran, 1994; İpek, 2009). Mixing ratios of reactive powder concretes are made according to the absolute weight method.

When the case of only no steel fibre in the mixture (fibreless-powdered) was examined, the mixing ratios given in 1 unit were taken into consideration, and the relationship between the total mixture weight and the amount of cement was converted into a formula as follows in order to facilitate the calculations (equation 1).

1 m³ RPC Mix Weight(kg)=2.909x1 m³ RPC Cement (1)

Amount (kg) If the 1 m³ RPC200 mix weight is 2388 kg, the amount of cement to be used in this mix will be approximately 821 kg as a result of the 2388/2.909 ratio from the formula above. After the amount of cement is found to be 821 kg, the amounts of other materials to be used in the mix are determined according to the following mix ratios. Considering the mix ratios given in 1 unit, in the production of RPC200 without steel fiber, silica fume is prepared as 23% by weight of the cement amount, sand content is 110% by weight of the cement amount, powder content is 39% by weight of the cement amount, hyper plasticizer is 1.9% by weight of the cement amount, mixing water is 17% by weight of the cement amount and the mix is created. Other mix materials and mix ratios according to the amount of 821 kg of cement to be used in 1 m³ mix are shown in Table 1. Table 1 shows the mixing ratios of RPC200 without steel fiber and powdered.

Table 1. Mixing ratios of RPC200 without steel fiber and powd

Materials	Calculation Method	MQFRC (kg/m³)
Cement	2388/2.909	821
Silica Rime	821x023	189
Sand (600-150 pm)	821x1.10	903
Powder (4 urn)	821x0.9	320
Hyper fluidizer/pListkizer	821x0.019	15.5
Steel fibers (L=12 mm)	•	-
Water	821x0.17	1395
Total		2388

MQFRC= material quantity found as a result of calculation

2.3.2. Mixing Ratios of RPCs in the Experimental Study

When the water/binder ratio was taken as 0.17 according to Table 1 in the RPC castings, it was observed that the cement did not show sufficient binding properties. In addition, taking the water/cement ratio instead of the water/binder ratio according to this table caused insufficient water in the castings. In addition, taking the amount of hyperplasticizer according to the water/cement ratio instead of the water/binder ratio and the insufficient percentage of hyperplasticizer caused the cement not to show sufficient binding properties. For this reason, in the experiments, the water/binder ratio was taken, and this value was brought to 0.19, and the samples were poured. In addition, the amount of hyperplasticizer was taken as 0.03 of the water/binder ratio. 5x5x5 cm cube samples were produced in the study. In this experimental study, RPCs were cast in 3 groups as silica fume at 20%, 25%, and 30% ratios, and each group was cured under autoclave conditions of 160 °C 10 Atm for 4 hours, 175 °C 15 Atm for 4 hours, 160 °C 10 Atm for 8 hours, and 175 °C 15 Atm for 8 hours. A total of 3x12=36 silica fume samples were produced, 3 for each cure condition of each group. The microsilica samples produced by using it instead of cement were cast in 3 groups of 5%, 10%, and 15%, and each group was cured in autoclave conditions of 160 °C (10 °A) for 4 hours, 175 °C (15 °A) for 4 hours, 160 °C (10 °A) for 8 hours, and 175 °C (15 °A) for 8 hours. A total of 3x12=36 microsilica samples were produced, 3 for each cure condition of each group. In general, 36+36=72 samples were produced. Table 2 shows the material amounts found as a result of the calculation for 20%, 25%, and 30% RPC. Table 3 shows the mixing ratios of 5%, 10%, and 15% Microsilica RPCs.

Table 2. The material amounts found as a result of the calculation for 20%, 25%, and 30% RPC

Materials	MQFRC (kg/m³)		
	20% silica fume	25% silica fume	30% silica fume
Cement	821	821	821
Silica Fume	164	205	246,5
Sand (600-150 µm)	903	903	903
Powder (4 µm)	345	304	262.5
Hyper fluidizer/plasticizer	30	31	32
Steel Fibers (L=12 mm)	-	-	-
Water	187	195	203
Total	2450	2459	2468

MQFRC= material quantity found as a result of calculation

Table 3. The mixing ratios of 5%, 10%, and 15% Microsilica RPCs

Materials	MQFRC (kg/m3)		
	5% Microsilica	10% Microsilica	15% Microsilica
Cement	780	739	698
Microsilica (0.05 µm)	41	82	123
Silica Fume	189	189	189
Sand (600-150 µm)	903	903	903
Powder (4 µm)	320	320	320
Hyper fluidizer/plasticizer	30	30	30
Steel Fibers (L=12 mm)	-	-	-
Water	192	192	192
Total	2455	2455	2455

MQFRC= material quantity found as a result of calculation

2.3.3. Production Method of RPCs in the Experimental Study

The RPCs in the experimental study were poured as follows:

- First, cement and silica fume were poured into the concrete container and mixed with a high-capacity concrete mixer for 1 minute at 1st speed.
- Then, hyper-fluidiser water was poured onto the mixture while the mixture was being mixed at 1st speed for 1 minute.
- This mixture was mixed at first speed for 1 minute.
- Then, the mixture was mixed at 2nd speed for 1 minute.
- Then, the mixture was mixed at 3rd speed for 1 minute.
- Then, half of the quartz sand and powder were poured onto the mixture and mixed at first speed for 1 minute.
- Then, the other half of the quartz sand and powder were poured onto the mixture and mixed at first speed for 1 minute.
- After this, the resulting mixture was mixed for 5 minutes in the 2nd cycle, and RPC was produced.
- The produced RPCs were placed in 5x5x5 cm steel moulds in 2 passes. Each pass was skewered 35 times with Φ6 iron.
- Then the surfaces of the RPCs were smoothed with light water.
- Finally, a well-wetted cloth was covered on the RPCs.

The production of silica fume RPCs takes 12 minutes. The 8th stage in the production of microsilica RPCs takes 7 minutes. The total production time is 14 minutes. The 2nd stage in the production of nanosilica RPCs is organised as follows: Less than half of the water and hyperfluidizer were collected in one container and mixed. The other part of the water, hyperfluidizer, and nanosilica were collected in another container and mixed to form a suspension. First, hyperliquefied water was added to the mixture for 1 minute, then the suspension was added to the mixture for 1 minute. The total production time is 13 minutes.

In addition, after the autoclave curing process applied to the samples produced in this experimental study, the samples to be broken in the concrete press after leaving the autoclave are shown in Figure 10, and the samples broken in the concrete press are shown in Figures 11 and 12.

Figure 10. Samples to be broken in the concrete press after leaving the autoclave.

Figure 11. Sample broken in the concrete press.

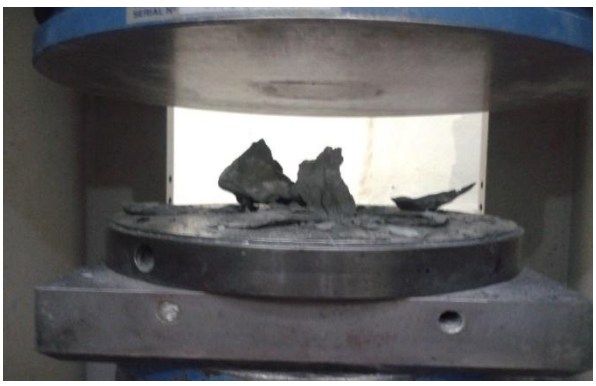

Figure 12. Sample broken in the concrete press.

3. Results

The average strengths of 3 samples in each cure condition of each group of silica fume samples are shown in Table 4, and the average strengths of 3 samples in each cure condition of each group of microsilica samples are shown in Table 5.

Table 4. Average strengths of silica fume samples

25% Silica Fume			
4 Hours		8 Hours	
160 °C	175 °C	160 °C	175 °C
10 Atm	15 Atm	10 Atm	15 Atm
150.5 MPa	152.6 MPa	189.1 MPa	210.5 MPa
25% Silica Fume			
4 Hours		8 Hours	
160 °C	175 °C	160 °C	175 °C
10 Atm	15 Atm	10 Atm	15 Atm
194.4 Mpa	200.5 MPa	203.2 MPa	223.4 MPa
30% Silica Fume			
4 Hours		8 Hours	
160 °C	175 °C	160 °C	175 °C
10 Atm	15 Atm	10 Atm	15 Atm
172.3 MPa	181.1 MPa	200.8 MPa	214.1 MPa

Table 5. Average strengths of micro silica samples

5% Silica Fume			
4 Hours		8 Hours	
160 °C	175 °C	160 °C	175 °C
10 Atm	15 Atm	10 Atm	15 Atm
202.8 MPa	206.8 MPa	205.9 MPa	224 MPa
10% Silica Fume			
4 Hours		8 Hours	
160 °C	175 °C	160 °C	175 °C
10 Atm	15 At tn	10 Atm	IS Atm
195.7 MPa	204.9 MPa	207.2 MPa	211.3 MPa
15% Silica Fume			
4 Hours		8 Hours	
160 °C	175 °C	160 °C	175 °C
10 Atm	15 Atm	10 Atm	15 Atm
186 MPa	186.6 MPa	196.3 MPa	204.2 MPa

The average strengths of the silica fume samples in Table 5 are shown in Figure 10, and the average strengths of the microsilica samples in Table 6 are shown in Figure 11.

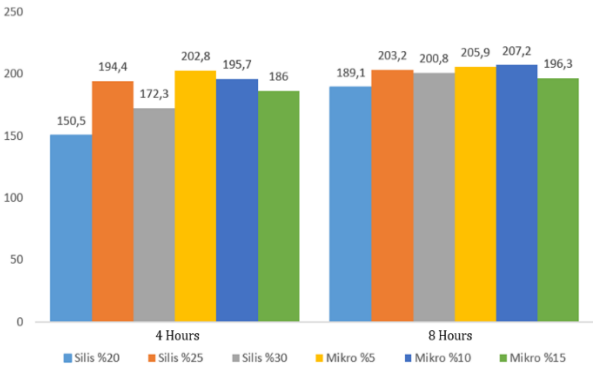

Figure 10. Compressive strength of samples applied with autoclave at 160˚C 10 Atm.

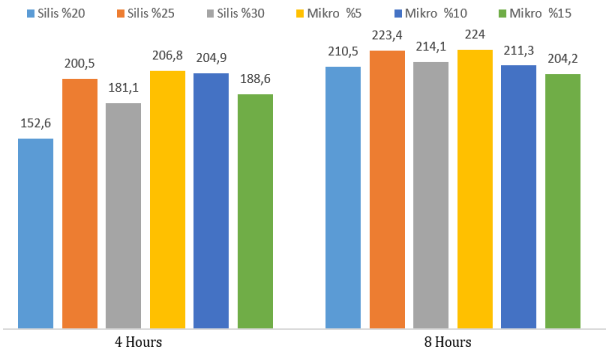

Figure 11. Compressive strength of samples applied with autoclave at 175˚C 15 Atm.

4. Discussion and Conclusions

In each curing condition, when the microsilica samples were increased from 5% to 10%, a slight decrease in the compressive strength of the samples was observed. When the ratio was increased from 10% to 15% in the microsilica samples, a greater decrease in the compressive strength of the microsilica samples was observed. In other words, a decreasing tendency is observed in the strength. It is thought that the reason for this is that since the specific surface of microsilica is higher than that of silica fume, it does not contribute to the strength by agglomeration after 5% and even causes a decrease.

In addition, it is seen that the curing time is more effective in increasing the strength of all samples according to the curing temperature.

Finally, the compressive strengths of the microsilica samples were generally higher than those of the silica fume samples.

Author Contributions

The percentages of the authors' contributions are presented below. All authors reviewed and approved the final version of the manuscript.

	Y.M.Ç.	A.E.S.
C	50	50
D	50	50
S	50	50
DCP	50	50

DAI	50	50
L	50	50
W	50	50
CR	50	50
SR	50	50
PM	50	50
FA	50	50

C=Concept, D= design, S= supervision, DCP= data collection and/or processing, DAI= data analysis and/or interpretation, L= literature search, W= writing, CR= critical review, SR= submission and revision, PM= project management, FA= funding acquisition.

Conflict of Interest

The authors declared that there is no conflict of interest.

Ethical Consideration

Ethics committee approval was not required for this study because of there was no study on animals or humans.

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