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Investigation of the Mechanical Properties of Self-compacting Concretes Containing Mineral Additives Produced by Substituting Fine Recycled Aggregate in Different Rates

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Abstract

In the study, the effect of fine recycled concrete aggregate (FRCA) replaced by natural fine aggregate on some mechanical properties of self-compacting concrete (SCC) containing different types and amounts of mineral additives was evaluated. In the concretes produced for this purpose, natural fine aggregate was replaced with FRCA at the ratios of 35%, 70% and 100% by weight. For comparison, concretes without FRCA were also produced. Three different mineral additives, namely fly ash (FA), metakaolin (MK) and silica fume (SF), were used in different ratios. In order to determine the fresh state properties of concretes, unit weight, slump-flow, T_{500} time, J-ring and sieve segregation tests were carried out, while compressive strength, splitting tensile strength, flexural strength, Böhme abrasion and dynamic elasticity modulus determination tests were carried out on hardened concretes. Based on the findings obtained, there is no significant adverse effect on the mechanical properties of concrete with 35% FRCA replacement. However, when FRCA is used at higher ratios, the negative effect on mechanical properties becomes evident. In particular, Böhme abrasion is quite high at high FRCA replacement ratios. Provided that the conditions in which the research was carried out are valid, the negative effects of FRCA substitution on the mechanical properties of concrete can be eliminated by changing the type and combination ratios of mineral additives used.

Keywords

fine recycled concrete aggregate (FRCA), self-compacting concrete (SCC), mechanical properties, mineral additives, Böhme abrasion test, resonant frequency test

1 Introduction

In parallel with the increasing population, consumption and renovation in the construction sector, as in all other sectors, is increasing rapidly. While on one hand, significant increases are observed in the building stock constructed to meet people's shelter and living needs, on the other hand, it is witnessed that many old buildings are being demolished within the scope of urban transformation. As a result, large amounts of debris are generated [1]. It has been reported that the recovery rate of construction and demolition waste (CDW) in the member states of the European Union varies greatly from one member to another, and this rate is between 10% and 95%. More than 800 million tons of CDW are generated each year in the construction sector in Europe [2]. It is reported that these CDWs constitute 25–30% of all waste [3]. Large amounts of CDW are being stored in certain areas. This situation rapidly reduces storage capacity and as a result, a significant increase in storage costs occurs. In addition, CDW waste causes visually undesirable problems in the living environment [4].

Aggregate is the most important constituent of concrete as it constitutes about 70% of the concrete by volume [1, 5]. Aggregates are widely used in the construction industry, primarily in concrete production and asphalt mixtures, as ballast and filling materials, in road foundations, decorative applications, filter and drainage environments and similar manufacturing processes. In this respect, aggregate is considered a strategic material closely related to the development of a country's infrastructure [6]. While it was reported that the consumption of natural aggregate in the world was approximately 45 billion tons in 2017, it is

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predicted that the use of natural aggregate in concrete production will reach 66 billion tons by 2025 [7].

Owing to significant amounts of carbon dioxide (CO_2) emissions result from the use of fuel, electricity, and explosives in aggregate production quarries. Additionally, various environmental issues such as depletion of natural resources, soil erosion, noise pollution, degradation of natural ecosystems, and decreased water quality are also noteworthy as other significant problems arising from aggregate production and its use in the construction industry [8].

The use of CDW, especially the concrete parts, as aggregate in structural concrete production has become widespread in recent years. As a result of the increasing use of recycled concrete aggregate (RCA) in concrete production, which is accepted as part of the sustainable development approach, some international regulations on concrete recommend replacing a portion of the natural aggregate in concrete with recycled aggregate [9]. Some important regulations have been made regarding the use of CDWs. These regulations define three waste material groups: broken concrete, broken wall and mixed demolition rubble [10].

The idea of substituting CDWs, especially broken concrete, obtained from concrete structures that have completed their structural life, into aggregate size or breaking up the remaining concrete from concrete production and replacing natural aggregates in certain proportions in concrete production has become widespread in recent years. It has been stated in many studies that the main difference between natural aggregate and RCA obtained in this way is the presence of old mortar adhering to the RCA surface, which has an important effect on the performance of the concrete [11]. It has been proven by many experimental studies that substituting RCA instead of natural aggregate in concrete production is suitable in terms of fresh state properties, mechanical properties and durability properties of concrete, especially for high-performance concretes [11, 12].

In the design of complex structures, there are still concerns about whether the concrete vibration process can be carried out properly in densely reinforced structural elements. In parallel with the advances in concrete technology and customer demands, the production of high-performance concrete has become an inevitable need. In order to meet the demand, researchers have succeeded in designing and producing self-compacting concrete (SCC), which can be compacted under its own weight, especially in densely reinforced structural elements. SCC is a concrete with sufficient viscosity to be placed uniformly in the formwork without showing bleeding or segregation under the effect of gravity, thanks to its good rheological properties in its fresh state. Interest in SCC has increased day by day and as a result, its global recognition has increased rapidly in recent years. Noise and similar problems frequently encountered in conventional concrete due to the placement and compression processes are not experienced in SCC. In addition, it is reported that the construction period is generally shorter in projects where SCC is used [13–15].

It is reported that when fine natural aggregate is replaced by fine RCA at 20%, the compressive strength of SCC decreases by 10% [16], increases by 7% when it is replaced by 20% [17], and decreases by 26% when it is replaced at 100% [18]. Another study indicated that the mechanical properties of concretes produced by replacing 30% of natural sand with fine recycled concrete aggregate (FRCA) were adversely affected [19].

RCA has a more porous structure compared to natural aggregate due to the cement paste adhering to its surface, and therefore has high water absorption and low density. For this reason, the usability of RCA in concrete is limited because concretes produced with RCA show weaker performance [20]. The presence of old cement paste adhering to RCA, together with the old and new interface transition zones (ITZ), is considered responsible for the decreased performance of the concrete [21].

The aim of this study is to produce SCC by using concrete road waste crushed into FRCA instead of natural fine aggregate in certain proportions. In addition, within the scope of the study, the relationship between some mechanical properties of SCC produced in this way and mineral additives such as fly ash (FA), metakaolin (MK) and silica fume (SF) was investigated. Although there are few studies in the literature on the use of FRCA in SSC, the number of studies using different mineral additives at different ratios together with FRCA is also quite limited. The purpose of using different mineral additives in different proportions is to find the effective amount on SCCs where different FRCA amounts are used. Another originality of this study is to use innovative experimental methods such as the resonance frequency testing method and to apply tests for different curing times.

2 Materials, mix proportions and methodology

2.1 Materials used

In the study, a cement named CEM I 42.5 R in TS EN 197-1 standard [22] was used. The properties of the cement used are given in Table 1.

Table 1 Properties of cement

Chemical composition (%)		Physical and mechanical properties		
SiO_2	19.45	Residue on 32 μ sieve (%)		8.77
Al_2O_3	4.77	Specific surface (Blaine) (cm^2/g)		3556
Fe_2O_3	3.11	Specific gravity		3.10
CaO	63.03	Setting times (Vicat) (d_{min})	Initial	175
MgO	1.97		Final	220
SO_3	3.06	Water demand (%)		30.46
Na_2O	0.29	Volume expansion (mm)		1
K_2O	0.91	Compressive strength (MPa)	2-day	30
Cl^-	0.01		7-day	43.7
Loss on ignition	3.75		28-day	53.7

Kütahya-Seyitömer Thermal Power Plant FA was used in the study. According to XRF analysis, FA is F type according to the classification made by ASTM C618-22 standard [23]. MK and SF were supplied from commercial companies. The specific gravity of SF is 2.2. The specific surface areas obtained from the suppliers for FA, MK and SF used in the study are 4890 cm^2/g for FA, 17400 cm^2/g for MK and 196800 cm^2/g for SF, respectively. Chemical analyses of FA, MK and SF are given in Table 2.

In the study, aggregate with a maximum aggregate size of 16 mm was used. Crushed stone was used as natural coarse aggregate (4 mm – 16 mm) and crushed sand (< 4 mm) was used as natural fine aggregate. The FRCA (< 4 mm) used in the study was obtained from a concrete road tested in the Karadeniz Technical University (KTU) fast road test laboratory. After the tests, this concrete road was broken, ground and washed in the concrete plant to obtain FRCA. Before crushing the concrete and turning it into aggregate, some tests were carried out on the concrete to determine the properties of the aggregate to be used as FRCA. For this purpose, cores were taken from the concrete and UPV (ultrasonic pulse velocity) and compressive strength tests were performed out on these cores. An average UPV of 4.13 km/h and an average compressive strength of 31.9 MPa were measured on the cores. It is known that crushed limestone aggregate and crushed sand were used in the construction of this concrete road. Therefore, the FRCA aggregate obtained is a crushed limestone based aggregate and consists of old cement paste adhered to its surface. Water absorption and specific gravities of natural coarse aggregate, natural fine aggregate and FRCA used in the production of SCC are given in Table 3. The natural moisture of the aggregates was determined one day before production. Saturation water, calculated by taking into account their water absorption capacity and natural moisture, was added to the mixture before mixing and waited for 10–15 min for this water to be absorbed by the aggregate.

Table 2 Chemical composition of FA, MK and SF (%)

Component	FA	MK	SF
SiO_2	49.4	51.4	93.00
Al_2O_3	19.9	45.2	0.58
Fe_2O_3	11.3	0.702	2.79
CO_2	4.85	–	–
CaO	4.35	0.301	0.60
MgO	3.86	–	1.00
K_2O	2.50	0.122	0.10
SO_3	1.73	–	0.50
V_2O_5	–	0.282	–
SnO_2	–	0.0504	–
P_2O_5	–	0.0824	–
SrO	–	0.0166	–
TiO_2	–	1.88	–
Na_2O	–	–	1.00

Aggregates with almost the same granulometry were used in all mixtures. The reason for this is to eliminate the possible changes in the properties of the concretes due to different granulometry. A polycarboxylic ether-based superplasticizer (SP) was used in order to provide the targeted fresh state properties in SCC. The properties of the SP used are given in Table 4. Tap water was used as mixing water in the production of concretes.

2.2 Mixture proportions

In the light of the preliminary experiments performed, it was decided to take the amount of binder as 550 kg/m^3 and the water to binder ratio as 0.38 for all mixtures. In this way, SCCs were produced by replacing fine natural aggregate with FRCA at ratios of 35%, 70% and 100%. Mineral additives of different types and combinations were also used in the production of concretes. Additionally, productions

Table 3 Some physical properties of the aggregates used

Aggregate type	Specific gravity	Water absorption (%)
Natural fine aggregate	2.66	2.49
Natural coarse aggregate	2.69	1.90
FRCA	2.39	9.30

Table 4 Properties of SP used

Origin of the admixture	Polycarboxylic ether based
Appearance	Brown-liquid
Specific gravity (at 20 °C)	1.11
pH	6.7
Alkali content (%)	≤ 3.00 (by mass)
Chlorine ion content (%)	≤ 0.10 (by mass)

without FRCA were also carried out for comparison. In this way, four SCC mixtures were prepared and produced depending on the mineral additive type and combination.

In this context, the changes in the properties of SCCs with different amounts of FRCA substitution in both fresh and hardened states were evaluated. Here, concrete mixtures containing mineral additives in four different combinations respectively as 30%FA, 20%FA+10%MK, 20%FA+10%SF and 20%FA+5%MK+5%SF were produced and tested. Cement constitutes 70% of the total binder, valid for all mixtures. Concrete mixtures designed in this context are given in Table 5. In Table 5, for example, the concrete mixture given as 30FA+%0MK+%0SF is hereafter designated as 30FA0MK0SF in the text.

2.3 Methodology and tests performed

SCC concretes were produced based on the criteria and recommendations given in the EFNARC [24, 25] specifications. Pan type mixer was used in the production of concrete. In production, attention was paid to ensuring that the fresh state characteristics foreseen for SCCs by EFNARC were met. For this purpose, a SP was used in required quantities in productions. Unit weight, slump-flow, T_{500} time, J-ring and sieve segregation tests were carried out on fresh concretes. Compressive strength, splitting tensile strength, flexural strength, Böhme abrasion and dynamic modulus of elasticity determination tests were also carried out on hardened concretes. Except for the Böhme abrasion and dynamic modulus of elasticity determination tests, all hardened concrete tests were carried out on specimens subjected to 28 and 90 days of standard curing. For the determination of Böhme abrasion and dynamic modulus of elasticity tests, only concrete specimens that subjected to standard curing of 28 days were used. Compressive strength tests were also performed on specimens that subjected to 7 days of standard curing.

Slump-flow and T_{500} time tests were carried out in accordance with the TS EN 12350-8 standard [26] and EFNARC [24, 25] specifications. For this test fresh SCC was filled into an Abram's cone placed on a metal plate. A weighted collar 9 kg is placed on the cone to prevent concrete from leaking from the bottom of the cone. The time until the concrete reaches a diameter of 500 mm on the metal plate was determined as the spreading time (T_{500}) by the chronometer that was started when the cone was pulled upwards. After the spreading was completed, the spreading diameter of the concrete was determined as the average of two measurements taken perpendicular to each other. EFNARC [25] recommends that the slump-flow for SCC should be 550–850 mm.

The J-ring test was carried out in accordance with the TS EN 12350-12 standard [27] and EFNARC [24, 25] specifications. The test was carried out by measuring the concrete heights just inside (h_1) and just outside (h_2) the J-ring circumference. The height difference determined in the test as ($h = h_2 - h_1$) is specified as a maximum of 10 mm in the EFNARC [24] specifications.

Sieve segregation test was also carried out in accordance with TS EN 12350-11 standard [28] and EFNARC [25] specifications. Photos of the slump-flow test, the J-ring test

Table 5 Mixture proportions for SCC (in kg/m^3)

Concrete mixtures	FRCA repl. ratio (%)	Cement	FA	MK	SF	Water	Coarse agg.	Fine agg.	FRCA	SP
30FA0MK0SF	0	385	165	0	0	209	619	918	0	7.6
	35							597	288	8.0
	70							275	577	8.1
	100							0	824	8.6
20FA10MK0SF	0		110	55	0		622	922	0	7.9
	35							599	290	8.6
	70							277	579	8.5
	100							0	828	8.7
20FA0MK10SF	0			0	55		618	916	0	10.9
	35							595	288	11.4
	70							275	575	11.5
	100							0	822	11.8
20FA5MK5SF	0			27.5	27.5		620	919	0	9.0
	35							597	289	9.6
	70							276	577	9.7
	100							0	825	9.8

and the sieve segregation test are given in Fig. 1. Fresh concrete unit weights were determined on 15 cm cube specimens in accordance with the TS EN 12350-6 standard [29].

The compressive strength test was carried out in accordance with the TS EN 12390-3 [30] standard and three 15 cm cube specimens were used for each measurement. The test was carried out in a press with a capacity of 250 tons. Splitting tensile test was carried out in accordance with TS EN 12390-6 [31] standard and two cylindrical specimens with a diameter of 10 cm and a height of 20 cm were used in the test for each measurement. The flexural test was carried out on prismatic specimens with dimensions of 100 × 100 × 400 mm in accordance with the TS EN 12390-5 [32] standard. In this test, two prisms were used for each measurement. Photographs of the equipment used in compression test, splitting tensile test and flexural tests are given in Fig. 2.

Böhme abrasion test was carried out in accordance with the DIN 52108 standard [33] and the equipment used in the test is given in Fig. 3. In the Böhme abrasion test, two 70 mm cube specimens were used for each measurement.

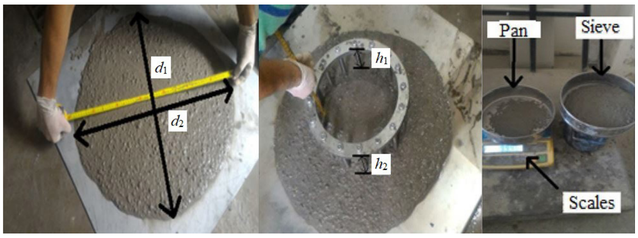

Fig. 1 Photos of the slump-flow test, J-ring test and sieve segregation test

Fig. 2 Equipment used in compression test, splitting tensile test and flexural test

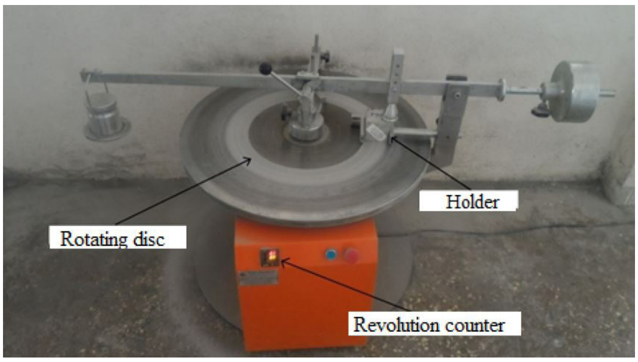

Fig. 3 Equipment used in Böhme abrasion test

Dynamic modulus of elasticity was determined by resonance frequency technique on prismatic specimens with dimensions of 100 × 100 × 400 mm in accordance with BS 1881: Part 209 standard [34]. The test was performed on prisms that were kept in the laboratory for approximately 5 h after 28 days of standard curing. Two prisms were used for each measurement in performing the test. The photo of the testing setup is given in Fig. 4.

As seen in Fig. 4, the sound given by the sound generator at one end of the prismatic specimen, which is placed on a support at its middle point, is received by the sound receiver at the other end. While the sound generator sends vibrations to the specimen at increasing frequencies, the sound receiver continuously transmits the changing vibrations and their intensities to the control unit in order to determine at which frequency the vibrating specimen resonates. After the sample is scanned at certain frequencies, the frequency at which the specimen resonates is determined and reflected on the control unit screen. This entire process is carried out automatically by the control unit. The dynamic modulus of elasticity of the concrete is calculated by substituting the obtained resonance frequency into the expression given in the BS 1881: Part 209 standard [34].

$$E_D = 4\eta^2 L^2 \rho 10^{-15} \tag{1}$$

In Eq. (1), E_D is the dynamic modulus of elasticity of the concrete (GN/m^2), L is the length of the specimen (mm), η is the longitudinal resonance frequency of the specimen (Hz), and ρ is the unit weight of the concrete (g/cm^3).

3 Results and discussion

3.1 Properties of fresh SCCs

Fresh state properties of SCC determined in accordance with relevant standards and specifications are given in Table 6.

As seen in Table 6, the slump-flows of SCCs vary between 650 and 730 mm. Therefore, all concretes meet the criteria specified in the EFNARC [25] specification in terms of slump-flow. The measured T_{500} times are greater than 2 s for all concretes and the concretes are in the VS2/VF1 class as stated in the EFNARC [25] specification. J-ring measurements for all concretes meet the 10 mm

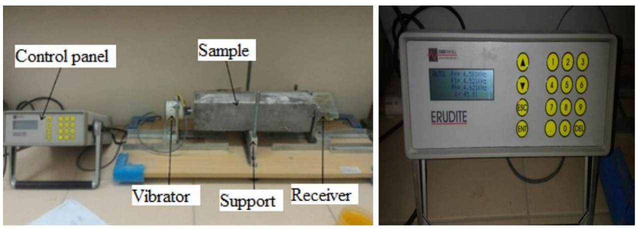

Fig. 4 Resonance frequency testing setup

Table 6 Properties measured on fresh SCCs

Concrete mixtures	FRCA replacement ratio (%)	Slump-flow (mm)	T_{500} (s)	J-ring (mm)	Sieve segregation (%)	Unit weight of fresh concrete (g/cm³)	SP (%)*
30FA0MK0SF	0	660	2.74	8	2	2.29	1.38
	35	730	2.1	9	12	2.29	1.45
	70	710	2.02	8	14	2.24	1.48
	100	715	2.14	8	14	2.19	1.56
20FA10MK0SF	0	670	2.22	9	1	2.26	1.44
	35	680	2.25	8	7	2.27	1.56
	70	660	2.18	9	7	2.23	1.54
	100	670	2.04	9	7	2.19	1.58
20FA0MK10SF	0	650	2.24	8	1	2.29	1.98
	35	690	2.28	8	8	2.25	2.08
	70	695	2.43	9	2	2.21	2.09
	100	710	2.1	8	2	2.19	2.15
20FA5MK5SF	0	728	2.24	9	7	2.29	1.63
	35	670	2.4	9	2	2.23	1.74
	70	670	2.4	8	3	2.20	1.76
	100	690	2.2	8	4	2.19	1.79

* SP (%) expresses the ratio of the amount of SP to the total amount of binder as a percentage

criterion specified in the EFNARC [24] specification. Sieve segregation test results are seen to be less than 15% for all concretes. Therefore, according to EFNARC [25] specification, all concretes are in SR2 class.

The measured fresh unit weights ranges from 2.19 g/cm³ to 2.29 g/cm³. Using high dosage binders in production, the low specific gravity of mineral additives compared to cement and the low unit volume weight of FRCAs compared to natural aggregates caused the unit volume weights of the produced concrete to be relatively low. The decrease in unit weight shows a significant increase parallel to the increase in the fine FRCA substitution ratio. As can be seen from the same table, as the FRCA substitution ratio increases, the amount of SP used also increases. This is because FRCA particles are more angular and rougher compared to natural aggregate and their friction with the cement paste is stronger. The fact that the structure of the aggregate is angular and rough and also has more pores naturally increases the need for water for a certain consistency [35]. Naturally, all these factors have an adverse effect on the workability of concrete. Considering the mineral additive combinations, the amount of SP used in the 20%FA+10%SF combination, where SF is used at a high ratio, is higher than in other combinations for equal slump. Since the use of high fineness SF in the mixture adversely affects the workability of the concrete, more water or SP is required for the target workability [36, 37].

3.2 Compressive strength measurements

Compressive strengths measured on SCCs at the end of 7 days of standard curing are given in Fig. 5. As can be seen from Fig. 5, while no significant change is observed in the compressive strengths of concretes with 35% FRCA replacement compared to concretes without FRCA, there is a decrease in the compressive strengths of concretes with 70% and 100% FRCA replacement. The decrease in compressive strength of concretes with 100% FRCA replacement compared to those without FRCA is on average 10% to 16%. Regardless of the FRCA replacement, the highest strength is provided by concretes containing 10% MK. For example; when concretes produced with natural fine aggregate are evaluated, it is seen that the compressive

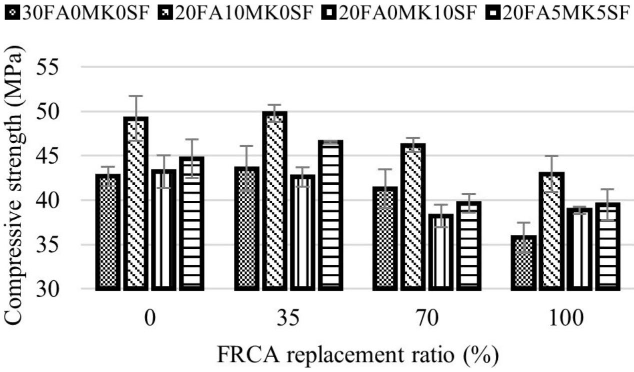

Fig. 5 Compressive strengths of concretes subjected to 7-day standard curing

strength of concrete containing 10% MK is 15% higher than that containing 30% FA, 14% higher than that containing 10% SF and 10% higher compared to the combination of 5% MK + 5% SF. It can be said that this is due to the high Al_2O_3 content of MK. MK provides an advantage over other mineral additives due to its high Al_2O_3 content, which makes a positive contribution to strength at early ages [38, 39]. There are studies in the literature indicating that Al_2O_3 makes a significant contribution to compressive strength at early ages. In a study where nano Al_2O_3 was used as a 1.5% replacement for cement, a 17% increase in compressive strength of concrete specimens subjected to standard curing of 7 days was reported [39]. The findings of the current study are consistent with the findings obtained from this study.

Compressive strengths measured on SCCs at the end of 28 days of standard curing are given in Fig. 6. As can be seen from Fig. 6, the compressive strengths of the concretes containing 30% FA show a slight decrease due to the increase in FRCA substitution, while there is no significant change in the compressive strengths of the other concretes in which FRCA is substituted. Compared to concrete without FRCA, the decrease in compressive strength of concretes containing 100% FRCA is 8% in concrete containing 30% FA, 3% in those containing 10% MK, 1% in those containing 10% SF and 3% in those containing 5% MK+5% SF. Even when fine natural aggregate is replaced by FRCA at a ratio of 100%, the decrease in compressive strength of concretes remains at a very low level. Regardless of the FRCA replacement, the highest compressive strength is obtained in concretes with a combination of 5% MK + 5% SF. The compressive strength of 5% MK+5% SF concretes without FRCA is 15% higher than concretes containing 30% FA, 10% higher than those containing 10% MK and 6% higher than those containing 10% SF.

In SCCs where MK and SF are used together, a higher level of strength is achieved compared to other concretes at the end of the 28-day standard curing. Considering the compressive strengths obtained at the end of 28 days, it is seen that the development of compressive strengths of concretes using FA is slower than those using MK and SF. Bayraktar et al. [40] reported a 29% decrease in the compressive strength of concretes with 80% FRCA replacement in their study. Similarly, in their study, Gesoglu et al. [41] reported a decrease of 20% in the compressive strength of concretes with 100% FRCA replacement. It can be said that the results obtained from the current study coincides with the literature in this context, but the loss observed in compressive strength remains at a lower level. It is thought that the positive effect of the combined use of MK and SF on compressive strength may be due to the synergetic effect and filler effect of these mineral additives, which increases with the extension of the curing period from 7 to 28 days. The effect that emerged in this way caused the strength to be higher.

Compressive strengths measured on SCCs at the end of 90 days of standard curing are given in Fig. 7. As can be seen from Fig. 7, compressive strengths tend to decrease slightly depending on the increase in FRCA replacement. Compared to concretes without FRCA, the decrease in compressive strength of concretes with 100% FRCA replacement is 21% in those containing 30% FA, 15% in those containing 10% MK, 14% in those containing 10% SF and 7% in those containing 5% MK+5% SF.

The study clearly shows that the decrease in strength due to FRCA substitution can be prevented by using different amounts and combinations of mineral additives. For example, as seen in Fig. 6, the 28-day compressive strength of the concrete without FRCA and 30% FA is 55.92 MPa, while the compressive strength of the concrete

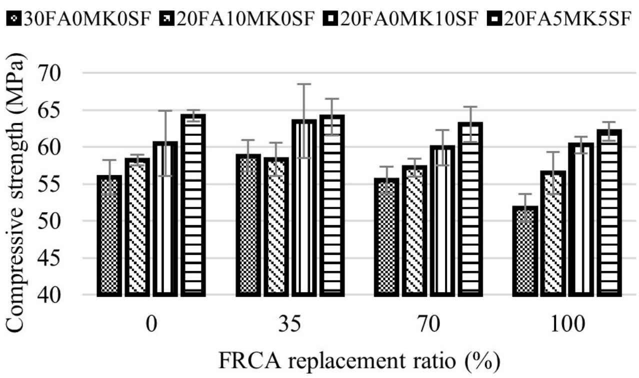

Fig. 6 Compressive strengths of concretes subjected to 28-day standard curing

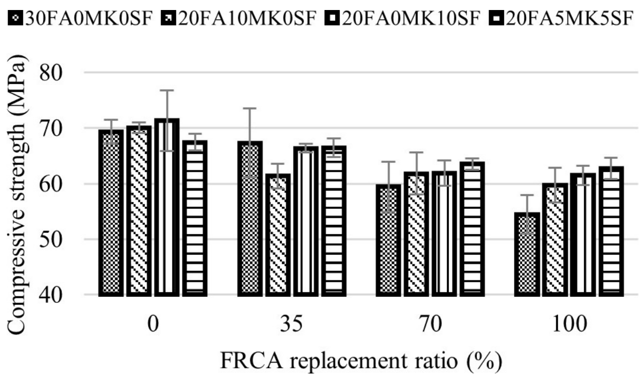

Fig. 7 Compressive strengths of concretes subjected to 90-day standard curing

with 100% FRCA replacement is 51.71 MPa. It is possible to prevent the 8% decrease in compressive strength by reducing the FA by 10% and replacing it with a combination of 5% MK + 5% SF, and it is possible to obtain up to 11% higher compressive strength. It may be possible to make the use of FRCA sustainable in concrete production by eliminating the loss in compressive strength due to the use of FRCA in this way. In addition, since the compressive strength of all SCCs is over 50 MPa at the end of the 28 days of standard curing, these concretes can be considered as high strength concrete. In addition, while MK has a positive effect on early compressive strength (7 days), SF is seen to be more effective at later ages (90 days).

While there is no significant change (except for 100% FRCA concretes) in 28-day compressive strengths regardless of FRCA substitution, there is a slight decrease in 90-day compressive strengths as the FRCA substitution ratio increases. In some studies, increases in the compressive strength of concretes are reported depending on the increase in the FRCA replacement. Kou and Poon [42] stated in their study that they found an increase in compressive strength up to 50% FRCA replacement level. Similarly, Hu et al. [43] observed a slight increase in the 28-day compressive strength of SCC up to 75% FRCA replacement level in their study.

3.3 Splitting tensile strength measurements

Splitting tensile strengths measured on SCCs at the end of 28 days of standard curing are given in Fig. 8. As can be seen from Fig. 8, while there is no significant change in the splitting tensile strength of concretes with 35% FRCA replacement compared to those without FRCA, the decrease in the strength of those with higher levels of FRCA replacement becomes evident. When natural fine aggregate is replaced with 100% FRCA, splitting tensile strength decreases by 7% to 17%. Regardless of the FRCA replacement, the splitting tensile strengths of concretes containing 5% MK+5% SF are higher than those of other concretes. The splitting tensile strengths of 5% MK+5% SF concretes without FRCA are 18% higher than those containing 30% FA, 12% higher than those containing 10% MK and 7% higher than those containing 10% SF. Therefore, it is highly probable that 5% MK+5% SF concretes will yield better results in terms of splitting tensile strength rather than concretes containing only 10% MK or 10% SF in SCCs. In their study, Bahrami et al. [44] observed a 30.7% decrease in splitting tensile strength of concretes with 100% FRCA replacement. Zhong et al. [45] produced concretes containing 5% MK + 15% FA with a total binder of 410 kg/m^3 and stated that the splitting tensile strengths of concretes containing 30% FRCA were higher than those without FRCA. They also report a 10% decrease in splitting tensile strength of concretes containing 90% FRCA. The findings obtained in the present study are consistent with these results.

Splitting tensile strengths measured on FRCA substituted SCCs at the end of 90 days of standard curing are given in Fig. 9. Compared to concretes without FRCA, the splitting tensile strengths of those containing 35% FRCA increased by 4%, while there was a significant decrease in the strengths of concretes with 70% and 100% FRCA replacement. When all of the fine natural aggregate is replaced with FRCA, the decrease in splitting tensile strength varies between 10% and 24%. This negativity observed in mechanical properties is due to the weakness of the old and new interfaces in the concrete and the presence of old cement paste between these interfaces.

As seen in Figs. 8 and 9, regardless of the type and combination of mineral additives, the use of 35% FRCA does not have any negative effect on the splitting tensile strength of concrete. This study has shown that the loss in strength due to the use of FRCA can be prevented by

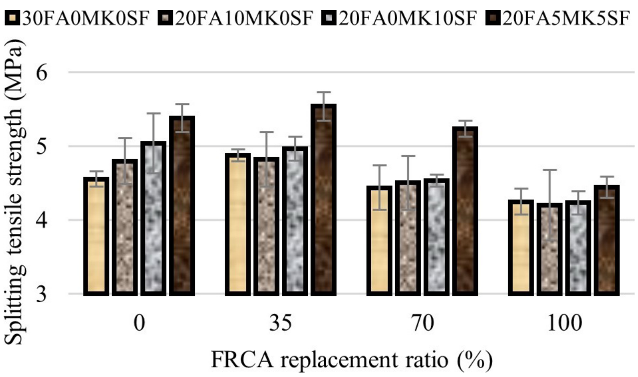

Fig. 8 Splitting tensile strengths of concretes subjected to 28-day standard curing

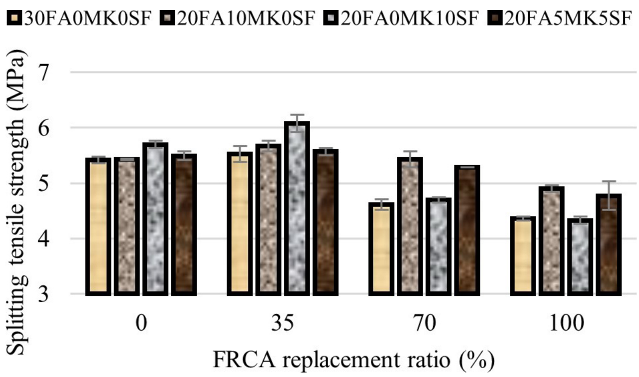

Fig. 9 Splitting tensile strengths of concretes subjected to 90-day standard curing

using different types and combinations of mineral additives. For example, as seen in Fig. 8, the splitting tensile strength of the concrete with 30% FA content without FRCA is 4.56 MPa, while the splitting tensile strength of the concrete with 100% FRCA replacement is determined as 4.25 MPa. It is seen that the very small decrease in tensile strength at splitting can be compensated by removing 10% FA from the mixture and adding 5% MK + 5% SF combination. While a very slight decrease in 28-day splitting tensile strengths is observed due to the increase in FRCA replacement ratio, the decrease observed in 90-day strengths is more pronounced. While a very small decrease in 28-day splitting tensile strengths was observed due to the increase in FRCA replacement, the decrease observed in 90-day strengths was more pronounced. Among the concretes produced with different aggregate combinations, 20FA5MK5SF concrete yielded the highest strength. The positive effect of SF is more evident in FRCA-free and 35% FRCA-containing concretes cured for 90 days.

3.4 Flexural strength measurements

Flexural strengths measured on SCCs at the end of 28 days of standard curing are given in Fig. 10. As can be seen from Fig. 10, as the FRCA replacement ratio increases, there is a slight decrease in the flexural strengths of the concretes. The decrease in flexural strength of concretes containing 100% FRCA compared to those without FRCA is 26% in those containing 30% FA, 24% in those containing 10% MK, 12% in those containing 10% SF and 16% in those containing 5% MK+5% SF. Among the FRCA substituted concretes, 5% MK+5% SF combination concretes provide the highest flexural strength, while those with 30% FA content provide the lowest strength.

Flexural strengths measured on SCCs at the end of 90 days of standard curing are given in Fig. 11. As seen from Fig. 11, the flexural strength of the concrete decreases

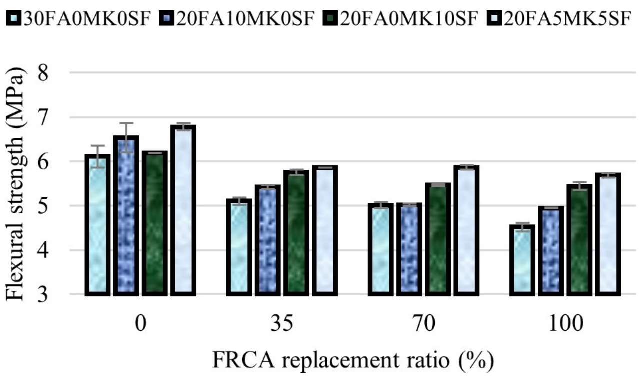

Fig. 10 Flexural strengths of concretes subjected to 28-day standard curing

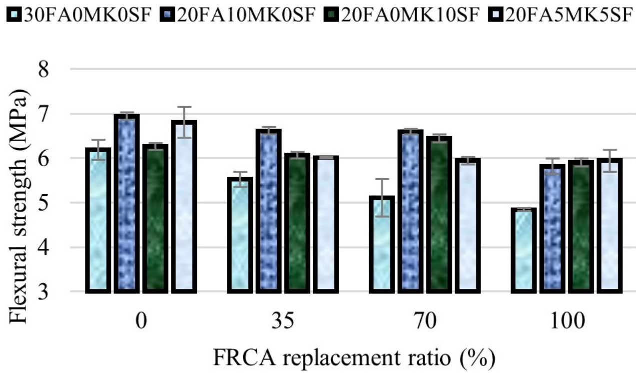

Fig. 11 Flexural strengths of concretes subjected to 90-day standard curing

slightly due to the increase in the FRCA replacement ratio. Compared to concretes without FRCA, the decrease in flexural strength of concretes with 100% FRCA replacement is 22% in those containing 30% FA, 16% in those containing 10% MK, 6% in those containing 10% SF and 13% in those containing 5% MK+5% SF. As seen in Fig. 11, regardless of the FRCA replacement and valid for all concretes, the flexural strengths of concretes with 10% MK replacement are higher than the others.

While Gesoglu et al. [41] reported in their study that the loss of flexural strength in SCCs with 100% FRCA was around 26%, Bahrami et al. [44] stated that this loss was around 28.2% in their study. In this respect, the results obtained in the current study are compatible with the literature.

It has been determined by the existing studies that the negative effect of FRCA substitution on the flexural strength can be eliminated by using different types and combinations of mineral additives. For example, as can be seen from Fig. 10, the flexural strength of the concrete with 30% FA content and no FRCA was determined as 6.11 MPa, while the flexural strength of the concrete with 100% FRCA replacement was determined as 4.52 MPa. It is clearly seen that the 26% decrease in flexural strength can be prevented by using 20% FA instead of 30% FA and adding 5% MK+5% SF. A very slight decrease is observed in both 28-day and 90-day flexural strengths of concrete due to the increase in FRCA substitution ratio.

3.5 Böhme abrasion measurements

Böhme abrasion measurements obtained on SCCs at the end of 28 days of standard curing are given in Fig. 12. As can be seen from Fig. 12, there is a significant increase in the abrasion of concretes due to the increase in the FRCA replacement in SCCs. There are some studies in the literature reporting increases in abrasion due to

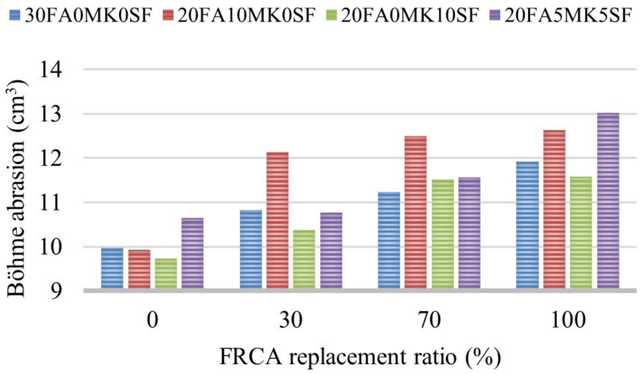

Fig. 12 Böhme abrasion measurement of concretes subjected to 28-day standard curing

increased FRCA usage ratios [46, 47]. There are also studies reporting significant increases in the abrasion of concrete as a result of the substitution of FRCA. For example, Bayraktar et al. [40] reported in their study that the abrasion of concrete with 80% FRCA replacement increased by 58%. In the current study, the increases in the abrasion of concretes in which the fine natural aggregate used was completely replaced with FRCA ranges from 19% to 27%. These findings are consistent with the results of some studies reported in the literature. The significant increase in the abrasion resistance of concretes as the FRCA replacement ratio increases is due to the porous and cracked structure of the old cement paste adhered to the FRCA. Regardless of the FRCA replacement, the lowest abrasion is obtained for concretes containing 10% SF, and a similar result is reported in another study [48]. Due to the high fineness of SF and its high pozzolanic properties, it provides better filling of the voids in the concrete with a dense structure. Abrasion is therefore thought to be lower in concretes containing high levels of SF. After 28 days, the 20FA5MK5SF combination concrete yielded the highest compressive strength, while the 20FA0MK10SF combination concrete showed high abrasion resistance. This indicates that it is not always true to expect a concrete with high compressive strength to also have high abrasion resistance. This is because compressive strength is highly dependent on microstructural properties, while abrasion resistance is more closely related to surface characteristics of the concrete, such as surface roughness and porosity [49]. Therefore, due to its high specific surface, the 10% SF partially improved the surface characteristics of the concrete.

3.6 Determination of dynamic modulus of elasticity

The dynamic elasticity modulus of concrete was determined by the resonance frequency technique. The dynamic modulus of elasticity of the specimens whose resonance frequencies were determined was calculated by means of the relation recommended by the relevant standard. In the test, 100 × 100 × 400 mm prismatic specimens subjected to standard curing for 28 days were used and the dynamic modulus of elasticities calculated by means of the relevant relation were given in Fig. 13. As seen in Fig. 13, the dynamic modulus of elasticities of concretes decrease significantly depending on the increase in the FRCA replacement ratio. The dynamic elasticity modulus of concretes in which natural fine aggregate is replaced by 100% FRCA decrease by 10% to 13%.

The decrease in the dynamic elasticity modules of concretes as the FRCA replacement ratio increases is due to the porous and cracked structure of the old cement paste adhered to the FRCA and the porous structure of the old cement paste. Tang et al. [50] indicate a 22.2% decrease in the dynamic modulus of elasticity of concrete in a study they conducted. It is seen that the findings regarding the dynamic modulus of elasticity of concretes within the scope of the current study are compatible with the literature.

4 Conclusions

The findings obtained from this study can be summarized briefly as follows:

- Up to 35% FRCA substitution has no adverse effect on splitting tensile and compressive strengths, regardless of the curing time. This is particularly important for sustainability in the construction industry.
- The positive contribution of SF to abrasion wear resistance even at high FRCA substitution levels is important for durability, especially in applications subject to wear.
- While MK has a positive effect on early age strength development, the MK+SF combination is effective on long-term mechanical performance.

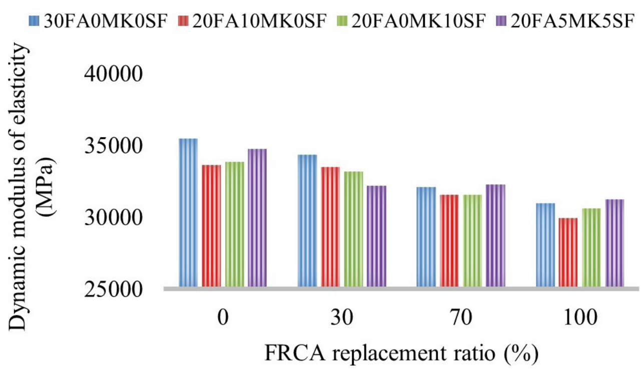

Fig. 13 Dynamic modulus of elasticities of concretes subjected to 28-day standard curing

- The disadvantage caused by the high FRCA substitution ratio in terms of mechanical performance can be compensated by applying long-term curing and appropriate mineral additive strategies, thus ensuring sufficient long-term strength and durability.
- The findings from this study support the possibility of more sustainable concrete production by promoting the use of recycled aggregate while maintaining structural performance and contributes to cyclical economy goals in the construction sector.

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References

[1] Kandil, U. "Some mechanical and durability properties of self-compacting concrete with recycled aggregate containing different mineral additives", PhD Thesis, Karadeniz Technical University, 2021.

[2] Deloitte "Study on Resource Efficient Use of Mixed Wastes, Improving management of construction and demolition waste – Final report", DG ENV, European Commission, Brussels, Belgium, 2017. [online] Available at: https://environment.ec.europa.eu/topics/waste-and-recycling/construction-and-demolition-waste_en

[3] Dodd, N., Donatello, S., Cordella, M. "Level(s) indicator 2.2: Construction and Demolition waste and materials User manual: overview, guidance and instructions (Publication version 1.0)", European Commission, Brussels, Belgium, 2020.

[4] Li, J., Zhang, J., Ni, S., Liu, L., Walubita L. F. "Mechanical performance and environmental impacts of self-compacting concrete with recycled demolished concrete blocks", Journal of Cleaner Production, 293, 126129, 2021.
https://doi.org/10.1016/j.jclepro.2021.126129

[5] Kubissa, W., Jaskulski, R., Brodňan, M. "Influence of SCM on the Permeability of Concrete with Recycled Aggregate", Periodica Polytechnica Civil Engineering, 60(4), pp. 583–590, 2016.
https://doi.org/10.3311/PPci.8614

[6] Kareem, M. A., Raheem, A. A., Oriola, K. O., Abdulwahab, R. "A review on application of oil palm shell as aggregate in concrete - Towards realising a pollution-free environment and sustainable concrete", Environmental Challenges, 8, 100531, 2022.
https://doi.org/10.1016/j.envc.2022.100531

[7] PMR "Global market study on construction aggregates: crushed stone product type segment projected to register high value and volume CAGR during 2017–2025", Persistence Market Research (PMR), New York, NY, USA, 2017.

[8] Hamada, H. M., Thomas, B. S., Tayeh, B., Yahya, F. M., Muthusamy, K., Yang, J. "Use of oil palm shell as an aggregate in cement concrete: a review", Construction and Building Materials, 265, 120357, 2020.
https://doi.org/10.1016/j.conbuildmat.2020.120357

[9] Boudali, S., Kerdal, D. E., Ayed, K., Abdulsalam, B., Soliman, A. M. "Performance of self-compacting concrete incorporating recycled concrete fines and aggregate exposed to sulphate attack", Construction and Building Materials, 124, pp. 705–713, 2016.
https://doi.org/10.1016/j.conbuildmat.2016.06.058

[10] Revilla-Cuesta, V., Skaf, M., Faleschini, F., Manso, J. M., Ortega-López, V. "Self-compacting concrete manufactured with recycled concrete aggregate: An overview", Journal of Cleaner Production, 262, 121362, 2020.
https://doi.org/10.1016/j.jclepro.2020.121362

[11] Berredjem, L., Arabi, N., Laurent, M. "Mechanical and durability properties of concrete based on recycled coarse and fine aggregates produced from demolished concrete", Construction and Building Materials, 246, 118421, 2020.
https://doi.org/10.1016/j.conbuildmat.2020.118421

[12] Guo, H., Shi, C., Guan, X., Zhu, J., Ding, Y., Ling, T.-C., Zhang, H., Wang, Y. "Durability of recycled aggregate concrete – A review", Cement and Concrete Composites, 89, pp. 251–259, 2018.
https://doi.org/10.1016/j.cemconcomp.2018.03.008

[13] Ghoddousi, P., Salehi, A. M. "The Robustness of Self Consolidating Concrete Due to Changes in mixing Water", Periodica Polytechnica Civil Engineering, 61(2), pp. 216–225, 2017.
https://doi.org/10.3311/PPci.8478

[14] Ahmad Wani, T., Ganesh, S. "Study on fresh properties, mechanical properties and microstructure behavior of fiber reinforced self compacting concrete: a review", Materials Today: Proceedings, 62, pp. 6663–6670, 2022.
https://doi.org/10.1016/j.matpr.2022.04.666

[15] Oualit, M., Irekti, A., Melinge, Y. "Saturation Point of Superplasticizers Determined by Rheological Tests for Self Compacting Concrete", Periodica Polytechnica Civil Engineering, 62(2), pp. 346–352, 2018.
https://doi.org/10.3311/PPci.11247

[16] Campos, R. S., Barbosa, M. P., Pimentel, L. L., de Freitas Maciel, G. "Influence of recycled aggregates on rheological and mechanical properties of self-compacting concrete", Revista Matéria, 23(1), e-11964, 2018.
https://doi.org/10.1590/s1517-707620170001.0300

[17] Vinay Kumar, B. M., Ananthan, H., Balaji, K. V. A. "Experimental studies on utilization of coarse and finer fractions of recycled concrete aggregates in self compacting concrete mixes", Journal of Building Engineering, 9, pp. 100–108, 2017.
https://doi.org/10.1016/j.jobe.2016.11.013

[18] Santos, S. A., Da Silva, P. R., De Brito, J. "Mechanical Performance Evaluation of Self-Compacting Concrete with Fine and Coarse Recycled Aggregates from the Precast Industry", Materials, 10(8), 904, 2017.
https://doi.org/10.3390/ma10080904

[19] Evangelista, L., de Brito, J. "Mechanical behaviour of concrete made with fine recycled concrete aggregates", Cement and Concrete Composites, 29(5), pp. 397–401, 2007.
https://doi.org/10.1016/j.cemconcomp.2006.12.004

[20] Xie, J., Kou, S., Ma, H., Long, W.-J., Wang, Y., Ye, T.-H. "Advances on properties of fiber reinforced recycled aggregate concrete: Experiments and models", Construction and Building Materials, 277, 122345, 2021.
https://doi.org/10.1016/j.conbuildmat.2021.122345

[21] Kong, L. J., Meng, Q. C., Du, Y. B. "Effect of Coarse Aggregate Types on the Microstructure of the ITZ and Durability of Concrete", Advanced Materials Research, 838–841, pp. 1801–1805, 2014.
https://doi.org/10.4028/www.scientific.net/amr.838-841.1801

[22] TSE "TS EN 197-1 Cement – Part 1: Composition, specification and conformity criteria for common cements", Turkish Standard, Ankara, Türkiye, 2012.

[23] ASTM "ASTM C618-22 Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete", ASTM International, West Conshohocken, PA, USA, 2023.
https://doi.org/10.1520/C0618-22

[24] EFNARC "Specification and guidelines for self-compacting concrete", European Federation of Specialist Construction Chemicals and Concrete Systems (EFNARC), Farnham, UK, 2002.

[25] EFNARC "European guidelines for self-compacting concrete: specification, production and use", European Federation for Specialist Construction Chemicals and Concrete Systems (EFNARC), Farnham, UK, 2005.

[26] TSE "TS EN 12350-8 Testing fresh concrete - Part 8: Self-compacting concrete - Slump-flow test", Turkish Standard, Ankara, Türkiye, 2019.

[27] TSE "TS EN 12350-12 Testing fresh concrete - Part 12: Self-compacting concrete - J-ring test", Turkish Standard, Ankara, Türkiye, 2011.

[28] TSE "TS EN 12350-11 Testing fresh concrete - Part 11: Self-compacting concrete – Sieve segregation test", Turkish Standard, Ankara, Türkiye, 2011.

[29] TSE "TS EN 12350-6 Testing fresh concrete - Part 6: Density", Turkish Standard, Ankara, Türkiye, 2019.

[30] TSE "TS EN 12390-3 Testing hardened concrete - Part 3: Compressive strength of test specimens", Turkish Standard, Ankara, Türkiye, 2019.

[31] TSE "TS EN 12390-6 Testing hardened concrete - Part 6: Tensile splitting strength of test specimens", Turkish Standard, Ankara, Türkiye, 2010.

[32] TSE "TS EN 12390-5 Testing hardened concrete - Part 5: Flexural strength of test specimens", Turkish Standard, Ankara, Türkiye, 2019.

[33] DIN "DIN 52108 Wear testing of inorganic, nonmetallic materials using the Böhme abrasive wheel", Deutsches Institut für Normung, Berlin, Germany, 2002.

[34] BSI "BS 1881: Part 209 Testing concrete: Part 209. Recommendations for the measurement of dynamic modulus of elasticity", British Standards Institution, London, UK, 1990.

[35] Popovics, S. "Fundamentals of Portland Cement Concrete: A quantitative approach Vol. 1: Fresh Concrete", John Wiley and Sons., Inc., 1982. ISBN 0471862177

[36] Sarıdemir, M. "Effect of silica fume and ground pumice on compressive strength and modulus of elasticity of high strength concrete", Construction and Building Materials, 49, pp. 484–489, 2013.
https://doi.org/10.1016/j.conbuildmat.2013.08.091

[37] Hamada, H. M., Abed, F., Binti Katman, H. Y., Humada, A. M., Al Jawahery, M. S., Majdi, A., Yousif, S. T., Thomas, B. S. "Effect of silica fume on the properties of sustainable cement concrete", Journal of Materials Research and Technology, 24, pp. 8887–8908, 2023.
https://doi.org/10.1016/j.jmrt.2023.05.147

[38] Jo, B.-W., Kim, C.-H., Tae, G., Park, J.-B. "Characteristics of cement mortar with nano-SiO_2 particles", Construction and Building Materials, 21(6), pp. 1351–1355, 2007.
https://doi.org/10.1016/j.conbuildmat.2005.12.020

[39] Nazari, A., Riahi, S., Riahi, S., Shamekhi, S. F., Khademno, A. "Influence of Al_2O_3 nanoparticles on the compressive strength and workability of blended concrete", Journal of American Science, 6(5), pp. 6–9, 2010.

[40] Bayraktar, O. Y., Kaplan, G., Benli, A. "The effect of recycled fine aggregates treated as washed, less washed and unwashed on the mechanical and durability characteristics of concrete under $MgSO_4$ and freeze-thaw cycles", Journal of Building Engineering, 48, 103924, 2022.
https://doi.org/10.1016/j.jobe.2021.103924

[41] Gesoglu, M., Güneyisi, E., Öz, H. Ö., Taha, I., Yasemin, M. T. "Failure characteristics of self-compacting concretes made with recycled aggregates", Construction and Building Materials, 98, pp. 334–344, 2015.
https://doi.org/10.1016/j.conbuildmat.2015.08.036

[42] Kou, S. C., Poon, C. S. "Properties of self-compacting concrete prepared with coarse and fine recycled concrete aggregates", Cement and Concrete Composites, 31(9), pp. 622–627, 2009.
https://doi.org/10.1016/j.cemconcomp.2009.06.005

[43] Hu, J., Wang, Z., Kim, Y. "Feasibility study of using fine recycled concrete aggregate in producing self-consolidation concrete", Journal of Sustainable Cement-Based Materials, 2(1), pp. 20–34, 2013.
https://doi.org/10.1080/21650373.2012.757832

[44] Bahrami, N., Zohrabi, M., Mahmoudy, S. A., Akbari, M. "Optimum recycled concrete aggregate and micro-silica content in self-compacting concrete: Rheological, mechanical and microstructural properties", Journal of Building Engineering, 31, 101361, 2020.
https://doi.org/10.1016/j.jobe.2020.101361

[45] Zhong, C., Zhang, L., Mao, W., Xing, S., Chen, J., Zhou, J. "An investigation on mechanical properties and durability of metakaolin reinforced modified recycled concrete", Case Studies in Construction Materials, 20, e02978, 2024.
https://doi.org/10.1016/j.cscm.2024.e02978

[46] Dhir, R. K., Hewlett, P. C., Chan, Y. N. "Near-surface characteristics of concrete: abrasion resistance", Materials and Structures, 24(2), pp. 122–128, 1991.
https://doi.org/10.1007/BF02472473

[47] Pedro, D., de Brito, J., Evangelista, L. "Structural concrete with simultaneous incorporation of fine and coarse recycled concrete aggregates: Mechanical, durability and long-term properties", Construction and Building Materials, 154, pp. 294–309, 2017.
https://doi.org/10.1016/j.conbuildmat.2017.07.215

[48] Nazeer, M., Kapoor, K., Singh, S. P. "Strength, durability and microstructural investigations on pervious concrete made with fly ash and silica fume as supplementary cementitious materials", Journal of Building Engineering, 69, 106275, 2023. https://doi.org/10.1016/j.jobe.2023.106275

[49] Neville, A. M. "Properties of Concrete", Pearson Education Limited, 2011. ISBN 978-0273755807

[50] Tang, W. C., Ryan, P. C., Cui, H. Z., Liao, W. "Properties of Self-Compacting Concrete with Recycled Coarse Aggregate", Advances in Materials Science and Engineering, 2016(1), 2761294, 2016. https://doi.org/10.1155/2016/2761294