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Effects of cement dosage and steel fiber ratio on the mechanical properties of reactive powder concrete

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Abstract. In this study, the mechanical properties of reactive powder concrete (RPC) with a constant cement to silica fume ratio of 4 were investigated. In the experimental program, reactive powder concretes with steel fiber at different ratios were produced. Five productions using quartz sand with a maximum grain size of 0.6 mm were performed. A superplasticizer with a ratio of 3% of the cement was used for all productions. 40×40×160 mm prismatic specimens were prepared and tested for flexural and compression. The specimens were exposed to two different curing conditions as autoclave and standard curing condition. Autoclave exposure was performed for 3 hours under a pressure of 2 MPa. It was observed that the compressive strength of concrete, along with the flexural strength exposed to autoclave was quite high compared to the strength of concretes subjected to standard curing. The results obtained indicated that the compressive strength, along with the flexural strength of autoclaved concrete increased as the amount of cement used increases. Approximately 15% increase in flexural strength was achieved with a 4% steel fiber addition. The maximum compressive strength that has been reached is over 210 MPa for reactive powder concrete for the same steel fiber ratio and with a cement content of 960 kg/m^3. The relationship between compressive strength and flexural strength of reactive powder concrete exposed to both curing conditions was also identified.

Keywords: autoclave; reactive powder concrete; mechanical properties; steel fiber; silica fume

1. Introduction

With the developing world, the need for high buildings, large span bridges and viaducts is rapidly increasing. Large cross-sectioned members are required, particularly for structural members subjected to great tensile forces. Therefore, high-strength concrete has progressively been used to reduce the cross-sections of the structural members. The design and production of reactive powder concrete (RPC), also called ultra-high-strength concrete or new generation concrete, have gained importance in recent years to meet such requirements. In the production of reactive powder concrete, use of a superplasticizer is inevitable to produce concrete with a water to cement ratio as low as possible as an inevitable target to produce concrete with a strength as high as possible. Silica fume and steel fiber are common ingredients to produce high strength concrete for ductility and quartz is mostly used as aggregate (Richard and Cheyrezy 1994, Richard and Cheyrezy 1995, Dugat *et al.* 1996, Chan and Chu 2004, Topçu *et al.* 2014). Reactive powder concretes possess obviously superior mechanical and durability properties due to their micro structures (Cheyrezy *et al.* 1995, Yanni 2009, Hiremath and Yaragal 2017).

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Reactive powder concretes were firstly developed by researchers at the laboratory of Bouygues's company in Paris at the beginning of the 1990s (Richard and Cheyrezy 1994, Richard and Cheyrezy 1995, Dugat *et al.* 1996). The first application for reactive powder concrete is the Pedestrian Bikeway Bridge in Sherbrooke, Canada. Reactive powder concretes have a limited application area, such as the production of manhole-covers and rainwater grids. Guangjie (2009) has pointed out that the use of reactive powder concretes in highway barriers may provide a long-term advantage. Reactive powder concretes are special concrete with compressive strengths of 150-800 MPa and flexural strengths of 15-140 MPa. These figures are considerably higher than those of the strengths of high strength concrete and conventional concrete (Richard and Cheyrezy 1994, Richard and Cheyrezy 1995, Dugat *et al.* 1996, Chan and Chu 2004, Yazıcı *et al.* 2009, Ng *et al.* 2010, Beglarigale *et al.* 2014, Gu *et al.* 2015, Sohail *et al.* 2018).

The considerations for the production of reactive powder concrete that should be taken into account can be summarized as follows: i) enhancing homogeneity by avoiding using coarse aggregate, ii) ensuring dense structure by applying pressure before and during setting, obtaining optimum grain distribution, iii) enhancing microstructure by applying heat treatment after setting, iv) increasing ductility by using small steel fibers, and v) maintaining mixing and casting processes as close as real application process (Richard and Cheyrezy 1995).

The first study on the design of reactive powder concrete was carried out by Pierre Richard and Marcel Cheyrezy. They designed two different reactive powder

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concretes as RPC200 and RPC800 in the study (Richard and Cheyrezy 1995).

Production of reactive powder concrete necessitates heat treatment applications such as steam curing and autoclave (steam curing under high pressure). The heat treatment significantly improves the mechanical properties of concrete by allowing the C-S-H to gain a denser structure. The improvement gained in mechanical properties may be attributed to the supportive effect of quartz used in the production of reactive powder concrete on the hydration process (Cheyrezy *et al.* 1995, Yazıcı *et al.* 2009).

As higher strengths are obtained in concrete, brittleness increased. Ductility is increased by using steel fiber in the production of reactive powder concrete. Steel fibers restrict the formation of cracks in concrete in the cases of compression and tension. Steel fibers are generally used in the range of 1.5%-3% by volume. (Cheyrezy *et al.* 1995, Zeng *et al.* 2013, Yunsheng *et al.* 2008, Al-Tikrite and Hadi 2017, Khan *et al.* 2017, Chen *et al.* 2018, Poorhosein and Nematzadeh 2018).

The main reasons for the use of silica fume in reactive powder concrete may be listed as follows: i) to produce a denser composite by filling the gaps in the cement paste, ii) contributing to strength with additional tobermorite gel formed by pozzolanic reaction (Cwirzen *et al.* 2008, Parande 2013, Yazıcı *et al.* 2013, Mostofinejad *et al.* 2016).

Zheng *et al.* (2013) have investigated the behavior of reactive powder concrete containing steel fibers and subjected to high temperatures. It is reported that the compressive strengths of steel fiber reactive powder concrete decreases at 100°C, it increases between 200-500°C, and decreases again at 600°C. Concretes containing steel fiber have indicated higher compressive and flexural strengths at 20°C compared to those without steel fiber.

Yanzhou *et al.* (2015) have produced reactive powder concretes different in composition as with 1% steel fiber and without steel fiber. Based on 7-day results evaluated, the increase in flexural and compressive strengths of steel fiber concretes with respect to concretes without steel fibers are approximately 29-30% and 15-25%, respectively.

Yazıcı *et al.* (2013) have studied the effects of autoclave pressure, temperature, and application duration on the mechanical properties of reactive powder concrete. It has been stated in the study that there is a significant increase in the compressive strength of autoclaved reactive powder concretes compared to standard cured ones. Autoclave pressure, temperature and application duration have significantly affected the mechanical performance of reactive powder concretes.

Tiefeng Chen *et al.* (2018) have studied the effects of autoclave and fly ash on the performance of ultra-high strength concrete. It has been stated that addition of fly ash and the autoclave duration reduced the porosity of ultra-high strength concrete. It has also pointed out that while the addition of steel fibers clearly improved the flexural strength, it did not significantly change the compressive strength.

There are many studies in the literature concerning the mechanical properties of reactive powder concretes incorporating different types of fibers and containing mineral admixtures such as fly ash and blast furnace slag and subjected to different curing conditions (Kumar *et al.* 2013, Rahmatabadi 2015, Nematzadeh and Poorhosein 2017).

In this study, the mechanical properties of reactive powder concretes were assessed by keeping the cement/silica fume ratio constant as 4. At the same time the effect of steel fiber at different ratios used in reactive powder concrete was also tested.

Table 1 Chemical composition and some physical properties of cement

Chemical composition (%)		Mineralogical composition (%)	
SiO_2	20.22	C_3S	51.2
Al_2O_3	5.67	C_2S	16.7
Fe_2O_3	2.91	C_3A	10.1
CaO	63.41	C_4AF	8.9
MgO	0.96	Physical properties	
SO_3	2.92		
Loss on ignition	3.32	Specific gravity	3.10
Insoluble residue	0.93	Specific surface (Blaine) (m^2/kg)	356.4
Free lime	1.20		

Table 2 Chemical composition of silica fume

Chemical composition (%)	
SiO_2	91.18
Al_2O_3	0.25
Fe_2O_3	0.65
CaO	1.06
MgO	2.78
SO_3	1.61
Loss on ignition	2.85

2. Experimental program

2.1 Materials

CEM I 42.5 R type cement manufactured by Trabzon Cement plant was used in the study. Chemical composition, along with physical properties of cement is given in Table 1.

Silica fume with a density of 2.2 Mg/m^3 was used in the study. The chemical composition of silica fume used is given in Table 2.

Quartz sand of 0.6 mm grain size and with a particle density of 2.78 Mg/m^3 was used. A polycarboxylate based superplasticizer chemical additive was used throughout experimentation.

Steel fibers were used for some designs to increase RPC strength, to provide a ductile structure and to increase energy absorption capacities. The steel fiber used had a slenderness ratio of 40, with a length of 6 mm and a diameter of 0.15 mm. The tensile strength of the steel fiber is 1100 MPa with a density of 7.85 Mg/m^3. Tap water was used as mixing water.

2.2 Mix design

A total of five productions were performed in the work.

Fig. 1 Three-gang-mold with prisms (left) and the prisms only (right)

Table 3 Mix proportions

Sample code	Steel Fiber (%)	W/C	Component quantities, kg/m^3 C	SF	W	QS	Steel Fiber (F)
900C0F	0	0.23	900	225	207	1030	0
930C0F	0	0.22	930	232.5	204.6	998.7	0
960C0F	0	0.23	960	240	220.8	915.7	0
960C3F	3	0.23	960	240	220.8	915.7	236
960C4F	4	0.23	960	240	220.8	915.8	314

C=Cement, SF= Silica fume, W=Water, QS= Quartz sand

RPC components were mixed in a 2-lt capacity electronic mixer. Initially quartz sand, along with cement and silica fume was poured in the mixer; the mixture was mixed for 5 to 6 minutes at slow speed of 96 rpm. Following the addition of half of the mixing water to the mix, the mixture was mixed for another 5 to 6 minutes at moderate speeded of 120 rpm. Finally, following the addition of the rest of mixing water with a superplasticizer and steel fiber were added in the mixture and mixed for 10 minutes at high speed of 175 rpm for completion of mixing process. Mini flow test was performed on the mixture following the mixing process. The mixer then was poured in a triple mold of 40×40×160 mm in two layers and each layer was compacted using a vibrating table for a certain period. The three-gang molds with prisms are given in Fig. 1. The cement to silica fume ratio by weight was kept constant as 4 and a superplasticizer were used as 3% of cement by weight for all mixes. The amounts of ingredients used for the mixtures are given in Table 3.

2.3 Methodology

After a period of 24 hours following mixing process, the specimens were demolded, and three specimens were placed in the autoclave apparatus while other three specimens were kept in standard curing condition. The samples were kept in the autoclave apparatus given in Fig. 2 for two hours under 2 MPa pressure. This period does not include the time required for the system to stabilize at the beginning and at the end of the autoclave process.

The mini flow test for each mixture was performed as per ASTM C 230 and TS EN 1015-3 standards. The test apparatus used for mini test and measuring process of flow diameter are given in Fig. 3.

Fig. 2 Autoclave apparatus

Fig. 3 Mini flow test apparatus (left) and the flow diameter of the sample (right)

Fig. 4 Execution of flexural and compressive strength tests

Flexural and compressive strengths were performed in accordance with EN 196-1. Flexural strength tests were carried out on the prisms of 40×40×160 mm and the compressive strength tests were performed on the halves of the prisms with a cross-sectional area of 40×40 mm^2. The experimental setups of flexural and compressive strength tests are given in Fig. 4.

3. Results and discussions

3.1 Mini flow test measurements

Flow diameter measurements obtained for the mixtures are illustrated in Fig. 5. As can be seen, the range for the flow diameters is between 120-140 mm for all mixtures.

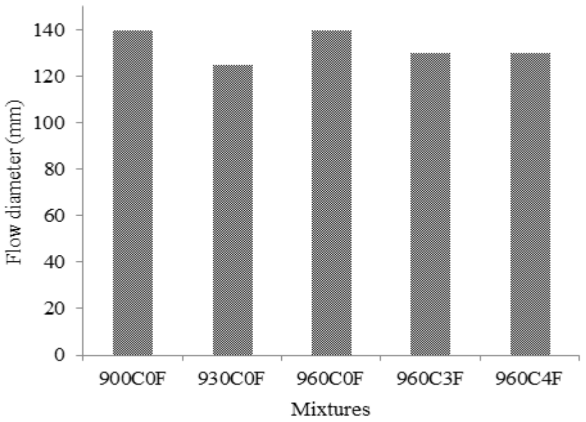

Fig. 5 Mini flow diameter measurements for the mixes

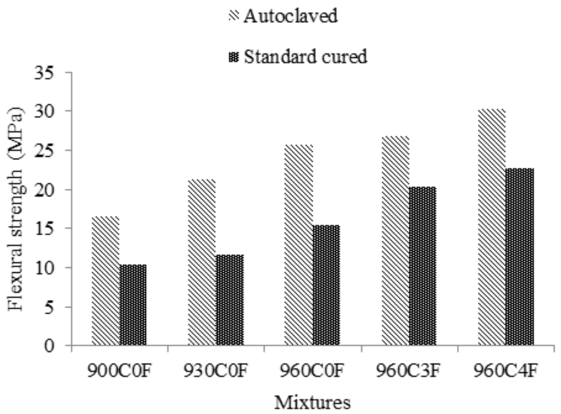

Fig. 6 Flexural strengths measured for the mixes

3.2 Flexural strength measurements

The flexural strengths measured are presented in Fig. 6. As can be seen from the figure, the flexural strengths significantly increase as the amount of cement used and the amount of steel fiber addition increase. For concretes with a cement dosage of 960 kg/m^3, the flexural strength of autoclaved concrete contains 4% steel fiber is about 17% higher than the strength of concrete without steel fiber. Similarly, standard cured concrete with a steel fiber content of 4% is about 46% greater than that of the strength of concrete without steel fiber. This is a good indication that steel fiber has a pronounced effect on the flexural strength development of RPCs. The flexural strength of autoclaved concretes is an average of 1.5 times greater than that of the strength of standard cured concretes irrespective of cement content and steel fiber inclusion.

Yazıcı *et al.* (2013), based on their experimental work, an average flexural strength of 26.1 MPa had measured on specimens containing 2% fiber with 772 kg/m^3 cement content that autoclaved for 4 hours. In the present study, the average flexural strength that measured for the prisms containing 3% fiber and 960 kg/m^3 cement that autoclaved for 3 hours is 26.75 MPa.

Baglerigale *et al.* (2014), based on their work, an average flexural strength of 5 MPa had measured for RPCs without fiber and with a cement content of 785 kg/m^3, with a cement to silica ratio of 4. In the present study, while an

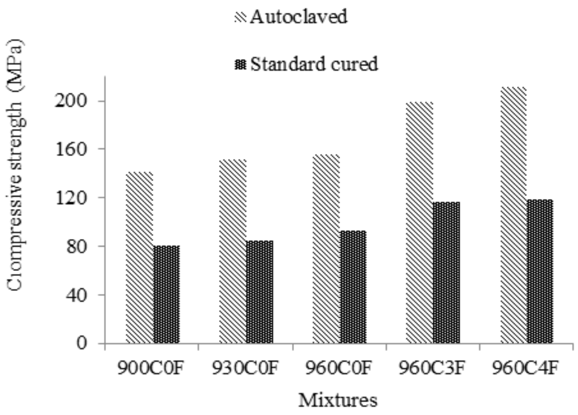

Fig. 7 Compressive strengths obtained for the mixes

average flexural strength of 16 MPa was measured for RPCs with a cement content of 900 kg/m^3, it has been 26 MPa for RPCs with 960 kg/m^3 cement content. There is an obvious increase in the flexural strength parallel with the increase of cement content.

3.3 Compressive strength measurements

The compressive strength measurements obtained for the prisms are illustrated in Fig. 7. As can be seen from the figure, there is a significant increase in the compressive strengths of the RPCs depending on the amount of cement and fiber used, particularly for those of autoclaved ones.

Autoclaved RPCs with a cement content of 960 kg/m^3 and with 4% steel fiber yielded 35% higher compressive strength compared to those of without steel fiber. Similarly, the compressive strength of the standard cured RPCs is about 27% higher than those of without steel fiber. The autoclaved RPCs with a cement content of 960 kg/m^3 yielded a compressive strength approximately 10% higher than that of the strength of RPCs with a cement content of 900 kg/m^3. Similarly, the compressive strength of autoclaved RPCs is about 14% higher than that of the compressive strength of the standard cured RPCs containing a cement content of 900 kg/m^3. It can clearly be seen that the compressive strength of autoclaved RPCs is about 1.75 times higher than the strength of standard cured RPCs, irrespective of cement content and steel fiber inclusion.

Beglarigale *et al.* (2014) have measured a compressive strength of about 210 MPa on the RPCs with 2% steel fiber inclusion and with a cement content of 785 kg/m^3, which were autoclaved for 8 hours. In the present study, the same compressive strength level was obtained on the RPC with a cement content of 960 kg/m^3 and %4 steel fiber addition, autoclaved for a period of 3 hours. This is a good indication that longer autoclave periods have a pronounced effect on the mechanical performance of RPCs.

3.4 Relationship between compressive and flexural strength

The relationship between the compressive strength and the flexural strength of conventional concretes is based on a mathematical expression of $ft=k\times(fc)+s$ in the literature

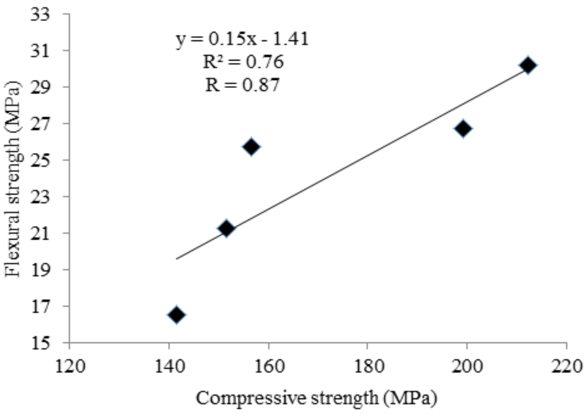

Fig. 8 Relationship between compressive and flexural strength of autoclaved RPCs

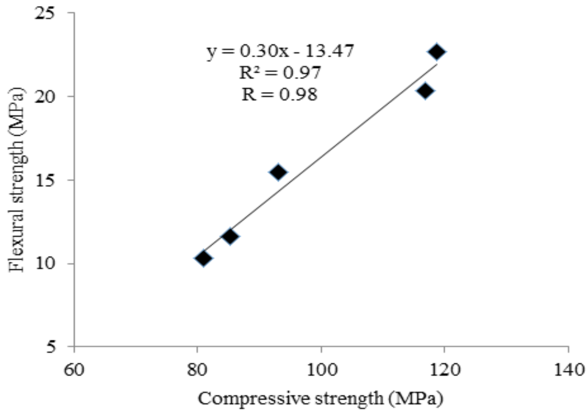

Fig. 9 Relationship between compressive and flexural strength of standard cured RPCs

(Ahmed *et al.* 2014, Amudhavalli and Poovizhiselvi 2017). Here, ft is the flexural strength and *fc* is the compressive strength of concrete; *k* and *s* are constants and varying depending on many factors such as concrete type and test type. The relationship between compressive and flexural strengths of autoclaved RPCs produced with quartz sand is illustrated in Fig. 8. As can be seen, the relationship is linear rather than exponential with an equation of $ft=0.15\times(fc)-1.41$ and a determination coefficient of 0.76.

The linear relationship between compressive strength and flexural strength of standard cured RPCs are given in Fig. 9. The relationship is a linear type with an equation of $ft=0.30\times(fc)-13.47$ and yields a relatively high determination coefficient of 0.97.

4. Conclusions

• The flexural strength of RPCs substantially increases as the cement content increases. The trend is quite similar for both concretes of autoclaved and standard cured ones.
• A close look up to the RPCs containing a cement content of 960 kg/m^3 indicates that the flexural strength increases as the steel fiber increases prevailing for both concretes of autoclaved and standard cured ones.
• The autoclaved RPCs indicate a comparable increase in compressive strength as the cement content increases. However, the increase is not so pronounced for standard cured RPCs. They indicate very limited increase in compressive strength regarding the cement content used.
• The maximum compressive strength measured is over 210 MPa for concretes containing 960 kg of cement and 4% steel fiber. The corresponding flexural strength is over 30 MPa for the same mix proportions.
• The flexural strength of autoclaved RPCs is highly correlated with the compressive strength. The coefficient of correlation for a linear type relationship is 0.87. A similar relationship is obtained for standard cured RPCs with a coefficient correlation of 0.98.
• Overall evaluation indicated that a compressive strength level of 200 MPa, which is accepted as the lower limit for RPC, is possible to reach with a cement content of about 950 kg and with a steel fiber ratio of 4% under a pressure of 2 MPa for 3 hours exposure. The flexural strength and the compressive strength of RPCs are highly linearly correlated with a coefficient of correlation of 0.87.

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