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THE ENGINEERING PERFORMANCE OF ECO-FRIENDLY CONCRETES CONTAINING DIATOMITE FLY ASH AND GROUND GRANULATED BLAST FURNACE SLAG

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Abstract. Approximately 10 % of CO_2 is emitted from an ordinary Portland cement production. In cement and concrete production, CO_2 emissions can be greatly reduced by using Supplementary Cementitious Materials (SCMs). In addition, the microstructure and durability properties of concrete are greatly improved when silica-rich SCMs are used. In this study, Eco-Friendly concrete design was carried out using three different SCMs. Diatomite, ground granulated blast furnace (GGBFS) and fly ash (FA) were used as the SCM in the concrete mixtures. SCMs were used instead of cement at ratios of 5, 10, 15, and 20 wt%. When diatomite was used at the rate of 20 %, the standard consistency water increased 1.7 times as compared to the reference mixture. With the increase in the replacement ratio, the final setting times of the pastes increased. The high active SiO_2 content of diatomite shortened the initial setting time and increased the compressive strength. The use of 5 % diatomite reduced the slump value by 57 % as compared to the reference mixture. The slump and Ve-Be tests of GGBFS and FA mixtures showed similar properties to the reference mixture. The 28-day compressive strength of concrete varied between 29.2–34.6 MPa. With the increase in the curing time of the concrete mixtures, up to 50 % improvements were observed in the compressive strength. Especially on the 180th day, a compressive strength of 44.1 MPa was obtained in concrete mixtures with a 10 % replacement ratio. While using the FA in the mixtures improved the abrasion properties, the opposite result was observed in the case of the GGBFS. It was observed that the mixtures with 5 % FA showed the closest properties to the reference mixture. As a result, it was determined that SCMs with different properties could be used in environmentally friendly concrete mixtures by up to a 20 % replacement ratio.

Keywords: Sustainability, diatomite, fly ash, ground granulated blast furnace slag, eco-friendly concrete.

1. Introduction

The three basic elements of built environment sustainability are resource conservation, life cycle costing (LCC), and human-friendly designs (HFD). In terms of resource conservation, the 3Rs (Reduce, Reuse, and Recycle) idea is currently widely used in the construction and manufacturing sectors [1]. Because of its durability and architectural freedom, concrete is the most important building material on the planet [2]. According to The Concrete Centre, the amount of embedded CO_2 (ECO_2) in concrete is a consequence of the cement content in mixtures [3]. Concrete has an ECO_2 impact of approximately 100 kg CO_2 per tonne. The embodied CO_2 content of concrete is taken into account in building a sustainable concrete structure [2]. Furthermore, it is generally known that the manufacturing of Portland cement is a polluting process, accounting for about 5-9 percent of global anthropogenic carbon dioxide emissions [4]. In 2016, 4200 million metric tons of cement were produced worldwide, according to the reports [5]. Furthermore, the production of Portland cement is an energy-intensive process that accounts for 10–15 percent of total global industrial energy use [6]. The industry adopted alternatives to balance the environmental impacts connected with the production of Portland cement and, consequently, concrete, to reduce the environmental footprint and costs [7]. Using Supplementary Cementitious Materials (SCM) in cement and concrete production is one of the most important methods. Supplementary Cementitious Materials (SCMs), such as Ground Granulated Blast Furnace Slag (GGBFS), Pulverized fly ash (PFA), Rice Husk Ash (RHA), Silica Fumes (SF), can be used to minimise the embodied CO_2 of the concrete. Over the last few decades, SCMs have been widely used in concrete manufacturing. However, sustainability is the main purpose of using SCMs in concrete and cement production. With the use of SCMs, CO_2 emissions will decrease and more sustainable structures can be designed. The advantages of utilizing SCM may include improved mechanical qualities, decreased porosity, permeability, adverse reactions, and other physical properties like pigmentation [8, 9].

The steel industry produces millions of tons of slag as a by-product [10, 11]. By-products account for about 50 % of all steel manufacturing [12]. 294 kg of slag is produced from 1 ton of liquid pig iron [13]. This slag is divided into three categories based on its origin and cooling method (air, water, or water + pressure). The GGBFS is created when the slag formed during the fabrication of pig iron is quickly cooled and powdered to be utilised as a binder by the Portland cement industry [13]. It is known that 530 million tons of GGBFS are released worldwide and only 65 % of it is used [14, 15]. The production of one ton of GGBFS generates just 70 kg of CO_2, which is only 7 % of the pollution created by cement [16]. GGBFS, a by-product of steelmaking, is often stored in landfills. Because of the stiffening of environmental restrictions, the disposing of GGBFS has become a complex and costly operation. GGBFS usually contains significant levels of silicon dioxide (SiO_2), aluminium oxide (Al_2O_3), calcium oxide (CaO), and other materials that allow it to be utilised in the concrete preparation process [17]. Studies are showing that many properties are improved by adding GGBFS to concrete. GGBFS has a slower hydration rate than ordinary Portland cement. As a result, the early hydration heat release of concrete containing GGBFS is typically lower, indicating that GGBFS could significantly improve early thermal cracking resistance [17]. In addition, GGBFS increases the sulphate resistance as it reduces the permeability of the concrete [18]. GGBFS is used to partially replace cement, is often very fine, and has a glassy texture. Because of the small size and glassy surface, less water is required to provide the necessary workability of fresh concrete [19, 20]. However, because GGBFS has a lower density than PC, replacing an equal quantity of cement with GGBFS results in a higher paste volume (about 10 %), significantly improving segregation resistance and flowability [21]. In terms of durability, GGBFS may improve resistance to chloride ion diffusion, maybe because the GGBFS improves pore size distribution and more C-S-H gels are generated, adsorbing more chloride ions and blocking the diffusing path [22].

Fly ash (FA) is a by-product of coal-fired thermal power plants frequently utilized as a supplemental cementitious material (SCM) in the concrete industry as a cement alternative [23]. While 450 million tons of FA is released worldwide, only 25 % of it is disposed of [24]. Thermal power plants in Turkey produce almost 15×10^6 tons of FA per year. One of the major issues with power plants is storing the FA or its removal from the facilities. As a result, the harmful consequences of waste FAs on the ecosystem should be studied [25]. FA is classified as an artificial pozzolan. The research was advanced because suitable volumes of FA were utilised in place of concrete. Numerous studies on FA have been published [26]. FA is beneficial in reducing CO_2 emissions in the cement and concrete industry. Furthermore, the pozzolanic reaction between FA and cement improves the long-term durability and strength of the concrete, making FA a popular mineral addition [27, 28]. Improved FA replacement ratios in concrete result in a higher use efficiency. However, the replacement ratio cannot be too high [29, 30]. For example, EN 197–1:2000 specifies a maximum of 35 percent FA [31]. Many authors have shown that a replacement of 40–60 % FA can result in a high strength development, good resistance to alkali-silica reaction, freezing, thawing, chloride ion penetration, sulphate attack, and water permeability [32–36]. It has also been reported to lower the hydration heat and the risk of thermal cracking [37]. However, due to the perception of enhanced surface scaling, the performance of FA (with high volume) concrete in applications where deicing salts are used is a concern [38]. Bouzoubaa et al. have shown that FA concretes generally have equal or higher mechanical and durability performance to concrete without FA, the exception being inferior salt-scaling resistance of the FA content [39]. Concrete containing FA is shown to carbonate faster than concrete without FA [40]. It has also been stated that FA reduces chloride ion permeability and increases corrosion resistance [41].

Bacillariophyceae are a family of single-celled aquatic algae known as diatoms [42]. Diatomite, made up of their skeletons, is a refined sedimentary deposit almost entirely made up of silica and is utilised in mortars and grouts [43]. Diatomite is a soft, siliceous rock with abrasive properties, low density, and high porosity crushed into white powder. Diatomite is formed from the remains of microscopic single-celled algae (diatoms) found in marine sediments. Dead fossilized diatoms can be found at the bottom of oceans, sea beds, and lakes [44]. Diatomaceous accumulations can be found in many countries around the world, including the United States (particularly in California), the Commonwealth of Independent States (USSR), Canada, South Korea, Romania, Belgium, Japan, Brazil, Denmark, Germany, the Isle of Man, South Africa, Mediterranean countries of Algeria, Italy, France, Turkey, Crete, Cyprus, Spain, and Morocco [45]. The Canadian market (17.900 t/year), Germany (12.000 t/year), Belgium (6.200 t/year), South Africa (4.600 t/year), and Russia (4.300 t/year) are the primary export markets. These five countries accounted for almost half of all stated exports, or 47 percent. Diatomite is used in many ways after being treated and calcined. Water, agro-food sugars, oils, table fats, and other chemical products are filtered with it [45]. One of the different uses of diatomite is in the cement and concrete industry. Diatomite is utilised as an additive, since it has been proved that its reactive silica concentration and high Blaine values can improve the mechanical characteristics [46]. It was proved that diatomite could be used as an enhancement component in cement [47]. This is performed by its capacity to improve paste cohesion and hence reduce segregation. This could be due to

	Cement (OPC)	Diatomite	GGBFS	FA
CaO	62,72	0,73	30,28	12,31
SiO_2	20	87,27	37,65	45,25
Fe_2O_3	3,76	0,5	0,54	6,75
Al_2O_3	4,92	2,64	12,36	11,17
MgO	1,84	0,29	16,55	12,16
Na_2O	0,26	0,00	0,59	4,12
K_2O	0,73	0,25	0,88	1,84
SO_3	2,65	0,07	0,45	3,68
LOI*	2,54	1,27	1,2	1,2
Insoluble residue	0,4	5,34	0,3	0,25
Specific gravity	3,02	2,01	2,97	2,27
Specific surface area**	3220	4470	2400	3378
Initial setting time [min]	150	-	-	-
Final setting time [min]	220	-	-	-

*Loss on ignition
**Blaine method [cm^2/g]

TABLE 1. Properties of cement and SCMs.

residual negative charges on the diatomite's surface, resulting in enhanced dispersion [42]. Various studies have examined the potential and interest of using it in cement, mortar, and concrete in the form of diatomite powder. Değirmenci and Yılmaz suggested that diatomite can be used instead of cement at a rate of 5 % [48]. Li et al. investigated green concrete's early-age behaviour, mechanical characteristics, and environmental effects with diatomite and limestone as a cement clinker replacement [49]. In their study, Xiao and Liu showed that diatomite reduces the thermal conductivity coefficient [50]. Using calcined diatomite improves the mechanical and microstructural properties of high-strength mortars at ambient and high temperatures, according to Saridemir et al. [51]. In the later stages of cement hydration, diatomite can significantly increase the amount of C-S-H. (28 days). Calcined diatomite solves the problem of strength reduction [52]. As a result, many studies suggest using different SCMs to reduce CO_2 emissions in cement and concrete production [53–58].

In this study, different supplementary cementitious materials (SCM) were used to improve concretes' mechanical and abrasion properties. Alternative materials in concrete are discussed to provide various options that contribute to a more sustainable concrete. In this context, diatomite, GGBFS, and FA were used in the Eco-Friendly concrete mixtures. FA and GGBFS stored in landfills are very dangerous for human and environmental health. The easiest and cheapest disposal method is their use in concrete production. The disposal of these waste products will reduce environmental pollution. If diatomite is used in concrete production, cement consumption will decrease. The decrease in cement consumption causes CO_2 emissions to decrease and more sustainable building material being produced. Within the study's scope, the effectiveness of concretes with relatively lower CO_2 emissions were investigated. Therefore, SCMs were added to the concrete at different replacement ratios, and their fresh, hardened, and abrasion properties were investigated.

2. EXPERIMENTAL MATERIALS AND METHODS

2.1. MATERIALS

Type 1 cement (ordinary Portland cement-OPC) conforming to ASTM C150 [60] standard was used in the experimental study. Diatomite, GGBFS, and FA were used as SCMs in the mixtures. FA was obtained from Çayırhan Thermal Power Plant in Ankara/Nallıhan region. Since the CaO content of FA is more than 10 %, it is in class C according to ASTM C618 [61]. GGBFS conforming to ASTM C989 standard was obtained from KARDEMİR facilities [62]. Diatomite was obtained from the Çankırı-Çerkeş region (Figure 1). Since diatomite (natural pozzolana) is different from other SCMs, SEM studies were performed (Figure 2). It can be seen that the particle size of diatomites vary between 5-50 µm and is generally smaller than 10 μm. A wide variety is observed in the shapes of the diatomite particles. These include pipe, long fish, strainer comb (toothbrush), and round shapes. The chemical and physical properties of cement and SCMs are presented in Table 1. Figure 3 shows the XRD patterns of SCMs.

A limestone aggregate conforming to ASTM C33 [63] standard was used to prepare the mixtures. The particle size of the fine aggregate is 0–4 mm, and

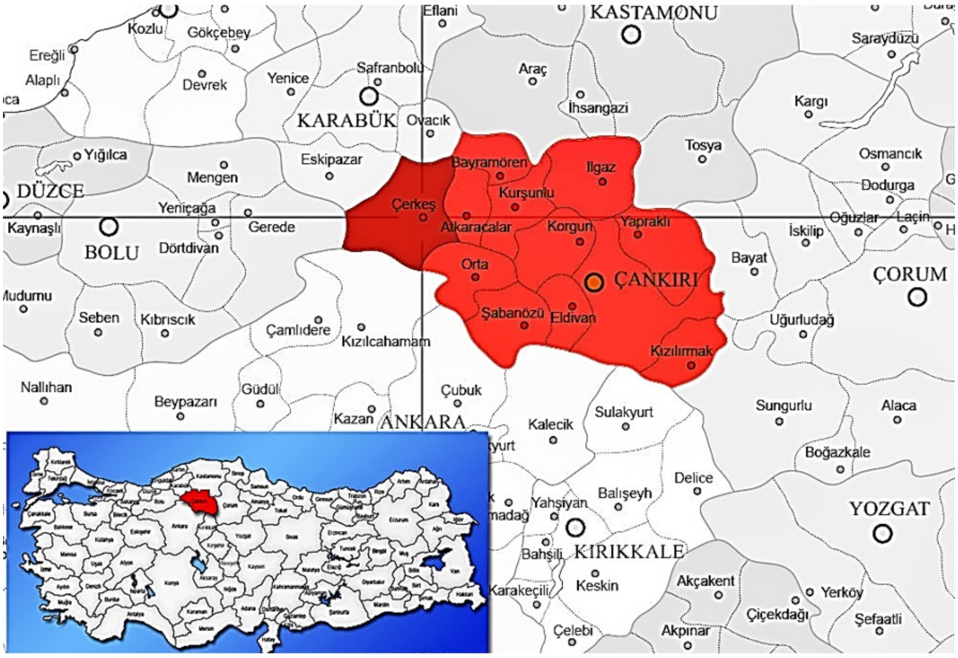


Figure 1. Region of diatomite reserves.

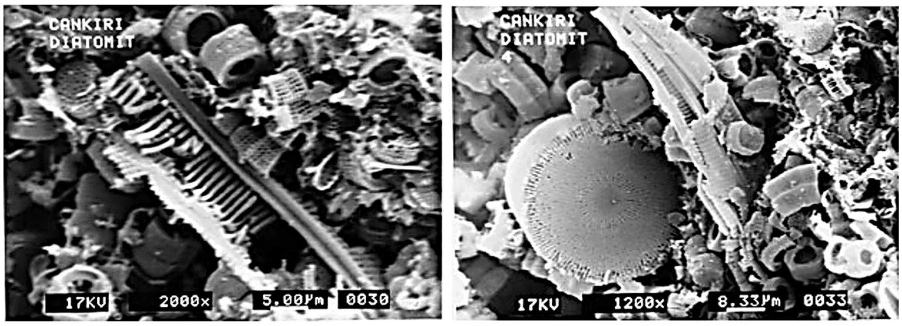


Figure 2. SEM image of the diatomite [59].

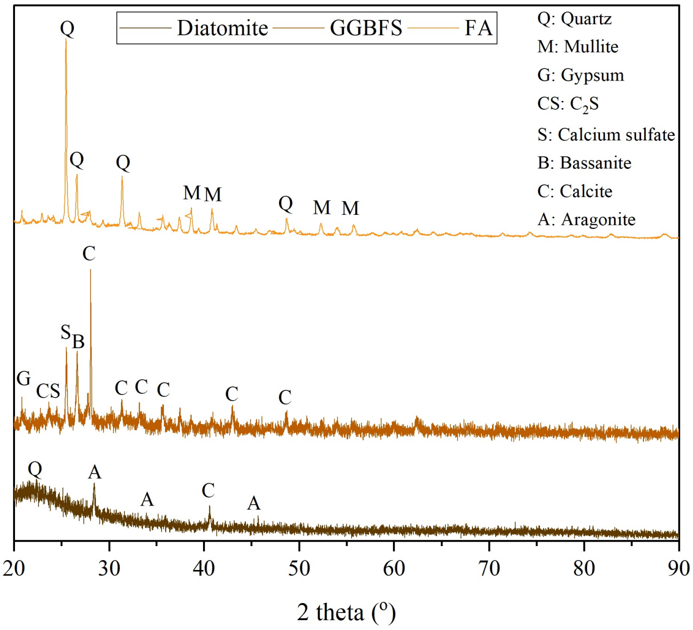


Figure 3. XRD patterns of SCMs.

Mix ID	Mixture properties		Material quantities [kg/m^3]						
	SCM	Replacement ratio [%]	Coarse aggregate	Fine Aggregate	Water	Cement	Diatomite	GGBFS	FA
M1	Reference	0	834.9	1070.5	167.0	315.0	-	-	-
M2	Diatomite	5				299.3	15.7	-	-
M3		10				283.5	31.5	-	-
M4		15				267.8	47.2	-	-
M5		20				252.0	63.0	-	-
M6	GGBFS	5				299.3	-	15.7	-
M7		10				283.5	-	31.5	-
M8		15				267.8	-	47.2	-
M9		20				252.0	-	63.0	-
M10	FA	5				299.3	-	-	15.7
M11		10				283.5	-	-	31.5
M12		15				267.8	-	-	47.2
M13		20				252.0	-	-	63.0

Table 2. Concrete mix proportions.

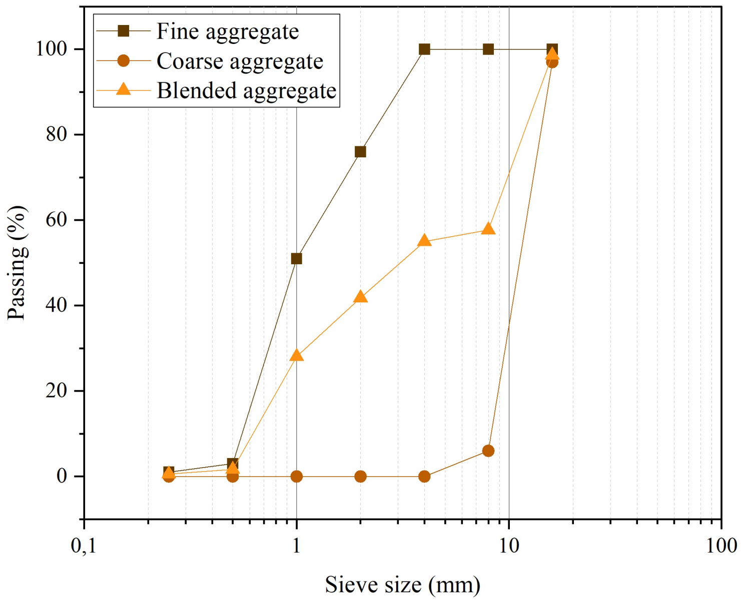


Figure 4. Sieve analysis of aggregates.

the coarse aggregate is 4–16 mm. The fine aggregate's specific gravity and water absorption values are 2.71 and 0.77, respectively. The coarse aggregate's specific gravity and water absorption values are 2.72 and 0.71, respectively. The particle distributions of the aggregates are given in Figure 4. The aggregates do not contain any organic matter. Potable water was used in the mixtures. Diatomite and GGBFS were ground in a ball mill until cement fineness was reached.

2.2. Mixture proportions

The ratios of concrete mixes were determined according to the TS 802 (Concrete Mixing Calculation Principles) standard. In the study, all concretes kept the w/c ratio (0.50) constant. The cement dosage was determined as 315 kg/m^3. The concrete class was chosen as C25/30 according to EN 206 standard [64]. SCMs were used in place of cement with four different replacement ratios. SCMs were used at the rate of 5, 10, 15, and 20 % instead of cement (by weight). Since the C25/30 class was the target in the concrete design, SCMs were not used at very high rates. Mixture properties and material amounts are given in Table 2. Concrete mixes were prepared in a vertical shaft mixer with a volume of 40 dm^3. The mixture was stirred for 1 minute in dry form and another 4 minutes after adding water. After the mixing was completed, fresh concrete experiments were carried out and the concrete was placed in pre-cleaned and oiled moulds. Compaction was done using an im-

Figure 5. Abrasion test and general view of samples.

mersion vibrator. The samples were removed from the mould after 24 hours and cured in a water tank with a temperature of 20 ± 1 °C until the day of the experiment.

2.3. Methods

2.3.1. Setting time, consistency, and soundness test

A Hobart mixer was used to mix all pastes at 140 RPM for 2 minutes and 285 RPM for 2 minutes. The physical properties of the cement were determined according to the EN 196-3 [65] standard. Vicat plunger and needle were used for the standard consistency water and setting time of the pastes. The volume expansion of the pastes was determined by the Le-Chatelier method.

2.3.2. Fresh properties

According to ASTM C 143 [7] standard, the slump test determined the mixtures' fresh properties. The fresh concrete was poured into the slump cone in 3 layers. With a standard 16 mm diameter rounded steel rod, each layer was tamped 25 times. After the slump, the cone was pulled up and the concrete was expected to collapse. The slump value of the concrete was measured with a ruler. The Ve-Be test of the concretes was carried out according to the TS EN 12350-3 standard [66]. The air content of fresh concrete was determined according to ASTM C231 [67], wet bulk density was determined according to ASTM C138 standard [68].

2.3.3. Compressive strength

The uniaxial compressive stress is reached when a material fails the compressive strength test. Compressive strengths of concretes were determined in 100 mm × 100 mm × 100 mm cube samples according to the ASTM C39 standard [69]. Concrete specimens were tested for compressive strength at 28, 90, and 180 days of curing. In each case, a set of three cubes was tested, and the average value of these three was reported.

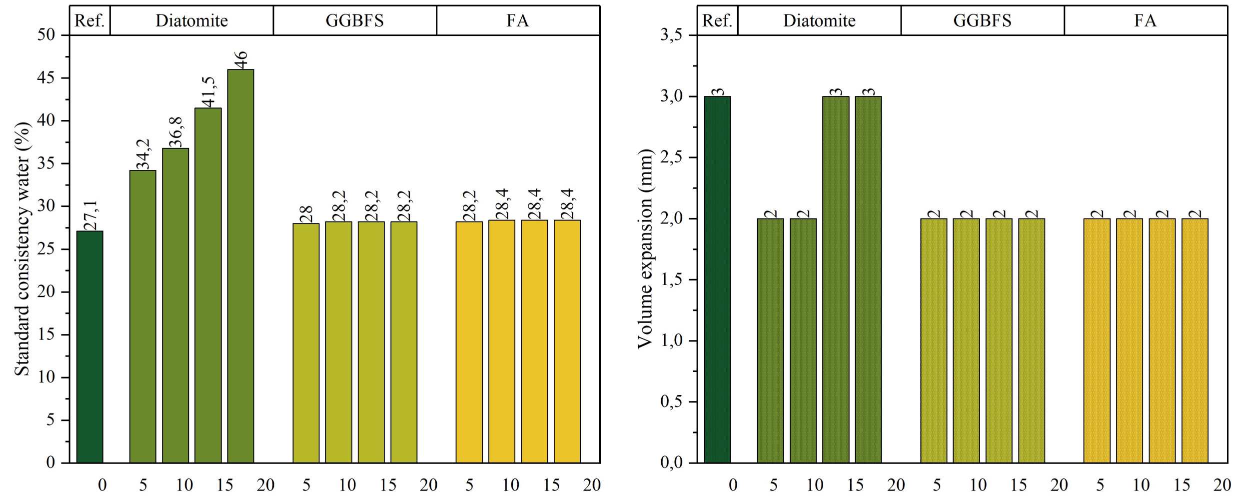
2.3.4. Abrasion resistance

The abrasion depth of concrete mixes was determined according to the ASTM C944 standard [70]. The abrasion depth was measured in cube samples of 100 mm × 100 mm × 100 mm. In addition, the abrasion depth was tested on 28-, 90-, and 180-day concrete mixes. In this way, the effect of different curing times on the pozzolanic activity was also observed. The depth of abrasion was determined after 6 minutes of testing. The device used in the abrasion test and the samples exposed to the abrasion are given in Figure 5.

3. Results and discussion

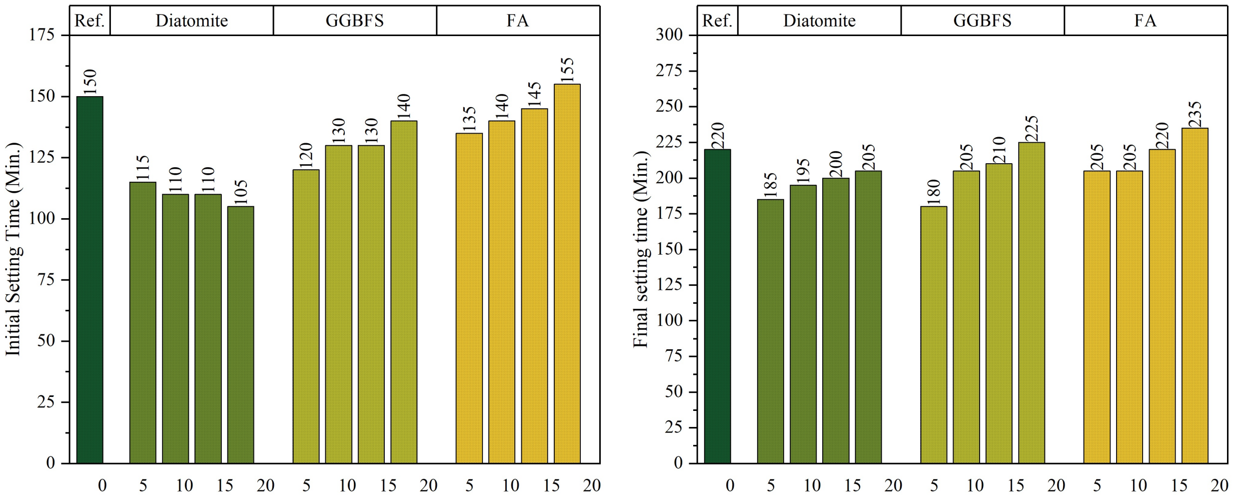
3.1. Physical properties of cement

As seen in Figure 6a, the standard consistency water of the reference mixture was determined as 27.1 %. AS Compared to the reference mixture, the standard consistency of water increased to about 4 % using FA and GGBFS. However, the increase in diatomite content led to a larger variation in the standard consistency of water. While the standard consistency water of cement using 5 % diatomite increased by 26.2 %, the standard consistency water of cement using 20 % diatomite increased by 69.7 %. The fact that the diatomite had a porous structure increased the standard consistency of water. Furthermore, the diatomite has a higher specific surface area than other SCMs. Therefore, the addition of diatomite significantly increased the standard consistency of water. The standard consistency of water increased negligibly in the case of FA and GGBFS. Although the specific surface area of FA is higher than that of cement, the standard consistency of water did not increase as much. The reason for this is explained by the fact that FA, generally, has a spherical particle structure. The specific surface area of GGBFS is approximately 25 % lesser than cement's. However, the GGBFS relatively increased the standard consistency of water, because the particle shape of GGBFS has an angular structure like limestone. The angular structure of GGBFS required a



(A) . Standard consistency water.

(B) . Volume expansion.



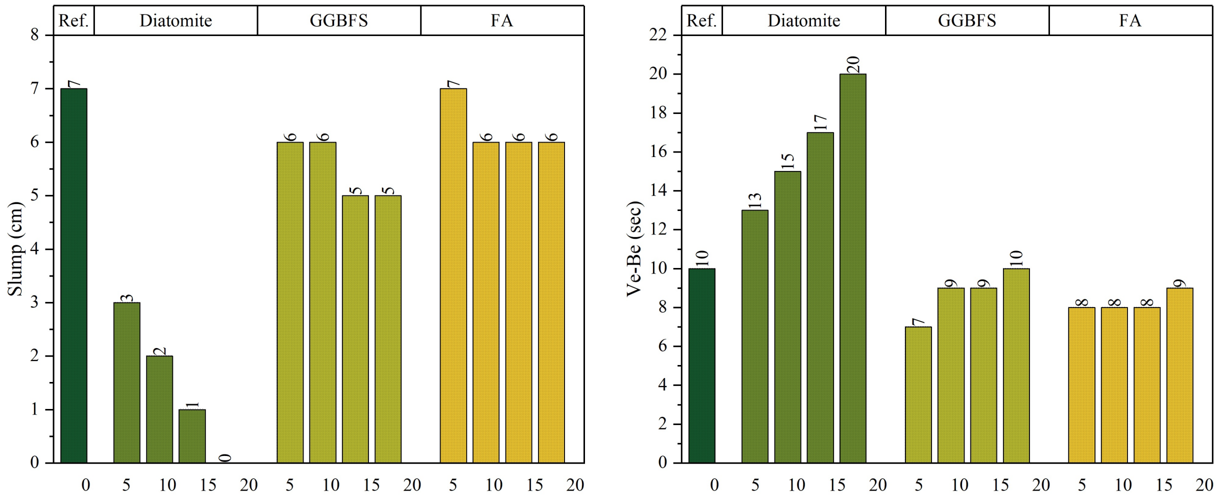
(C) . Initial setting time.

(D) . Final setting time.

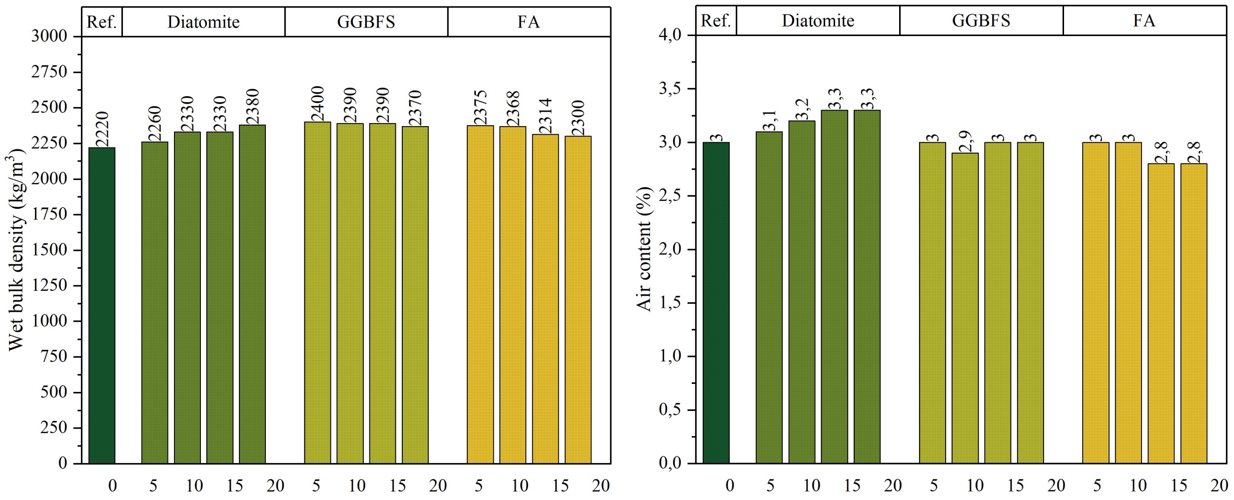
Figure 6. Physical properties of cement.

higher consistency water content because of greater internal friction. In the study conducted by Hasan and Saidi, the amount of standard consistency water increased as the diatomite content increased [71]. Water requirement for blended cement is also higher than for standard Portland cement, according to Kastis et al. [72]. Das et al. stated that FA has a spherical structure, whereas GGBFS has an angular structure. They also stated that SCMs with angular structures directly reduce workability. They found that rice husk ash reduced workability due to its high porosity [73]. Diatomite had the same properties as rice husk ash in this study. Volumetric expansion values of cement are given in Figure 6b. The volumetric expansion of cement varies between 2–3 mm. It was observed that the volumetric expansion values were very close to each other. According to EN 196-3 standard [65], the volumetric expansion of cement should be below 10 mm. It was determined that the cement produced from different SCMs complied with this standard.

As seen in Figure 6c, the reference mixture's initial setting time was 150 minutes. Diatomite-containing cement's initial setting time varies between 105–115 minutes. In addition, as the diatomite content increases, the setting time becomes shorter. In particular, the initial setting time of the cement with 20 % diatomite content decreased by approximately 1.4 times as compared to the reference mixture. The diatomite's high SiO_2 content (87.3 %) and specific surface area reduced the setting time. While the setting time of a cement mixture containing GGBFS varies between 120–140 minutes, the initial setting time for mixtures with FA varies between 135–155 minutes. As the FA and GGBFS content increases, the initial setting time increases. Due to the higher hydraulic properties of GGBFS, the initial setting time is relatively shorter than that of the FA cement. In Figure 6d, it was observed that as the replacement ratio increased in the diatomite-containing cement, the final setting time increased. A similar situation was observed for the cement using FA and GGBFS.



(a) . Slump. (b) . Ve-Be time.



(c) . Wet bulk density. (d) . Final setting time.

Figure 7. Fresh properties of concrete.

However, when different SCMs are used at 5, 10, and 15 % ratios, the final setting time is shorter than that of the reference mixture. As the replacement ratio increases, the setting times are longer because the clinker in the cement decreases.

C_3S is responsible for the early setting of cement paste because it hardens quickly in the presence of water [74]. When C_3A is hydrated, it produces a considerable amount of heat, raising the prevailing setting temperature, causing OPC to set faster than blended cement. As the temperature increases, the setting time of the cement is shortened [75, 76]. The fact that blended cement contains pozzolanic additives, which increase their water demand/standard consistency, could also account for their extended setting time. Cement pastes with high standard consistency water are observed to have a slower setting time. The cohesiveness/rheology of the pastes is reduced by high standard consistency water, which extends the setting time [77, 78].

3.2. Fresh properties of concrete

The slump values of the concrete decrease as the replacement ratio increases, as shown in Figure 7a. The slump value decreased between 14 and 28 % when GGBFS was used. When FA was used, the slump value decreased by approximately 14 %. The spherical particle structure of FA did not reduce the slump value much. However, the angular particle structure of the GGBFS noticeably reduced the slump value. Although the specific surface area of the GGBFS was low, the particle shape had a greater effect on the slump value. The most significant slump value decrease was observed in the diatomite cement concrete. The slump values of concrete made with diatomite cement decreased between 57 and 100 %. The high specific surface area and porosity of diatomite led to a decrease in slump values. It is seen that the Ve-Be times of the concretes produced from these cements vary between 13–20 seconds (Figure 7b). In particular, the Ve-Be time of concretes made with 20 % diatomite cement has increased by two times. The Ve-Be times

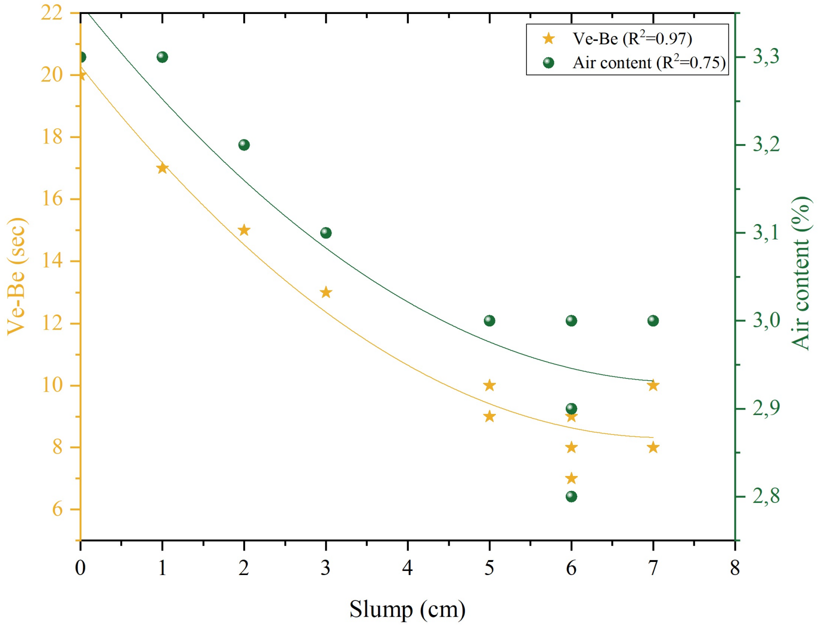


Figure 8. Correlation of fresh concrete properties.

of GGBFS and FA mixtures are close to the reference mixture. The Ve-Be time of the concretes produced with 5 % GGBFS cement was shortened by 30 %. The specific surface area of the GGBFS, 2400 cm^2/g, was very effective. However, as the replacement ratio in the GGBFS increased, the Ve-Be time also increased. The Ve-Be time of the FA mixtures was shortened by 10–20 %. Because of the angularity and irregular forms of the cementitious materials, friction between small particles increased, making the fresh mixture coarse. This effect may increase the water requirement as compared to the reference mix. [79]. In this study, the workability of GGBFS decreased due to its particle structure.

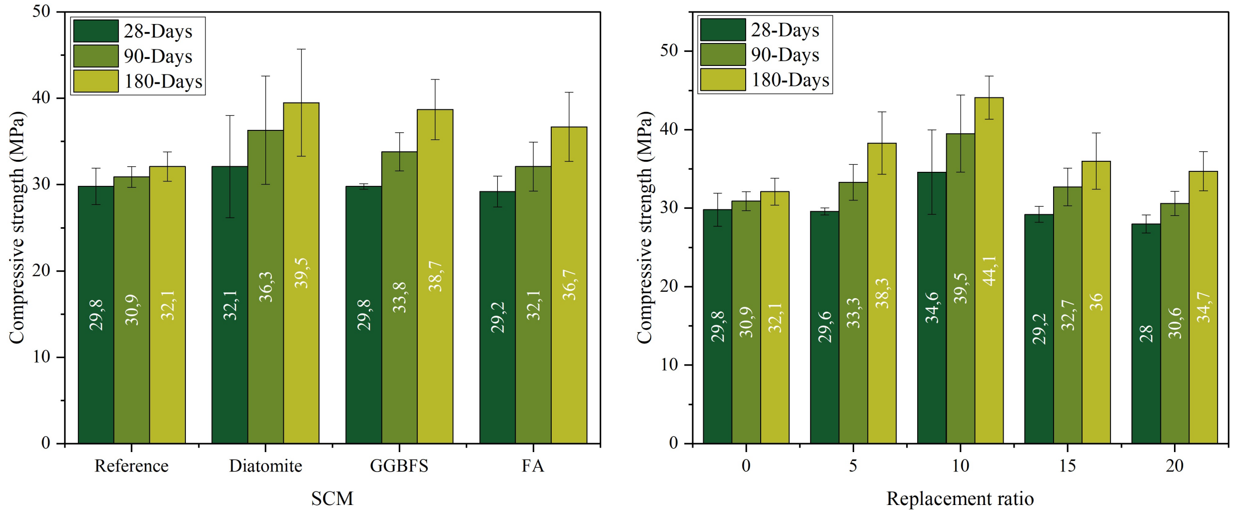
As seen in Figure 7c, the wet bulk densities of the concrete vary between 2220–2400 kg/m^3. However, the wet bulk density of all concretes with SCM is higher than that of the reference concrete. As the replacement ratio increased in GGBFS and FA mixtures, the wet bulk density of the concretes decreased. However, in the case of diatomite concrete, the wet bulk density values increase as the replacement ratio increases. The amount of aggregate in concrete mixtures was kept constant. When diatomite is used instead of cement, the paste volume increases. When 20 % diatomite is used in mixes, the paste volume rises by approximately 10 %. The increase in paste volume increases the wet bulk density of the mixtures. The wet bulk density of the concretes produced with 20 % diatomite cement increased by 7 %. Similar results are also seen for the air content of concretes (Figure 7d). The air contents of the GGBFS and FA mixtures are very close to the reference mixture. Since FA has a higher specific surface area than cement, it fills the voids between cement particles. However, the air content increased by up to 10 % in diatomite mixtures. Because diatomite affects the workability of concrete, pouring it in the mould becomes problematic. As a result, the air content of the mixtures increased.

Nawaz et al. stated that the density increases as the replacement ratio increases in the case FA concrete. The rise in workability of FA explained the reason for this increase. FA micro-spherical particles may act as lubricants to enhance concrete density while maintaining the same compaction energy [80]. In the study conducted by Pokorny et al., the bulk density increased when diatomite was used up to 10 % [81]. Since diatomite has a smaller particle size than cement, it effectively filled the gaps between the cement and the aggregate. As a result of this effect, it increased the wet bulk density of concretes.

Figure 8 shows the relationship between slump values and other fresh concrete properties. It is seen that the R2 value between the Slump and Ve-Be time is 0.97. As the slump value of the mixtures increases, Ve-Be times decrease. The R2 value between the slump value and the air content was 0.75. As the slump value of the mixtures increases, the air content decreases. The decrease in the slump value increases the amount of energy required for vibration. Since the constant vibration energy was used in this study, the air content of the concretes increased as the slump value decreased.

3.3. Mechanical properties

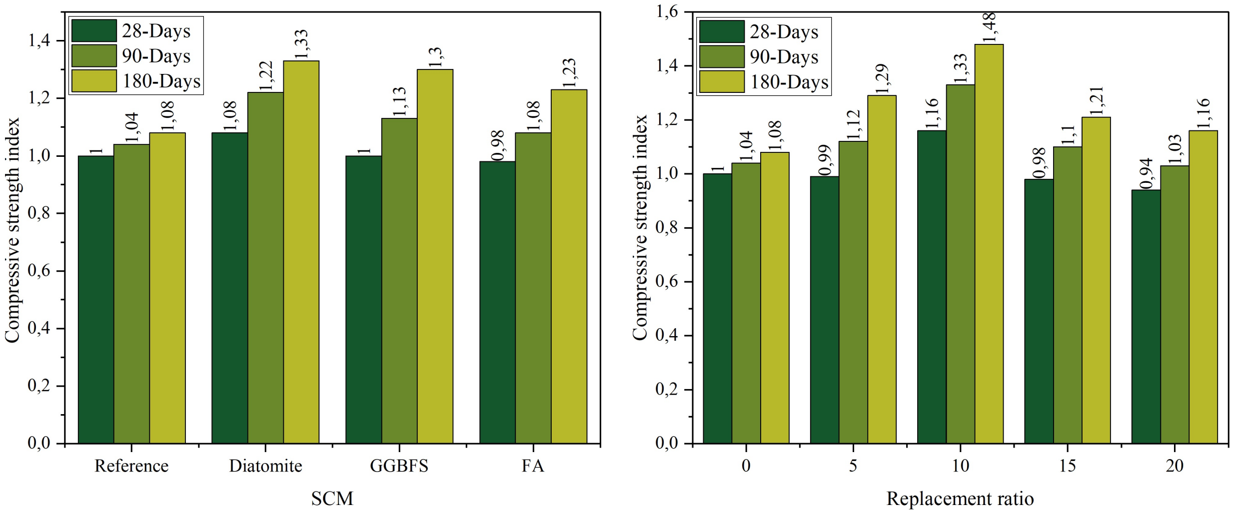
As seen in Figure 9a, the increase in curing time increases the compressive strength of the concrete. The 28-day compressive strength of the concrete varies between 29.2 and 29.8 MPa, while 180-day compressive strengths vary between 32.1 and 39.5 MPa. Using SCM in concrete mixtures did not affect the 28-day compressive strength much. When the compressive



(a) . Effect of SCM.

(b) . Effect of replacement ratio.

Figure 9. Compressive strengths of concrete mixes.



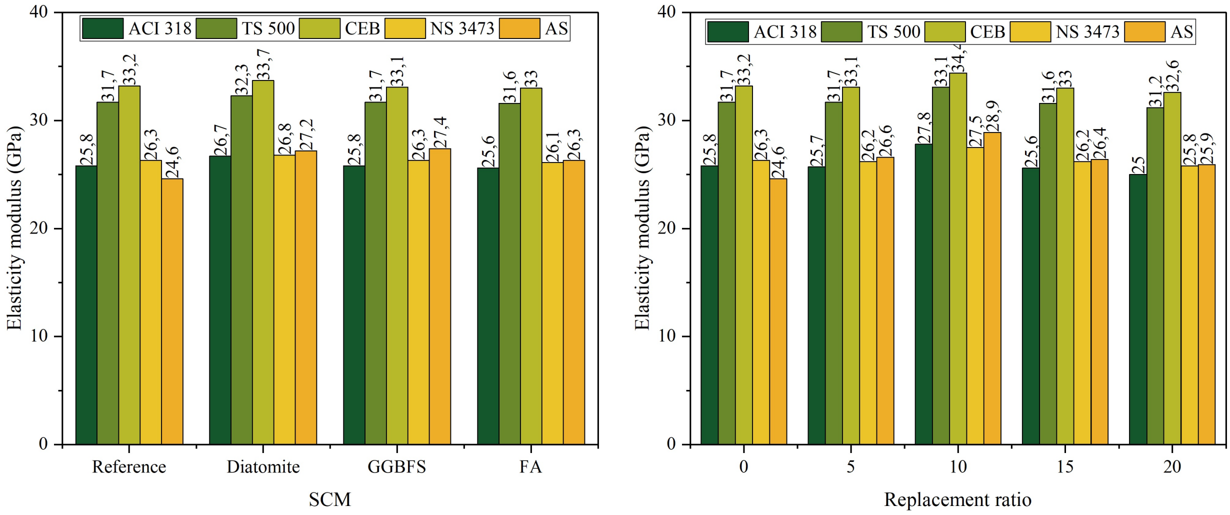
(a) . Effect of SCM.

(b) . Effect of replacement ratio.

Figure 10. Compressive strength index of concrete mixes.

strengths of 90 and 180 days were examined, it was observed that the use of diatomite increased the compressive strength more significantly. The high SiO_2 content and specific surface area of diatomite increased the compressive strength. It was observed that concretes produced with GGBFS had a relatively higher compressive strength than concretes with FA. The hydraulic properties of GGBFS ensured its compressive strength to be higher than that of the reference mixture. Figure 9b shows that the use of SCM up to 10 % increases the compressive strengths. However, when the 180-day compressive strengths are examined, the compressive strengths of the mixtures using 15 and 20 % SCM are higher than that of the reference mixture. When a high proportion of SCM is used, the curing time should also be increased. Especially the use of 10 % SCM improved the compressive strengths considerably. In addition to the pozzolanic activity, the micro filler effect of SCMs also helped to increase the compressive strength. If 20 % SCM is used, the 28-day compressive strength is reduced by 6.7 %.

The compressive strength indexes in Figure 8 were determined according to the 28-day compressive strength of the reference mixture. The 180-day compressive strength of the reference mixture increased by 8 % as compared to the 28th day (Figure 10a). The 28-day compressive strength of the FA mixture decreased by 2 %. Concrete mixes containing diatomite had the greatest values in terms of 90 and 180-day compressive strengths. While the 180-day compressive strength of GGBFS increased by 30 %, this ratio was 23 % for FA mixtures. When the 28-day compressive strengths were examined, the compressive strength increased only at a 10 % replacement ratio (Figure 10b). If 20 % SCM is used, the compressive strength is reduced by approximately 6 %. For the 90- and 180-day curing times, higher compressive strengths were observed for the 10 % replacement ratio. In particular, the com-



(a) . Effect of SCM.

(b) . Effect of replacement ratio.

Figure 11. The elasticity modulus of concrete mixes.

pressive strength increased approximately 1.5 times for the 10 % replacement on the 180th day.

Shaikh and Hosan increased the compressive strength of the pastes by using 60 % GGBFS [82]. El-Chabib and Syed [14] observed similar results. Due to the hydraulic activity and slag activity index of GGBFS, the addition of GGBFS increases the compressive strength of concrete [83]. The increase in compressive strength of FA and diatomite is related to the pozzolanic activity. The delayed pozzolanic reaction of the SCM causes a reduction in the size of the crystalline compounds in the paste matrix, particularly calcium hydroxide, resulting in an increase in compressive strength development with age in mixtures prepared with high contents of SCM [84]. Ahmadi et al. explained the increase in compressive strength in diatomite-containing mixtures with rich SiO2 content. They stated that diatomite is an active pozzolan and can be replaced by up to 40 % with cement [85].

3.4. Theoretical elasticity modulus

Some empirical formulas estimated the elasticity modules of the mixtures in the literature. In these formulas, the mixtures' 28-day compressive strength and bulk density are used. The equations (1)–(5) used are presented below. ACI 318-95 (ACI Committee 318 1995):

$$E_c = 4.73(f_c)^{1/2}. \tag{1}$$

TS 500 (Turkish Standardization Institute 2000):

$$E_c = 3.25(f_c)^{1/2} + 14. \tag{2}$$

CEB (Comité Euro-International du Béton-Fédération Internationale de la Précontrainte (CEB-FIP) Model Code 1993):

$$E_c = 10(f_c + 8)^{1/3}. \tag{3}$$

NS 3473 (Norwegian Council for Building Standardization 1992):

$$E_c = 9.5(f_c)^{0.3}. \tag{4}$$

AS (Standards Australia Concrete structures 2009):

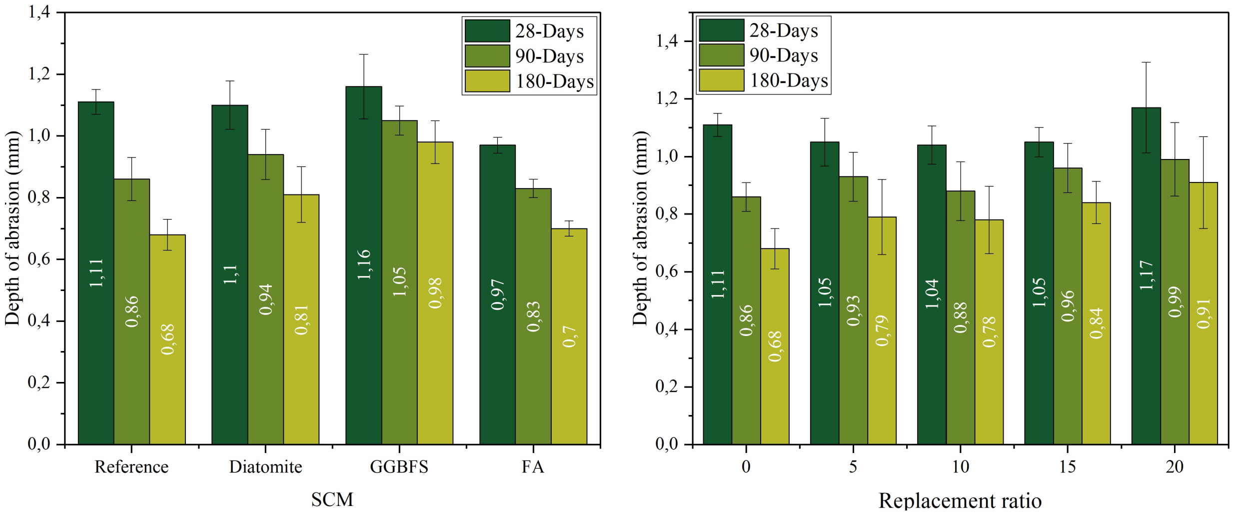
$$Ec = 0.043w^{1.5}(f_c)^{1/2}, \tag{5}$$

where; f_c [MPa] and E_c [GPa] are 28-day compressive strength and modulus of elasticity of the concrete, respectively, and w [kg/m^3] is the bulk density of concrete.

As shown in Figure 11a and Figure 11b, the elasticity modules of the mixtures using SCM are quite close to the reference mixture. It has been determined that the modules in elasticity determined according to TS 500 and CEB are similar. The modulus of elasticity of the mixes using diatomite is relatively higher. In addition, using SCM up to 10 % noticeably increases the elasticity modulus. While the modulus of elasticity of concrete varies between 32.6–34.4 GPa according to TS 500, it varies between 25–27.8 GPa according to ACI 318. The E-modulus is determined by the components and qualities of the concrete. In particular, the E-modulus, aggregate shape, and cement paste structure significantly impact the findings. However, since no fibre was used in this study, no significant difference was observed between the moduli of elasticity of different mixtures. Letelier et al. produced concrete with compressive strengths ranging from 22.8–31.4 MPa using up to 15 % diatomite. The elasticity modulus of the concrete varies between 16.7–24.2 GPa [86]. Gencel et al.'s study showed that as the FA content increased, the modulus of elasticity decreased [87].

3.5. Abrasion resistance

The abrasion depths of concretes determined according to ASTM C944 are given in Figure 12. As the



(a) . Effect of SCM.

(b) . Effect of replacement ratio.

Figure 12. Abrasion depth of concrete mixes.

curing time applied to the concretes increased, the abrasion depth decreased (Figure 12a). It has been observed that the curing time has a significant impact the abrasion effect. In particular, the pozzolanic activity was effective in concretes with SCM. However, the abrasion depths of concrete with SCM are relatively larger than that of the reference concrete. Using FA in SCM concretes reduced the abrasion depth more than using GGBFS and diatomite. While the abrasion depth of the GGBFS on the 180th day was approximately 1 mm, the abrasion depth of the FA was 0.70 mm. As seen in Figure 12b, the use of SCM by up to 15 % in 28-day mixtures reduced the depth of abrasion. However, this effect was not observed for the abrasion depth of the 90- and 180-day mixtures. Especially on the 180th day, the abrasion depth of the mixtures with 20 % SCM increased by 34 % as compared to the reference mixture. Abrasion depths of concrete mixtures decreased below 1 mm from the 90th day onwards. It is more appropriate to use FA in concretes exposed to abrasion. The replacement ratio should be 10 %, as in the compressive strength. Since diatomite has a porous structure, it did not contribute to the abrasion resistance. In addition, the low specific gravity of GGBFS as compared to cement adversely affected its abrasion resistance.

Sujjavanich et al. determined the abrasion resistance of the concretes they prepared using FA and metakaolin. It was observed that concretes containing 20 % FA lost less weight due to abrasion. This effect was explained by the improvement of the microstructure of pozzolans [88]. The abrasion resistance of concrete is typically affected by the strength of mortar and the mortar-aggregate bond for the same coarse aggregate types and volume. As a result of improving the mortar strength and bonding with aggregate particles, SCMs with strong pozzolanic reactivity, such as silica fume and metakaolin, are expected to improve the surface abrasion resistance of surface abrasion concrete [89]. The chemical characteristics of FA were largely responsible for the abrasion resistance of concrete using FA [90]. Amini et al. improved the abrasion resistance of concretes by using up to 40 % of GGBFS [91]. In the literature, not many studies show diatomite's effect on abrasion. However, due to SCM's high porosity, the abrasion's depth increased.

3.6. Statistical analysis and optimization

In Table 3, statistical analyses of the experimental data are given. The relevance of independent factors on dependent variables is displayed by the p-value. If the p-value is less than 0.05, the independent variables will be considered important. When the p values were examined, it was observed that the change in the SCM type generally affected many properties of the concretes. A higher F value shows that the performance characteristics are significantly affected by the variability in the process parameter. As with the p-value, it is seen that the change in the SCM type causes a larger change in the F value. The change of the SCM type affects mostly the fresh state properties of the cement and concrete. In particular, standard consistency water and initial setting time are highly affected by the SCM type. In addition, the SCM type also affects the depth of abrasion. If FA is used instead of diatomite in 28-day mixtures, the depth of abrasion decreases by 12 %. The change in the replacement ratio of SCMs affects concretes' fresh and hardened properties. The SCM type has no significant effect on 28-day compressive strength. This is an indication that SCMs have similar characteristics to each other.

The optimization was performed according to the test parameters given in Table 4. The concrete mix using 5 % FA has the best properties as compared to the reference mix. Although 5 % FA increased the standard consistency water by 4.1 %, it decreased the 28-day abrasion depth by 15.5 %. However, if CO_2 emissions are considered, 10 % FA can be used.

Test Parameters	SCM				Replacement Ratio [%]			
	p	F-Value	Effect [%]	Significance	p	F-Value	Effect [%]	Significance
S. Cons. Water	0.001	19.03	99.0	Yes	0.899	0.19	1.0	No
Initial Setting Time	0.000	22.12	98.8	Yes	0.921	0.16	1.2	No
Slump	0.042	4.61	83.1	Yes	0.465	0.94	16.9	No
28 Days-Comp Str	0.553	0.63	22.5	No	0.171	2.17	77.5	No
28 Days-Depth of abrasion	0.035	4.98	86.5	Yes	0.536	0.78	13.5	No

Table 3. Statistical analysis results.

Test parameters	**Target function**	**Optimum Mix (FA5)***	**Reference**	**Difference**
S. Consistency Water	Minimum	28.2	27.1	-4.1
Initial setting time	Minimum	135	150	10
Slump	Maximum	7	7	0
28 Days-Comp Str	Maximum	30.2	29.8	1.3
28 Days-Depth of abrasion	Minimum	0.93	1.1	15.5

* Optimum mix design: %5 FA

Table 4. Optimum mixing ratios.

4. Conclusions

- Diatomite increased the standard consistency of water as compared to other SCMs. The standard consistency water amount of GGBFS and FA showed similar properties to the reference mixture.
- Due to diatomite's highly active SiO_2 content being shortened, the replacement ratio's initial setting time increased. However, as the diatomite replacement ratio increased, the final setting times were prolonged. As the GGBFS and FA replacement ratio increases, the setting times become longer. However, pastes' setting times (initial and final) with SCM are generally shorter than that of the reference mixture.
- While the high specific surface area and porosity of diatomite decreased the slump values, it led to the prolongation of Ve-Be times. Despite the low specific surface area of the GGBFS, the rough particle shape reduced the slump values. The FA mixtures showed similar properties to the reference mixture in the slump and Ve-Be tests.
- There was no significant difference between wet bulk densities in fresh concrete. The wet bulk densities of the concrete vary between 2220–2400 kg/m^3. While the wet bulk densities increased as the diatomite replacement ratio increased, the opposite could be observed for the FA mixtures. Such an effect was observed because the diatomite increased the paste volume more than other SCMs. In addition, as the diatomite replacement ratio increased, the air content increased relatively.
- The high specific surface area and active SiO_2 content of diatomite were more effective in increasing the compressive strength. As the curing time increased, the strength development of the mixtures with SCM was greater than that of the reference mixture. In addition, it was determined that the optimum replacement ratio was 10 % in the mixtures with SCM. All concrete mixes' theoretical modulus of elasticity is more than 20 GPa.
- As the curing time increased, the abrasion depths decreased due to the development of both the hydration and the pozzolanic activity. The abrasion depth of FA mixtures was smaller. It was observed that the abrasion depth was larger for the GGBFS. In addition, the abrasion depths increased at a 20 % substitution rate for the mixtures with SCM.
- Statistically, the change in the SCM type affects the engineering performance of concrete more significantly than the change in the substitution ratio, which did not have as pronounced effect on the engineering properties. It was determined that the 5 % FA mixtures had the closest properties to the reference mixture. However, considering environmental factors and CO2 emissions, it is thought that the optimal replacement ratio might be 10 %.

- As a result, it has been determined that Eco-Friendly concrete can be produced by using SCMs with different properties of up to 20 %.

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