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Investigating the combination of natural and crushed gravel on the fresh and hardened properties of self-compacting concrete

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Abstract. Self-compacting concrete is widely used around the globe today due to its special and unique properties. This study examines the effect of natural and crushed gravel combinations in different percentages in short-and long-term properties of concrete. The best utilized sand had a fineness modulus of 2.7. In the mentioned mix designs, silica fume was used with 0 and 7% of the weight of the cement. In order to check the properties of fresh and hardened concrete, 9 and 5 test types were performed, respectively. The carried out tests were slump flow, V-funnel, J-ring, L-box, U-box and column segregation for fresh concrete, and compressive, tensile and flexural strengths for hardened concrete. A mix with only 100% natural gravel was considered as the control mix. According to the results, the control mix design and the one containing 100% crushed gravel with silica fume were the best in fresh and hardened concrete tests, respectively. Finally, using the optimization method, a mix design with 25% natural gravel, 75% crushed gravel and silica fume was introduced as the best mix in terms of the results of both fresh and hardened concrete tests.

Keywords: crushed gravel; mechanical properties; natural gravel; rheology; self-compacting concrete

1. Introduction

With an annual consumption of about eleven billion tons, concrete is the most widely used construction material in the world (Naik and Moriconi 2005). Concrete is the main element in large and prominent structures. This material is used in the construction of skyscrapers, theaters, hotels, nuclear power plants, oil and gas drilling, ports, airports, highways, railways, and residential buildings (Broekmans 2012).

Concrete is considered a two-phase material, including the paste and aggregate phase. The paste phase includes all cement, powder, water, all kinds of mineral and chemical additives and air. The volume of the aggregate phase is much larger, and it is composed of coarse and fine aggregates (Tangtermsirikul and Tatong 2001). Coarse aggregate has a diameter greater than 4.75 mm and remains on sieve No. 4. While fine aggregate has a diameter of less than 4.75 mm and passes through sieve No. 4. Aggregates usually make up 70 to 85% of the weight of concrete and 60 to 80% of its volume (Mehta and Monteiro 1993). The parameters related to the coarse-

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aggregate part are expected to have an important effect on the properties of concrete (Khayat and De Schutter 2014).

With the development of urban life, researchers have always been trying to make changes in different components of concrete, make amendments according to the existing needs and achieve new or superior properties of concrete. One of these types of concrete, which dates back to several decades ago, is self-compacting concrete (SCC). SCC is usually known as a high-performance concrete that can pass through the gaps between the reinforcements and completely fill the mold by relying only on its own weight during the concreting process (Hunger *et al*. 2009, Zhu and Bartos 2003, Felekoğlu *et al*. 2007). Therefore, without the need for any vibration, the concreting process will be carried out, which significantly reduces costs, simplifies strict safety protocols, shortens construction time and ensures the uniformity and non-separation of concrete components (Persson 2001, Ouch *et al*. 2008).

Due to the advantages of SCC, considerable attention has been paid to this type of concrete (Saak *et al.* 2001). SCC is much more sensitive than ordinary concrete in the mix design and the composition of constituent materials. The quality of concrete can be directly affected by changes in the shape of aggregates, water content, quality of additives, and the properties of binders. They can affect the mechanical and rheological properties of concrete. The European guide states that self-compacting and normal concrete mixtures should have similar properties in the hardened state (European EFNARC 2005). To increase the rheology of concrete, superplasticizer is used. In SCC, the amount of superplasticizer used is higher than that in normal concrete, and there is a risk of segregation in SCC. Therefore, in SCC, the grading of aggregates becomes more important. In a comprehensive paper, silica fume was replaced by cement with different percentages of 5 to 10%, and finally, it was found that the tensile strength in the 5% replacement was 28% higher than the 10% replacement (Jeevetha *et al*. 2014).

Around the globe, according to the available materials, weather conditions, economic savings, no damage to the environment, and other justifications, researchers have been trying to make changes in concrete components, and SCC is not an exception. Several hybrid design methods have been recently proposed. In a study, the direct effect of properties such as the maximum gravel size, texture, and types of coarse aggregates, including crushed gravel and natural gravel on SCC was analyzed, and it was concluded that by increasing the coarse aggregate size, the flowability of concrete decreased. However, the flowability of concrete with natural gravel was higher than crushed gravel, and the strength of concrete with crushed limestone coarse aggregate was higher than other gravels. Moreover, the SCC made with 10 mm coarse aggregate had more strength than the one made with 20 mm coarse gravel (Khaleel *et al*. 2011). In another research, the effect of recycled aggregate in different percentages on SCC has been examined, and the results were acceptable (Revathi *et al.* 2013). They concentrated on both fresh and hardened properties SCC. In a study, the obtained results show that the optimal replacement of fine aggregates by 50% in combination with 20% of glass powder improved the efficiency. The compressive, tensile and bending strengths increased by 20.95%, 17.05% and 24.44% compared to normal concrete (Bharathi and Adari, 2022).

By replacing 50% of coarse aggregate with waste gravel, the compressive, tensile and bending strengths of concrete did not decrease (Saxena and Pofale 2017). In both fresh and hardened properties of SCC, the combination of natural and crushed gravel in the mix design gave better results than the mixes with only one type of gravel. The combination of both types of gravel had acceptable slump flow (Al-Harthy *et al*. 2007). The effect of sands with different fineness modulus of 2.3, 2.5, 2.7, 2.9 and 3.1 on the fresh properties of concrete was studied, and the best results were obtained in the sand with the fineness modulus of 2.7 (Kumar and Sashidhar 2018). In another concrete mix design, optimal aggregate has been used, which increased the compressive strength (Sabih *et al*. 2016). According to European guidelines, adding superplasticizer to SCC increases the properties of fresh concrete (European efnarc 2005).

In another research, it has been mentioned that natural, round, semi-crushed, or crushed aggregates can be used to produce SCC (Bader and Howell 1996). The properties of aggregates should be considered for the performance required for fresh and hardened concrete (Janssen and Kuosa 2001, Khayat 1999). The shape and size of coarse aggregate has a vital effect on the volume of mortar and paste required to cover all the particles. Natural gravel often requires less mortar or paste. Crushed aggregates reduce the flowability due to the interlocking of angular and crushed particles, while round aggregates improve the smoothness of the mix due to less internal friction (Nikbin 2014). The key to success in producing economic self-compacting concrete is to use a well-graded aggregate.

More use of crushed aggregates instead of natural ones can help prevent harmful effects on the environment caused by excessive river gravel extraction. In case of excessive extraction of natural aggregates, destructive consequences will affect rivers (Chehreghani and Hosseinzadeh 2020). Natural gravel is useful for improving the rheology of concreate; however, crushed gravel improves the mechanical properties of concrete. By combining these two types of gravel, better results can be obtained in the properties of fresh and hardened concrete (Osuji and Inerhunwa 2015).

According to the mentioned cases, a lot of research has been done in order to optimize self-compacting concrete. In this research, an attempt is made to improve the fresh and hardened properties of self-compacting concrete by making a combination of natural and crushed gravel. The percentages of crushed gravel were 0, 25%, 50%, 75%, and 100%. The experiments were done to identify the optimal proportion of the mentioned gravels.

2. Laboratory program

2.1 Materials

In this research, the drinking water of Tehran was used because the water in concrete should be free of acid or alkali properties as much as possible (ASTM C1602/C1602M-22, 2022). Type II cement with a specific density of 3.14 g/cm^3 and the Blaine fineness of 3300 cm^3/g was used (ASTM C150, 2012). The utilized silica fume had a specific density of 2.21 g/cm^3. Silica fume improved the properties of hardened concrete, and its particles were much finer than those of cement (ASTM C1240, 2015). The chemical characteristics of cement and silica fume are presented in Table 1. According to the results of Section 3.1, the best sand particles used had a fineness modulus of 2.7 and a density of 2.478 g/cm^3. Fig. 1 shows the granularity diagram of the sand (ASTM C33/C33M-18, 2018). The gravel used had a maximum size of 12.5 mm and a specific density of 2.411 g/cm^3. Fig. 2 shows the granularity diagram of the gravel (ASTM C33/C33M-18, 2018).

In the mix designs, the utilized superplasticizer was based on polycarboxylate. Its physical and chemical characteristics are presented in Table 2. The molecular structure of polycarboxylate is basically determined by the carboxyl group. The polyethylene oxide chains can improve the rheology of the mixtures (Yoshioka 1994).

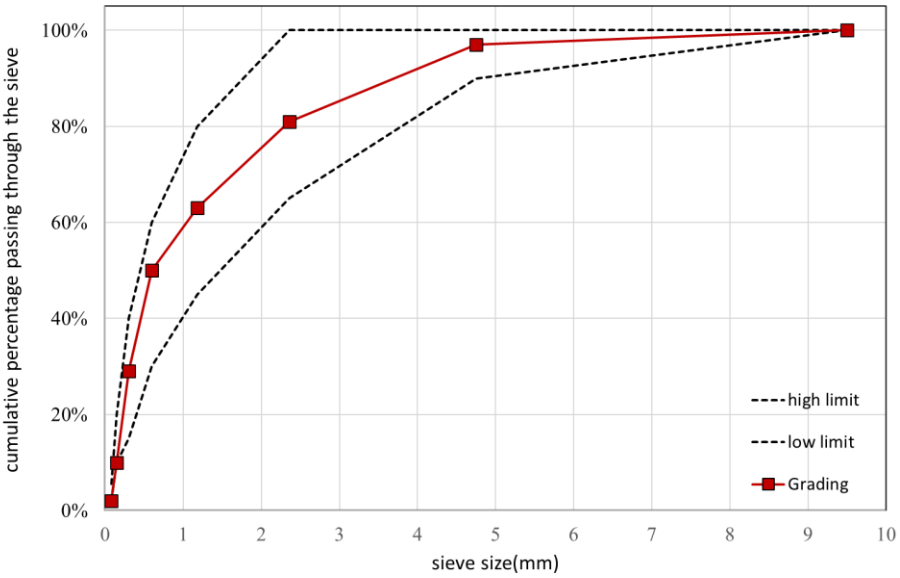

Fig. 1 Granulation curve of the sand with a fineness modulus of 2.7

Table 1 Chemical characteristics of cement and silica fume

Combination	**Silica fume (%)**	**Cement (%)**
SiO_2	96.4	20.42
Al_2O_3	1.32	4.68
Fe_2O_3	0.87	4.20
MgO	0.97	1.32
SO_3	0.1	2.55
K_2O	1.1	0.73
NaO_2	0.31	0.38
CaO	0.49	63.7
H_2O	0.02	-
Cl	0.04	-
C	0.3	-
P_2O_5	0.16	-
SiC	0.5	-
C_3S	-	59
C_2S	-	14
C_3A	-	3.5
C_4AF	-	13

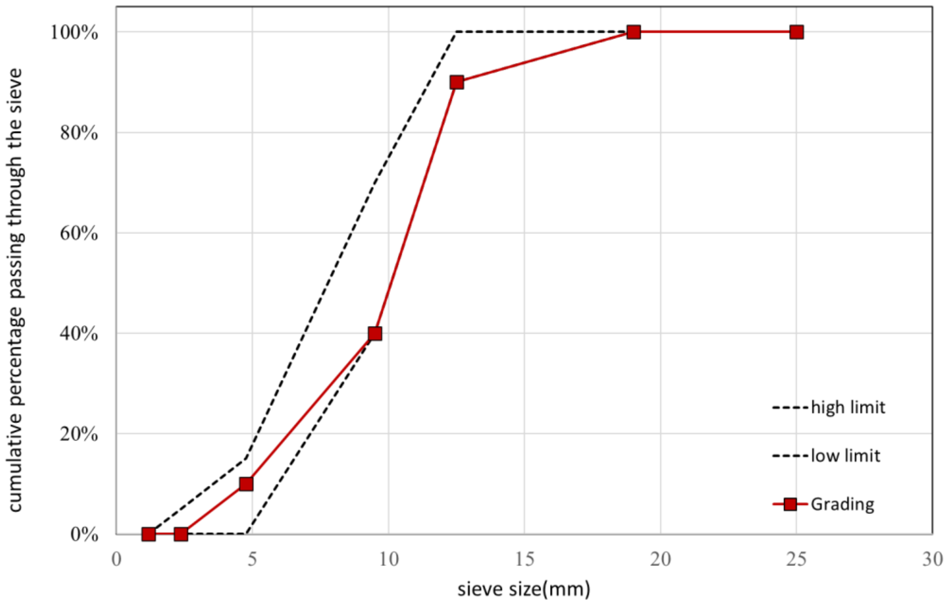

Fig. 2 Granulation curve of the gravel

Table 2 Technical specifications of super lubricant

Properties	**Amount**
Color	Amber
Specific mass	1.12 ± 0.02
Chloride amount	-
pH	4 ± 1
Air entraining rate	Less than 2% according to consumption rate

2.2 Mix design and making samples

In order to investigate the effect of a combination of natural and crushed gravel on the fresh and hardened properties of self-compacting concrete, 5 mixes were made in the presence of silica fume and 5 in the absence of it. Moreover, 3 samples for tensile strength, 3 specimens for bending strength, and 3 samples for water absorption were prepared for each design. The mix designs are presented in Table 3.

Mix 1 was considered as a control mix. It had 100% natural gravel and no silica fume. Mixtures 2 to 5 did not contain silica fume; they had 75% natural gravel and 25% crushed gravel, 50% natural gravel and 50% crushed gravel, 25% natural gravel and 75% crushed gravel, and 100% crushed gravel, respectively. The gravels used in mixes 6 to 10 were similar to that of mix designs 1 to 5, respectively. The only difference between mixes 1-5 and 6-10 was the presence of silica fume in the second group. The amount of silica fume used in mixtures 6-10 was 7% of cement weight. The water to cementitious materials ratio was 0.4 in all the mixes. The amount of

Table 3 Design of self-compacting concrete mix

Design code	**Design No.**	**Water to cement ratio**	**Water (kg)**	**Natural gravel (kg)**	**Crushed gravel (kg)**	**Sand (kg)**	**fineness modulus of sand**	**Silica fume (kg)**	**Cement (kg)**	**Superplasticizer (kg)**
BM-0T-100G	1	0.4	180	500	0	1165	2/7	0	450	2/94
BM-0T-100G – 2.3	1/1	0.4	180	500	0	1165	2/3	0	450	2/94
BM-0T-100G - /3.1	1/2	0.4	180	500	0	1165	3/1	0	450	2/94
BM-25T-75G	2	0.4	180	375	125	1165	2/7	0	450	2/94
BM-50T-50G	3	0.4	180	250	250	1165	2/7	0	450	2/94
BM-75T-25G	4	0.4	180	125	375	1165	2/7	0	450	2/94
BM-100T-0G	5	0.4	180	0	500	1165	2/7	0	450	2/94
M-0T-100G	6	0.4	180	500	0	1165	2/7	5/31	5/418	4/48
M-25T-75G	7	0.4	180	375	125	1165	2/7	5/31	5/418	4/48
M-50T-50G	8	0.4	180	250	250	1165	2/7	5/31	5/418	4/48
M-75T-25G	9	0.4	180	125	375	1165	2/7	5/31	5/418	4/48
M-100T-0G	10	0.4	180	0	500	1165	2/7	5/31	5/418	4/48

superplasticizer used were 4.48 kg and 2.94 kg based on the presence or absence of silica fume, respectively. The symbols G, T, M, and BM are used in naming the mixes for the percentage of natural gravel, the percentage of crushed gravel, the presence of silica fume, and the absence of silica fume.

2.3 Preparation and description of test samples

The tests on SCC are defined by three features: filling ability, passing ability, and separation resistance (Khayat and De Schutter 2014). The ability of SCC to flow under its own weight and fill the molds, which usually has obstacles such as reinforcement, is called filling ability. It is evaluated by slump flow (ASTM C1362-09, 2014), T50 cm (ASTM C1362-09, 2014), and V-Funnel tests (BS EN 12350-9, 2010). The capability of SCC to flow and pass through sections with a large volume of reinforcement or narrow sections is called passing ability, which is evaluated by J-ring (ASTM C1621/C1621M, 2017), L-box (BS EN 12350-10, 2010) and U-box tests (European EFNARC, 2005). The uniformity of the fresh concrete components in different parts and the lack of separation of the mixture during concreting and before setting is evaluated by stability index (ASTM C1362-09, 2014), T5min (BS EN 12350-9, 2010) and column segregation tests (ASTM C1610/C1610M-06a, 2021). For hardened concrete tests, the concrete mixes were poured into cubic and cylindrical molds. After 24 hours, the molds were opened and the samples were processed in a water pool with a temperature of 23±2°C until 30 minutes before the tests (ASTM C192/C192M-02, 2015).

The compressive strength test was performed on cubic samples with the dimensions of 150*150*150 mm at the ages of 3, 7 and 28 days with a loading rate of 0.4-0.8 MPa/s (BS 1881-Part 124-88, 2021). The tensile strength tests at the age of 28 days were performed on cylindrical samples with a height of 300 mm and a diameter of 150 mm; the loading rate was 0.7-1.4 MPa/min (ASTM C496-96, 2017). The bending strength test at the age of 28 days was performed on prism samples with the dimensions of 400*100*100 mm^3. The loading rate for the three-point

Table 4 Fresh properties of mixing designs with different fineness modulus

Design code	Design No.	Slump flow (cm)	V-funnel (s)	J-ring (cm)	L-box (cm)	U-box (cm)
BM-0T-100G	1	76.5	6.28	0.5	0.969	0.62
BM-0T-100G – 2.3	1/1	66	6.67	0.4	0.866	2.36
BM-0T-100G - /3.1	1/2	77.5	6.22	0.4	0.967	0.48

bending test was 0.9-1.2 MPa/min (ASTM C78/C78M, 2021). Next, the non-destructive half-hour water absorption test was used to estimate the concrete durability (BS 122-1881, 2011). The results of flexural tests can be used to investigate the fracture energy of the mixes (Abna and Mazloom 2022b). Fracture energy is another effective parameter in hardened concrete properties (Afzali-Naniz *et al.* 2021, Karamloo and Mazloom 2018, Mazloom *et al.* 2021, Salehi and Mazloom 2018). In the next step, scanning electron microscopy test was done on the crushed samples. Finally, by relying on optimization, the best mix design was selected.

3. Laboratory results

3.1 Results of fresh concrete tests

The fineness modulus of sand is a measure used in concrete technology to indicate the particle size of sand. It is defined as an empirical factor obtained by adding the cumulative percentages retained on the sieves with mesh sizes at 0.075 mm (No. 200), 0.3 mm, 0.6 mm, 1.18 mm, 2.36 mm, 4.75 mm, 9.5 mm, 19.0 mm, and 37.5 mm, and dividing the sum by 100 (Mazloom and Salehi 2018, Mazloom *et al.* 2020, Mazloom and Mahboubi 2017, Mazloom *et al.* 2018). A lower fineness modulus indicates finer sand particles, while a higher fineness modulus indicates coarser sand particles. The fineness modulus is a helpful parameter for assessing the overall gradation of a sand sample and its suitability for various construction applications, such as in concrete mix design.

Elevating the sand fineness modulus improves the fresh properties for SCC; however, higher fineness modulus leads to the decrease of segregation resistance In most cases, increasing the fineness modulus of sand positively affects the hardening properties of SCC (Mazloom and Salehi, 2018, Mazloom *et al.* 2020, Mazloom and Mahboubi 2017, Mazloom *et al.* 2018).

Although the main concentration of this research is on coarse aggregates, some tests are done to find the best fine aggregate for the research. At first, fresh concrete tests on mix designs No 1, 1/1 and 1/2 were done. The fineness modulus of their sand were 2.7, 2.3 and 3.1, respectively. The results showed that the sand with a fineness modulus of 2.7 was the best choice for the fresh concrete. The results are shown in Table 4.

Fresh concrete tests were conducted to evaluate the flowability of the mix designs. The results of fresh concrete tests were based on filling ability, passing ability and stability. The results are given in Tables 5 to 7.

3.1.1 Results of SCC filling tests

According to Table 5, the final diameters of the slump flow tests for all samples were in the range of 710 to 790 mm, which were in the standard range (ASTM C1362-09, 2014). As expected,

Table 5 Results of SCC filling tests

Design code	Design No.	Slump flow (cm)	T 50 cm (s)	V-funnel (s)
BM-0T-100G	1	76.5	2.05	6.28
BM-25T-75G	2	76	2.09	6.33
BM-50T-50G	3	74	2.18	6.39
BM-75T-25G	4	73.5	2.21	6.44
BM-100T-0G	5	71	2.26	6.6
M-0T-100G	6	79	2.01	6.2
M-25T-75G	7	79	2.06	6.4
M-50T-50G	8	78.3	2.08	6.63
M-75T-25G	9	78	2.09	6.72
M-100T-0G	10	77.5	2.13	7

Table 6 Results of SCC passability tests

Design code	Design No.	J-ring (cm)	L-box (cm)	U-box (cm)
BM-0T-100G	1	0.5	0.969	0.62
BM-25T-75G	2	0.5	0.951	0.73
BM-50T-50G	3	0.5	0.93	0.91
BM-75T-25G	4	0.75	0.893	1.09
BM-100T-0G	5	0.75	0.855	1.27
M-0T-100G	6	0.25	0.983	0.49
M-25T-75G	7	0.25	0.976	0.55
M-50T-50G	8	0.5	0.948	0.59
M-75T-25G	9	0.5	0.94	0.63
M-100T-0G	10	0.5	0.924	0.65

the presence of crushed gravel decreased the diameter of the slump flow. Comparing the control mix, there was a decrease of 18.7% in the diameter of the slump flow in mix 5. The addition of silica fume also reduces the flowability of concrete and reduces the diameter of the slump flow in normal conditions (Esmailpour *et al.* 2018). In this paper, due to the proper mix design and increasing the level of superplasticizer, the slump diameter of mix 5 was in the acceptable range. According to this issue, there was a 26.3% increase in the control mix compared to mix 6.

It can also be seen that due to the increase in the use of crushed gravel instead of natural one, the time for concrete to reach a diameter of 500 mm increased. Moreover, with the use of silica fume, the dosage of superplasticizer increased, and the time for concrete to reach a diameter of 500 mm remained in the range. The test results of V-funnel of all the mixes were within the permissible limits, and the possibility of segregation was low in them. The control sample had the best performance and mix 5 had the weakest performance in terms of the filling ability. The important point is that all the mixes had acceptable filling properties.

3.1.2 Passing ability test results of SCC

According to Table 6, the difference in the concrete height before and after the reinforcements

Table 7 Results of SCC stability tests

Design code	Design No.	column Segregation (%)	T 5 min (s)	Stability index
BM-0T-100G	1	13.677	6.88	0
BM-25T-75G	2	13.715	7.10	0
BM-50T-50G	3	13.753	7.32	0
BM-75T-25G	4	13.791	7.54	0
BM-100T-0G	5	13.831	7.72	0
M-0T-100G	6	14.846	6.95	0
M-25T-75G	7	14.625	6.98	0
M-50T-50G	8	14.406	7.21	0
M-75T-25G	9	14.184	7.51	0
M-100T-0G	10	13.963	7.85	0

in the J-ring test was less than 10 mm. Greater deference in the above height indicates a low passing ability, which can lead to the phenomenon of blockage (Abna and Mazloom 2022a). As expected, the mixes with natural gravel had better results. With the presence of silica fume along with the appropriate percentage of superplasticizer, the results were still acceptable.

In L-box test, the criterion for measuring was the height ratio of the end to the beginning of the path of the mix. The closer result to one shows that the mix has a better performance. In the U-box test, the difference in concrete height in two parts should be less than 30 mm. The use of superplasticizer and silica fume together guaranteed the passing ability of the mixes. The control mix had the best performance, and mix 5 had the weakest performance. It is worth noting that according to the test results, all the mixes had acceptable passing ability properties.

3.1.3 Results of SCC stability tests

According to Table 7, no signs of segregation and water leakage were seen in the mixes. The percentages of segregation in column test results were within the allowed range, and all the mixes had acceptable stability properties.

3.2 Results of hardened concrete tests

Hardened concrete tests were done to determine the strength and durability of concrete. The results of compressive, tensile and bending tests were analyzed to determine the mechanical properties of the concrete mixes

3.2.1 Results of compressive strength tests

As mentioned in the previous section, the compressive strength test was performed on cubic samples of 150*150*150 mm^3 with a loading rate of 0.4-0.8 MPa/s. In order to reduce the error rate, the results of compressive strength were calculated as the average of three crushed samples at the ages of 3, 7 and 28 days. The results are shown in Table 8.

As can be seen in Table 8, the compressive strength of the control sample was 32.71 MPa. The presence of silica fume increased the strength of the concrete. At the age of 28 days, the

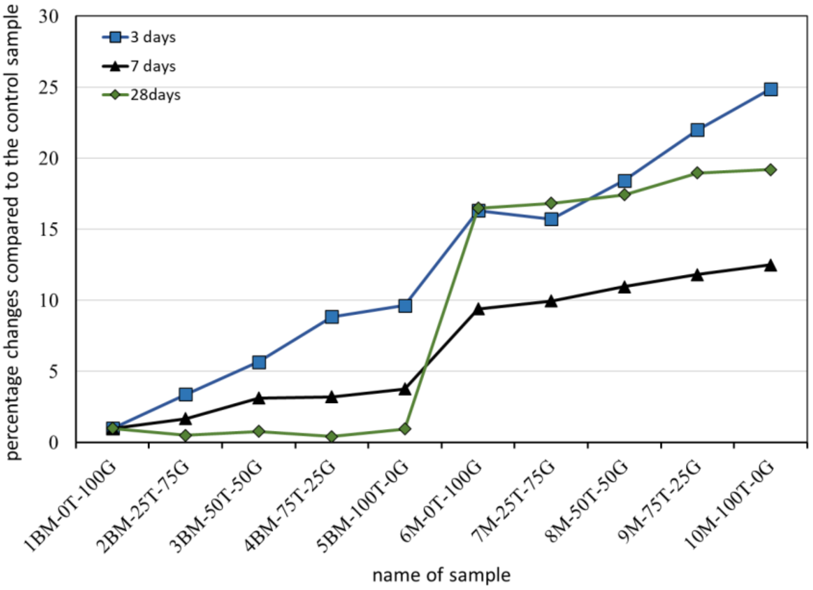

Fig. 3 Comparing the results of compressive strength at 3, 7 and 28 days

Table 8 Results of compressive strength tests at different ages in terms of MPa

Design code	Design No.	3-day compressive strength	7-day compressive strength	28-day compressive strength
BM-0T-100G	1	24.6882	30.0110	32.7123
BM-25T-75G	2	25.7211	30.5126	32.8763
BM-50T-50G	3	26.872	30.95.2	32.9681
BM-75T-25G	4	26.8711	30.9765	32.96
BM-100T-0G	5	27.0694	31.1439	33.0220
M-0T-100G	6	28.7161	32.8353	38.1228
M-25T-75G	7	28.5710	33.1000	38.2204
M-50T-50G	8	29.2385	33.3051	38.4203
M-75T-25G	9	30.1200	33.5610	38.9200
M-100T-0G	10	30.8323	33.7607	38.9970

compressive strengths increased by 16.5%, 16.21%, 16.53%, 18.47%, and 18.09% in mixes 6 to 10, compared to mixes 1 to 5, respectively. In mixes 1 to 5, as the amount of crushed gravel increased and the amount of natural gravel decreased, the compressive strength increased slightly. For example, comparing the compressive strength value in the control mix and mix 5, only 0.94% increase was obtained. In other words, the low effect of the gravel type is quite clear in compressive strength. According to the literature, the gravel size has a direct effect on the compressive strength, and the greater size of gravel leads to a decrease of compressive strength (Khaleel *et al*. 2011). Fig. 3 shows the percentage change in the compressive strength of the mixes

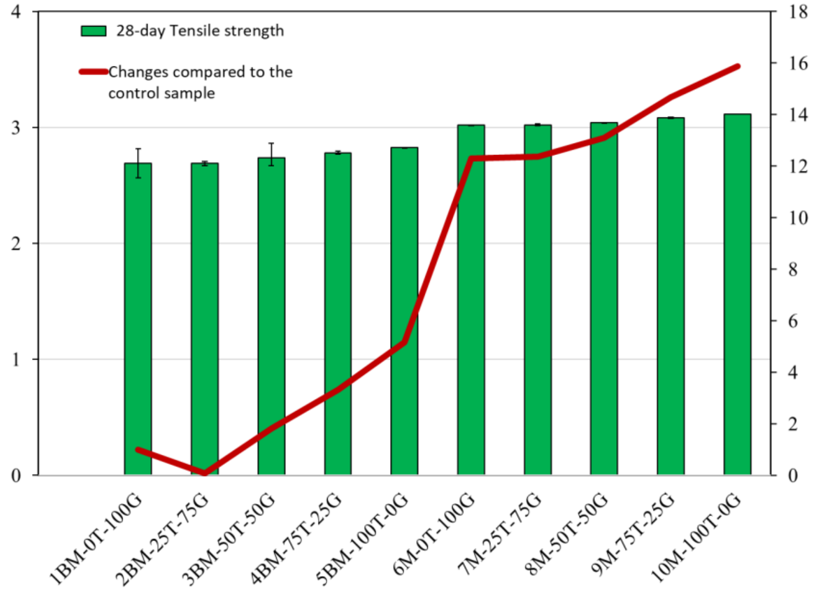

Fig. 4 The results of tensile strength tests at the age of 28 days in terms of MPa

compared to the control mix. According to the test results, the maximum presence of crushed gravel and silica fume intensified the compressive strength.

3.2.2 Results of tensile strength tests

As mentioned earlier, the splitting or Brazilian tensile strength test was performed on cylindrical samples with a height of 300 mm and a diameter of 150 mm. The loading rate was 0.7-1.4 MPa/min. In order to reduce the error rate, the tensile strength results were obtained as the average of three crushed samples at the age of 28 days. The results are shown in Fig. 4.

Fig. 4 shows that the tensile strength of the control sample was 2.689 MPa. The presence of silica fume increased the tensile strength. In Mixes 6 to 10 containing silica fume, compared to Mixes 1 to 5, the tensile strength increased by 12.3%, 12.3%, 11.06%, 10.97% and 10.18%, respectively. In Mixes 1 to 5, as the amount of crushed gravel increased and the amount of natural gravel decreased, the tensile strength increased. The research conducted on the dimensions of the aggregates, shows that the tensile strength decreases with the increase in the aggregate size (Tsiskreli and Dzhavakhidze 1970). Considering the mentioned test results, the maximum presence of crushed gravel and the presence of silica fume increased the tensile strength.

3.2.3 Results of bending strength tests

The bending strength test was carried out on rectangular prism samples with dimensions of 400*100*100 mm^3 and the loading rate was 0.9-1.2 MPa/min using the displacement control method. Three-point bending test method was used for this purpose. Fracture energy is defined as the ability of materials to absorb energy and represents one of the basic parameters of fracture and represents the crack resistance of concrete. In order to reduce the error rate, the bending strength results were obtained as the average of three crushed samples at the age of 28 days, according to which, the fracture energy results were also obtained. All the results are shown in Figs. 5 and 6.

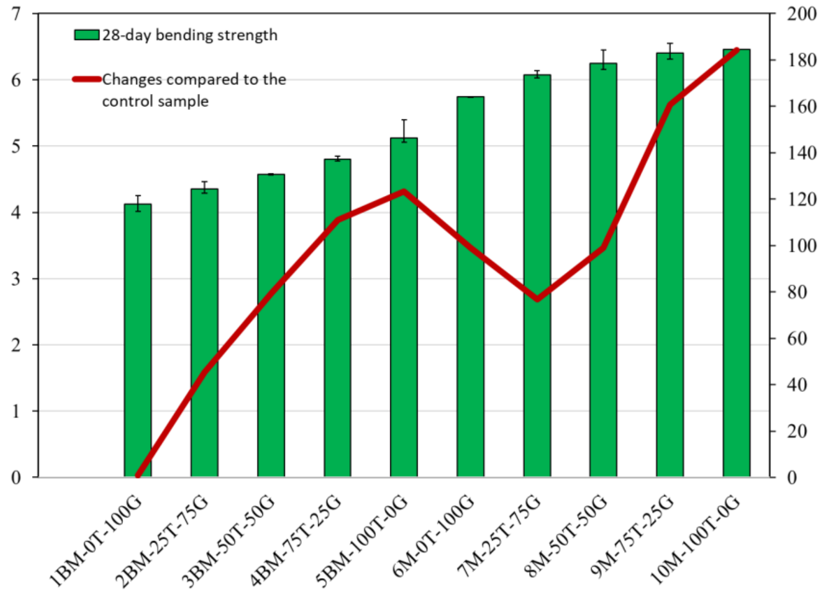

Fig. 5 The results of bending strength tests at the age of 28 days in terms of MPa

Fig. 6 (a) ADR-Touch device for compressive and tensile strength tests and (b) universal device for bending strength tests

Fig. 5 shows the values of bending strength. The bending strength of the control sample was 4.121 MPa. The fracture energy was also calculated by dividing the total area under the load-deflection curve to the cross-section of the prism (Mazloom and Mirzamohammadi 2021, Mazloom *et al*. 2020, Mirzamohammadi and Mazloom 2021, Mazloom and Mirzamohammadi

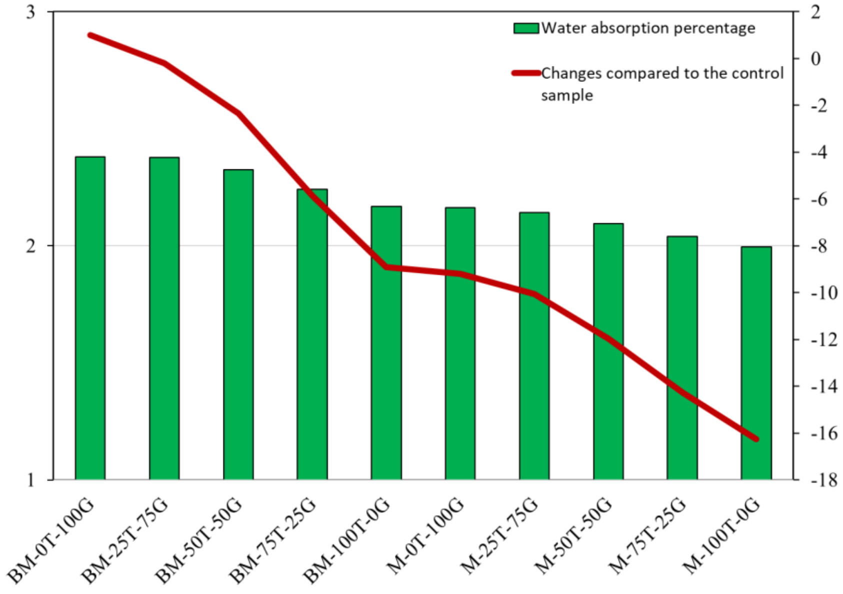

Fig. 7 Test results of water absorption tests

2021). The mode of sample cracking and the fracture energy is significant in the strength of concrete (Karimpour and Mazloom 2022). The presence of silica fume increased the bending strength. In Mixes 6 to 10, compared to Mixes 1 to 5, the bending strength increased 39.31%, 39.71%, 36.69%, and 26.12%, respectively. In Mixes 1 to 5, as the amount of crushed gravel increased and the amount of natural gravel reduced, the bending strength increased. According to another research, the size of aggregate has a great effect on bending strength. It means the increasing the dimensions of gravel decreased the bending strength. According to the mentioned tests, the maximum presence of crushed gravel next to silica fume increased the fracture energy of concrete. Fig. 6 shows the devices for compressive, tensile and bending strength tests.

3.2.4 Half hour water absorption

This non-destructive test was used to check the permeability of concrete. One of the factors that directly affects the concrete durability is its permeability. The higher the percentage of water absorption, the less durable concrete is. The presence of silica fume decreased the percentage of water absorption (see Fig. 7). In Mixes 6 to 10, compared to Mixes 1 to 5, the percentage of water absorption decreased by 9.19%, 9.89%, 9.84%, 8.92% and 8.06%, respectively. In Mixes 1 to 5, as the amount of crushed gravel increased and the amount of natural gravel decreased, the percentage of water absorption decreased. According to the mentioned tests, the maximum presence of crushed gravel next to silica fume reduced the percentage of water absorption.

3.3 Scanning electron microscopy (SEM)

Scanning electron microscopy (SEM) is a new and non-destructive method that can be used to examine the structure and behavior of concrete. As shown in Fig. 8, the analysis of the images

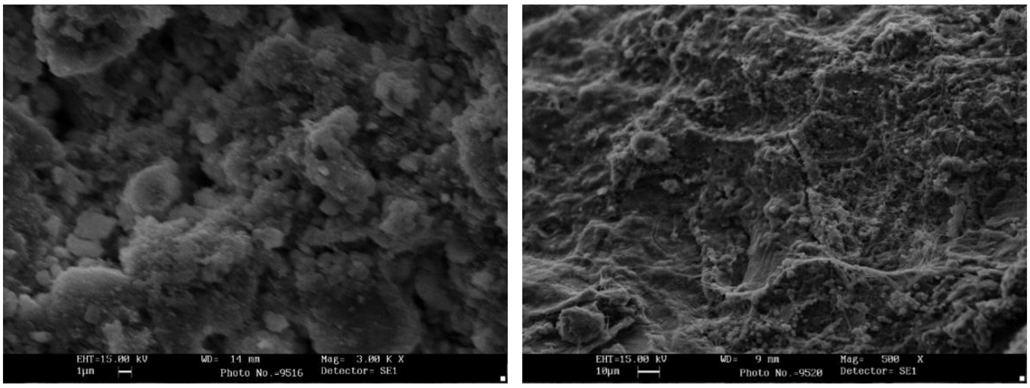

Fig. 8 (a) Control design with 100% natural gravel and (b) Design 10 with 100% crushed gravel and silica fume

Table 9 Evaluation results of the best mixing plan

Design code	Design No.	Hard concrete properties	Fresh concrete properties	Total
BM-0T-100G	1	0	1	1
BM-25T-75G	2	0.26	0.84	1.1
BM-50T-50G	3	0.55	0.6	1.15
BM-75T-25G	4	0.9	0.28	1.18
BM-100T-0G	5	1	0	1
M-0T-100G	6	0	1	1
M-25T-75G	7	0.175	0.82	0.995
M-50T-50G	8	0.4	0.425	0.825
M-75T-25G	**9**	**0.93**	**0.32**	**1.25**
M-100T-0G	10	1	0	1

obtained from the mixes displays that the presence of silica fume and the angularity of the crushed gravel shape have reduced the voids and increased the concrete uniformity. These factors have caused the reduction of voids and weak points in the samples. As a result, the highest compressive, tensile, and bending strengths were obtained in Mix 10 containing 100% crushed gravel and silica fume.

3.4 Choosing the best mix design

Based on the analysis of test results, choosing the best mix considering all the fresh and hardened properties of concrete is complicated. Therefore, it is decided to use the optimization method to find the best mix in this research (Ehsani *et al*. 2022). Optimization in civil engineering refers to the process of finding the best solution to a problem within a set of constraints. Optimization can be used as a crucial aspect of concrete mix design. Some key aspects and methods of optimization in engineering are objective functions, Constraints, and decision Variables. Decision variables are the parameters that can be adjusted or controlled to achieve the optimum solution. The decision variables of this research can be seen in Table 9.

Because of the limited number of data, a simple numerical method was used to find the best mix design. According to the previous experiences (Mazloom and Salehi 2018, Mazloom *et al.* 2020, Mazloom and Mahboubi 2017, Mazloom *et al.* 2018), a score was chosen for the fresh and hardened properties of each mix (see Table 9). In fact, according to the performance of each mix in the tests, some scores between 0 and 1 are assigned to the results in Table 9. Finally, the fresh and hardened scores of each mix were summed. Based on this method, Mix 9 was introduced as the best mix among all the mix designs.

4. Conclusions

In this investigation, the effects of using the combination of natural and crushed gravel in self-compacting concrete (SCC) is studied. The main results obtained from fresh and hardened SCC are:

- In the initial fresh concrete test results, Mix 1 with 100% natural gravel and without silica fume was the best mix. As the percentage of natural gravel reduced, the rheology of concrete decreased. This means that to have SCC properties in all the mixes, the level of superplasticizer was not constant. With the increase of 52.38% in the dosage of superplasticizer in the mixes containing silica fume and crushed gravel, the problem of reducing the rheology of concrete was solved.
- In the compressive strength tests, the type of gravel used did not have a significant effect on most of the test results.
- The presence of silica fume in the mixes could increase the compressive strength. Mix 6 with 100% natural gravel and silica fume resulted in an increase of 16.53% compared to the control mix which included 100% natural gravel.
- The presence of both silica fume and crushed gravel increased the tensile strength in all the tests. Compared to the control mix, Mix 10, which contained both of the above factors, had an increase of 15.87% in tensile strength.
- By increasing the amount of crushed gravel instead of natural gravel and silica fume, the bending strength improved. In Mix 10, the bending strength experienced a significant increase of 56.63% compared to the control mix.
- Considering both fresh and hardened properties of SCC, neither Mix 1 with 100% natural gravel and nor Mix 10 with 100% crushed gravel was the best mix. The results of optimization analysis showed that Mix 9 with 25% natural gravel, 75% crushed gravel and silica fume was the best mix.

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