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Investigation of Engineering Properties of Self-Compacting Concretes Produced with Different Mineral Additives

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Abstract

In this study, Self-Compacting Concrete (SSC) was produced by using Fly Ash (FA) and Marble Powder (MP), which reduces the amount of cement, causes less damage to the environment and has some superior properties compared to normal concrete. The changes in the physical and mechanical properties of the produced SSCs with increasing age were investigated. CEM I 42.5 R cement was used as a binder in the production of SSC. It was used with FA and MP cement at the rates of 10%, 20% and 30% by weight. In general, a high percentage of powder material is needed in the production of SSC. Instead of obtaining the required amount of powder material from binder material, Stone Dust (SD) was preferred as filling material and hyperplasticizer additive was preferred as chemical additive. In the design of the SSC mixture, the amounts of used materials were determined in accordance with the standard. The produced SSCs were cured in the standard curing pool until the day of the experiment. 7, 28, 56 and 90 days compressive and splitting tensile strengths were determined as mechanical strength. As for the physical properties, water absorption, porosity, capillary water absorption, ultrasound pulse velocity and electrical resistivity values at 28, 56 and 90 days were determined as a result of the experiments. Moreover, it was observed that the mechanical strengths increased with the increase of concrete age, while the ideal ratio was determined as 20% for both mineral admixtures.

1. INTRODUCTION

Self-Compacting Concrete (SSC) was first used by Okamura in Japan at the end of the 22nd Century [1]. The purpose of its development is to solve the problem of difficult placement of concrete in molds due to the reinforcement placements are generally very frequent in the design of structural elements to be manufactured in Japan, especially in earthquake zones. In addition, SSC is an innovative type of concrete that can be easily placed without losing its workability, thanks to its high fluidity [2]. With the increasing needs for high strength concrete structures over time, SSC has become important research [3,4]. SSC has high machinability, cohesion resistance and does not require the use of vibration; It makes it ideal for use in high-rise buildings, bridges, tunnels, anchor blocks, prefabricated elements and reinforcement works [5-7]. SSC can be produced using the same components as regular concrete production. However, the determination of the mixing ratios of SSC should be much more sensitive than normal concrete. Compared to normal concrete, SSC mixture requires high dust content, a lower coarse aggregate content, and high superplasticizer or viscosity regulator [8]. It will be harmful for the environment and be expensive to provide the high amount of powder material used to improve the fluidity, spreading, self-compacting and segregation resistance of SSC with cement as in normal concrete. The production of concrete or SSC with cement, which is responsible for about 5% to 7% of CO_2 emissions globally, causes low environmental efficiency [9-11]. In this context, the use of materials that are less harmful to the environment and more sustainable, instead of cement with high environmental impact [12,13]. The high amount of dust contained in SCCs includes the use of various by-products or waste products instead of cement [14,15]. On the other hand, it is an effective way to reduce carbon emissions by reducing the amount of cement in SSC by using

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industrial wastes instead of cement. The use of limestone dust, marble dust, fly ash, granulated blast furnace slag and metakaolin in SSC has been studied by various researchers [16-19]. Thanks to the powder materials used, the granulometry improves, the cohesion is provided better in the fresh state and increases the fullness by reducing the capillary gaps in the hardened concrete [20]. Fly ash (FA), one of the waste materials used, is a waste product obtained from coal-fueled power plants. The regular production of waste FA from thermal power plants has attracted the attention of researchers for waste disposal, and many studies have conducted to focus on substitute for cement or using that the production of cementless concrete [21-24]. Use of FA in worldwide is between 3% and 60%, but the average use is only 16% [25]. Recent studies have shown that it is possible to use up to 30% FA for more efficient SSC production, both economically and environmentally [26,27]. The use of FA in the production of concrete or SSC has a positive effect on the rheological properties, heat of hydration and crack development in hardened concrete [28]. It is an important waste material for cement reduction, especially in a special type of concrete such as SSC where the amount of powder material is required in high amounts. Another waste product used in this study is Marble Powder (MP). The marble cutting industry produces a large amount of powdered marble waste. In the cutting process of marbles, a high amount of powder in the form of slurry is produced and this material can replace fine aggregates in concrete. In the marble quarries, where the stones are cut into blocks by various methods, approximately 20-30% of the marble blocks become waste marble powder during the cutting process of these stones [29,30]. The disposal or storage of these marble wastes poses significant threats to the environment, and for this reason, it is seen that there are studies that indicate the importance of these wastes and that they should be evaluated. Considering these conditions, MP is one of the best materials to be used in concrete production, especially as a filler in SSCs or as a cement-replaced pozzolanic material [30,31].

In this study, it is aimed to investigate in detail the changes in engineering properties with the age of SSC by reducing the amount of cement by 30%, producing environmentally friendly SSCs with superior properties compared to normal concrete. For this purpose, MP, which is a waste mineral, was chosen in addition to FA, which is widely used in the literature, and two different waste mineral additives were used at rates of 10%, 20% and 30%. 7, 28, 56 and 90-day compressive and splitting tensile strengths were determined for 7 different SSC samples produced only with cement and using mineral additives at the mentioned ratios. 28, 56 and 90 days water absorption, porosity, capillary water absorption, ultrasonic pulse velocities and electrical resistivity values were determined.

2.MATERIALS AND METHODS

2.1. Material

In this study, CEM I 42.5 R type Portland Cement conforming to TS EN 197-1 standard was used as the binder [32]. The FA used in the scope of the study complies with the F type ASTM C618-93 standard [33]. The hardness of MP used as a mineral additive is 3 on the Morhr's scale. The FA used in the study was obtained from the İSKEN Sugözü Thermal Power Plant, MP was obtained from the marble quarry in Osmaniye, and SD was obtained from the ERTAN stone quarry in Osmaniye. The physical and chemical properties of cement, MP, FA and SD used in the preparation of the mixtures are given in Table 1.

Table 1. *Physical and chemical properties of Cement, FA, MP and SD*

Chemical Analysis	**CEM I 42.5/R**	**FA**	**MP**	**SD**
SiO_2	19.33	47.4	4.67	50.7
Al_2O_3	4.74	19.8	0.08	23.8
Fe_2O_3	2.72	11.8	0.03	8.32
CaO	63.20	6.66	51.80	4.56
MgO	0.98	4.76	18.38	2.28
Na_2O	0.12	0.57	0.05	4.34
Loss of Ignition	3.94	2.76	45.98	2.45
Specific Surface Area (cm^2/g)	3983	3126	6740	3954
Specific Weight (g/cm^3)	3.12	2.39	2.63	2.73

FA: Fly Ash, MP: Marble Powder, SD: Stone Dust

Two different types of aggregates in accordance with the TS 706 EN 12620 standard were used in the production of the samples. Aggregate with 0-4 mm grain size as fine aggregate and 4-16 mm grain size as coarse aggregate was used [34]. The specific weights of crushed sand and coarse aggregate used are 2.70 gr/cm3 and 2.67 gr/cm3, respectively, and their water absorption percentages are 1.51% and 1.75%, respectively. Mixing water was used in the production of Osmaniye city tap water in accordance with TS EN 1008 standard, as well as in the curing phase [35]. Sika brand Viscocrete 4567 Hi-Tech was used as chemical additive.

2.2. Method

2.2.1. Design And Preparation of Ssc Mixing

Unlike normal concrete, SSCs must have sufficient cohesion and segregation resistance. In order to provide these properties in SSC, the amount of coarse aggregate in the concrete is used less, the water/powder material ratio is kept low, and high water reducing plasticizer chemical additives are used. Mixtures were prepared by using the limitation of mixing values recommended by the EFNARC (2005) committee in the design of the SSC [36]. In the mixtures, the dose was kept constant as 400 kg and the used FA and MP were used by replacing cement 10%, 20% and 30%. The chemical additive rate for 1 m^3 SSC was kept constant as 1.85% and the amount of SD as 125 kg. The ratios of crushed sand (0-4 mm) and coarse aggregate (4-16 mm) used in the mixture were determined as 55% and 45%, respectively. In addition to series produced only with cement, which does not contain minerals. A total of 7 series of SCCs were produced by using 2 different mineral additives in 3 different ratios. Mixture amounts for 1 m3 SSC are given in Table 2.

Table 2. *Required material quantities for 1 m^3 SSC*

Mixture Name	Cement (kg)	Mineral Additive (kg)	Stone Dust (kg)	Water (kg)	Chemical Additive (kg)	Crushed Sand (kg)	Coarse Aggregate (kg)
Ref	400	0	125	189	7.4	909.8	744.4
%10 MP	360	40	125	189	7.4	905.4	740.8
%20 MP	320	80	125	189	7.4	900.9	737.1
%30 MP	280	120	125	189	7.4	896.5	733.5
%10 FA	360	40	125	189	7.4	900.0	736.3
%20 FA	320	80	125	189	7.4	890.1	728.3
%30 FA	280	120	125	189	7.4	880.2	720.2

2.2.2. Experimental Procedure

Physical properties of SSCs such as water absorption, porosity, capillary and ultrasonic pulse velocities were determined at 28, 56 and 90 days, and compressive and splitting tensile strengths at 7, 28, 56 and 90 days.

Porosity and water absorption properties were determined in accordance with the TS EN 12390-7 (2010) standard with the help of a scale working with the Archimedes principle [37]. According to TS EN 772-11 (2012), capillary water absorption coefficients of concretes are determined by performing capillary water absorption test in order to have information about capillary voids [38]. Ultrasonic pulse velocities is one of the non-destructive testing methods. Ultrasonic pulse velocities gives information about concrete quality. Ultrasonic pulse velocities have been determined in accordance with the TS EN 12504-4 (2021) standard [39]. In order to be able to measure independently of the effect of humidity conditions, the resistivity of electrical conductive were measured on the samples removed from the curing pool and saturated with water by the two-plate method in accordance with the ASTM C 1760 (2021) standard [40]. The resistance was measured at 0.1, 0.12, 1 and 10 kHz at direct current. The purpose of determining the electrical resistivity at different frequencies is to determine the resistivity value that can be obtained depending on the measurement frequency. The compressive strengths of SSCs were determined in accordance with the TS EN 12390-3 (2019) standard, and the split tensile strengths were determined in accordance with the TS EN 12390-6 (2010) standard [41,42].

3.RESULTS

The 7, 28, 56 and 90 day compressive strength results of the samples are given in Figure 1. The compressive strengths of all SCCs increase with increasing concrete age. The compressive strength of the samples with FA added as a mineral additive was higher than the samples with MP added. The 7, 28, 56 and 90-day compressive strengths of the reference sample were determined as 29.53 MPa, 40.17 MPa, 50.23 MPa and 56.70 MPa, respectively. The 28-day compressive strengths of 10%FA, 20%FA and 30%FA samples were 61.2 MPa, 61.98 MPa and 59.21 MPa, respectively. The 28-day compressive strengths of 10%MP, 20%MP and 30%MP were 52.7 MPa 53.8 MPa, 56.23 MPa, respectively. The highest compressive strength of 56 days was measured as 67.82 MPa in the 20%FA sample and the lowest compressive strength was measured as 50.23 MPa in the REF sample. With the addition of mineral additives to REF concrete, it was observed that the compressive strength increased especially at 28 days and older ages. Mineral additive increases strength in later ages rather than early ages [43]. Mineral additives have to wait for the cement hydration product Ca(OH) to form an additional C-S-H gel. With the increase in the mineral additive ratio, the compressive strength increased up to 20%, while a decrease was observed with the increase to 30%. However, higher strengths were obtained compared to REF.

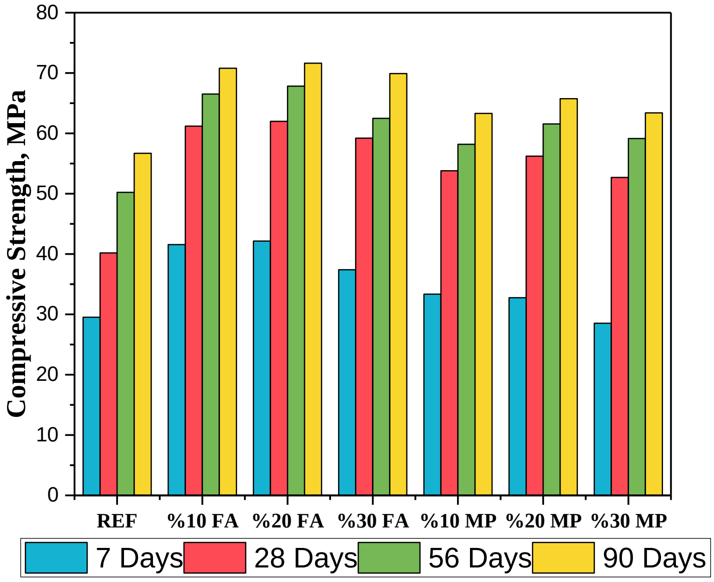

Figure 1. *Compressive Strength Results*

The 7, 28 and 56 days split tensile strength results of the samples are given in Figure 2. The split tensile strengths of all SSCs increase with increasing concrete age. In general, splitting concrete is neglected because it has much lower tensile strength. The split tensile strengths of SSCs were found to be low compared to the compressive strengths. However, a similar increase in split tensile strength was observed with the addition of mineral additives. The split tensile strength of the samples with FA added as a mineral additive was higher than the samples with MP added. The 7, 28, 56 and 90-day splitting tensile strengths of the reference sample were determined as 1.31 MPa, 2.56 MPa, 2.60 MPa and 2.83 MPa, respectively. The tensile strengths of 28 days 10%FA, 20% FA and 30%FA samples were 2.98 MPa, 3.50 MPa and 3.08 MPa, respectively. Tensile strengths of 10%MP, 20%MP and 30% samples were 2.98 MPa, 3.54 MPa and 2.81 MPa, respectively. The highest splitting tensile strength of 56 days was measured as 3.90 MPa in the 20%FA sample and the lowest splitting tensile strength was measured as 2.60 MPa in the REF sample. With the increase in the mineral additive ratio, the splitting tensile strengths increased up to 20%, while a decrease was observed with the increase to 30%. However, higher strengths were obtained compared to REF.

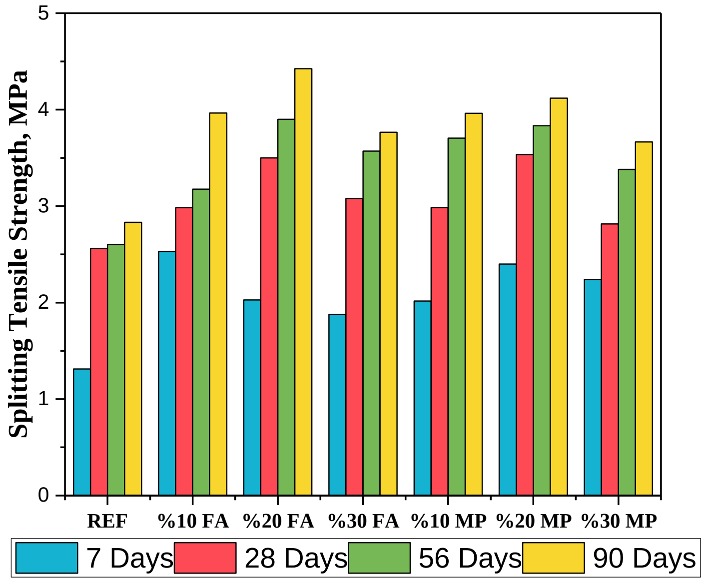

Figure 2. *Split Tensile Strength Results*

The 28, 56 and 90-day water absorption values of the samples are given in Figure 3, and the porosity values are given in Figure 4. The water absorption values of SSCs decreased with increasing age. As the concrete ages, additional C-S-H gels continue to form and fill the voids in SSC. Due to C-S-H gels fill the voids, the amount of water absorption also decreased [44]. The 28 and 56-day water absorption values of the REF sample were 3.81% and 3.62%, respectively. The porosity values of the REF sample at 28 and 56 days were 7.59% and 6.77%, respectively. Water absorption and porosity values decreased with the addition of mineral additives. The 28-day water absorption values of 10%FA, 20% FA and 30%FA samples were 3.36%, 3.11% and 3.65%, respectively, and the 28-day water absorption values of 10%MP, 20% MP and 30%MP samples were, respectively. 3.73%, 3.72% and 3.90%. The 28-day %10FA, %20FA, %30FA porosity values were determined as 6.72%, 6.26% and 7.28%, respectively, and the 28-day porosity values of 10%MP, 20% MP and 30% MP samples were 7.46%, 7.01% and 7.80%, respectively. The lowest water absorption value of 56 days was determined as 3.03% in the 20%FA sample and the highest as 3.90% in the 30%MP sample. The lowest porosity value of 56 days was determined as 5.73% in the 20%FA sample and the highest as 6.86% in the 30%MP sample.

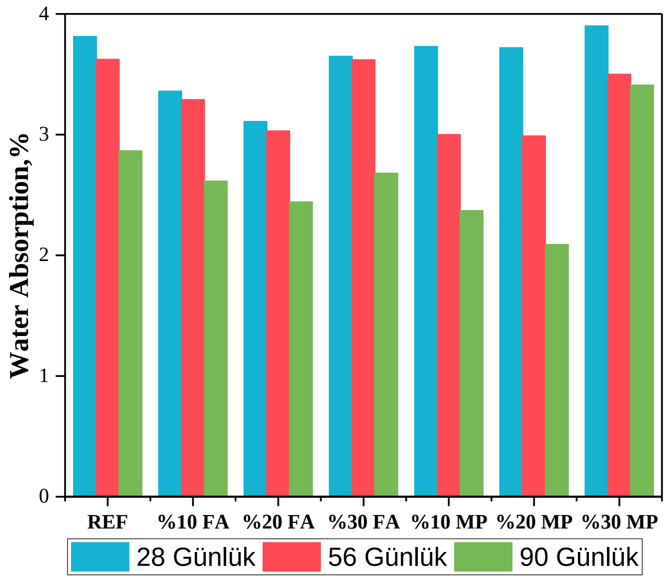

Figure 3. *Water Absorption Results*

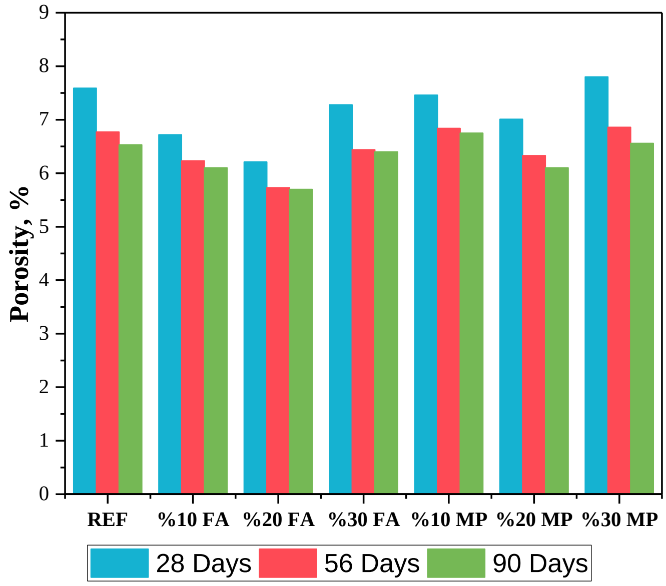

Figure 41. *Porosity results*

The 28-day electrical resistivity values of the samples are given in Figure 5, the 56-day electrical resistivity results in Figure 6, and the 90-day electrical resistivity results in Figure 7. All electrical resistivity measurements were measured at 4 different frequencies as 0.1 kHz, 0.12 kHz, 1 kHz and 10 kHz. In cementitious composites, electrical conductivity occurs with ion mobility in the cavity solution. The number of revolutions per second of the alternating current signal is called the frequency. With the increase in the frequency value, the ion mobility in cement-based composites accelerates and therefore the electrical resistivity decreases [45]. In all measurements, it was observed that the electrical resistivity values decreased with the increase in the frequency value. It was observed that the resistivity values increased with the addition of mineral additives. It is known that the Ca (OH) ions that emerge as a result of cement hydration with the use of mineral additives bind and are converted into C-S-H gels. Ion reduction with the use of mineral additives decreased the electrical conductivity and increased the electrical resistivity values.

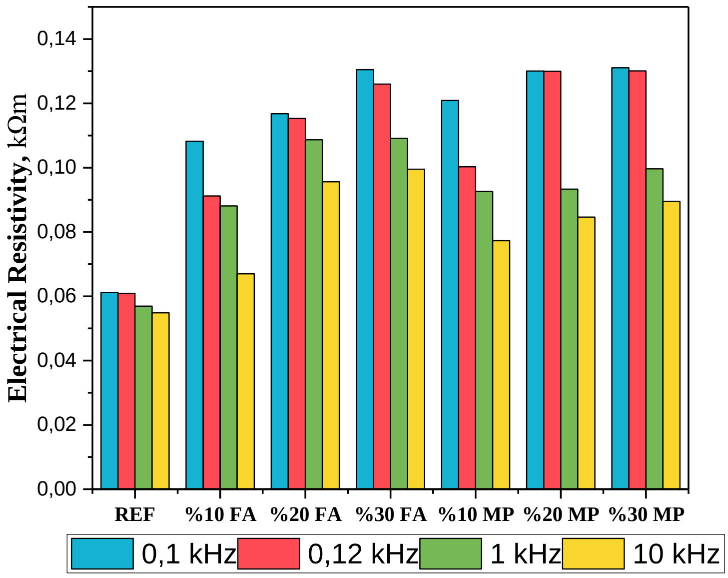

Figure 5. *28-Day Electrical Resistivity Results measured at different frequency values*

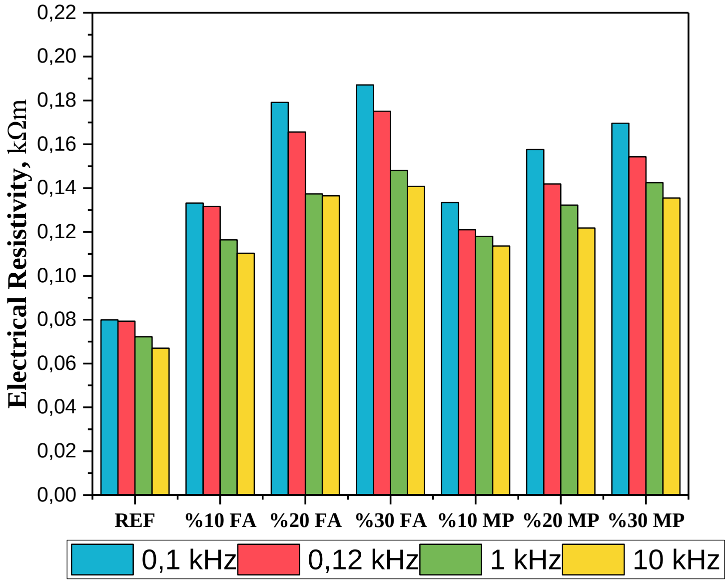

Figure 6. *56-Day Electrical Resistivity Results measured at different frequency values*

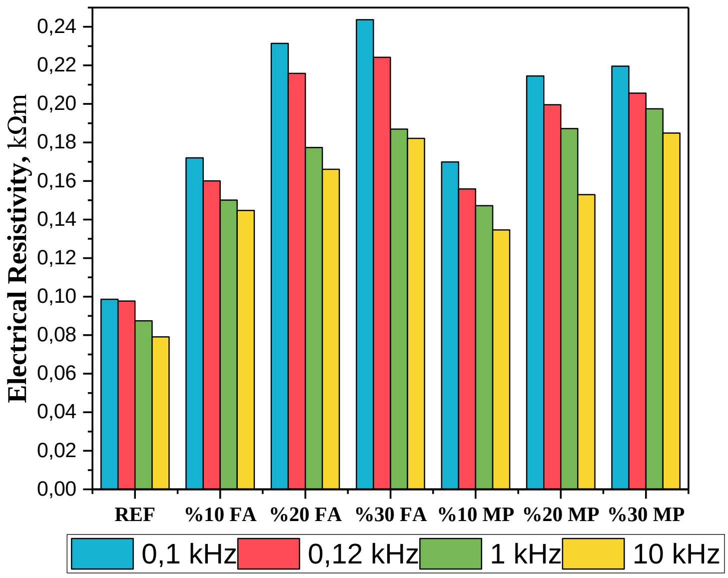

Figure 7. *90-Day Electrical Resistivity Results measured at different frequency values*

Capillary water absorption coefficients of the samples at 28, 56 and 90 days are given in Figure 8. It was observed that capillary water absorption coefficients decreased with increasing SSC age. Although the cement reaches its final strength on the 28th day, hydration continues. With continued hydration, additional C-S-H gels form and fill the capillary spaces in the SSC [46]. It has been observed that capillary voids are reduced with the use of mineral additives, thanks to the high powder content of SSC and different mineral content. It is known that there is a reaction in the use of mineral additives, not at early ages, but at later ages. The reason for this is that the mineral additives are waiting for the calcium hydroxides that will be formed as a result of cement hydration. It has been observed that the use of mineral additives causes fewer voids than the use of cement alone. The use of FA was found to fill capillary space better than the use of MP.

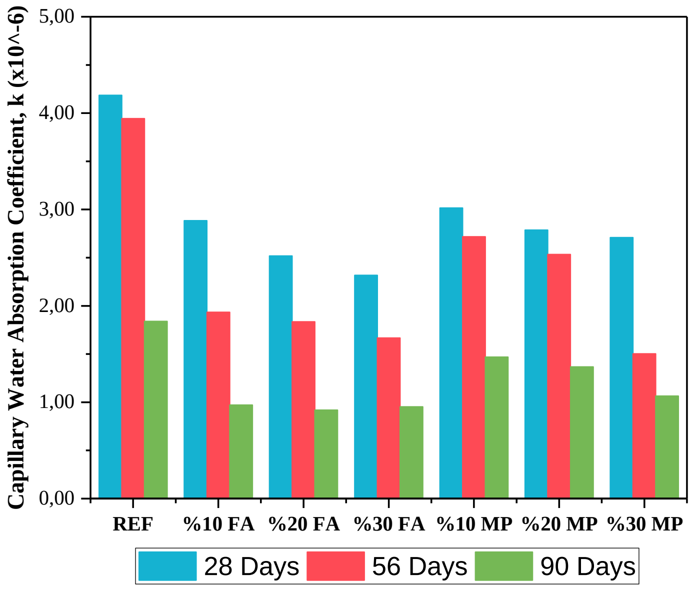

Figure 8. *Capillary water absorption coefficient results*

The 28, 56 and 90 day ultrasonic pulse velocities results of the samples are given in Figure 9. Ultrasonic pulse velocities is one of the non-destructive test methods that gives information about the void structure of building composite materials such as concrete. The smaller the gap, the faster the transmitted sound wave will pass through the SSC. A high ultrasonic pulse velocities means that the void ratio of SSC is low and therefore its mechanical strength is also high [47,48,49]. When the ultrasonic pulse velocities results of SSCs were examined, it was observed that ultrasound pulse velocities increased with the increase of concrete age. As the concrete ages, it continues to gain strength and fills the voids with additional hydration products with the pozzolanic effect. It was observed that the ultrasonic pulse velocities increased at all ages with the addition of mineral additives. It was observed that SSC shows similar behavior to other physical behaviors performed within the scope of this study.

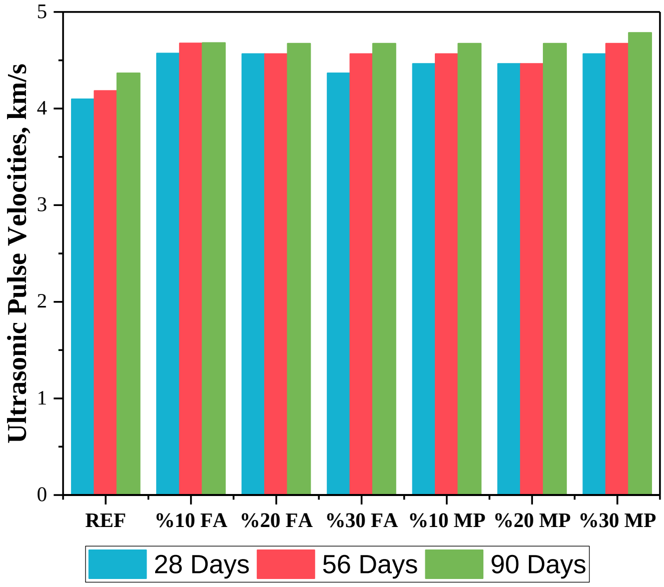

Figure 9. *Ultrasonic pulse velocities results*

4.CONCLUSIONS

The 7, 28, 56 and 90-day engineering properties results of SSCs produced using FA and MP minerals are as follows:

- With the increase of SSC age, compressive and splitting tensile strengths increase, and with the use of mineral additives, higher strengths have been determined compared to the REF sample produced only with cement, especially at later ages.
- When the 28-day compressive strengths were examined, an increase of 54.29% with the use of 20%FA and an increase of 39.98% with the use of 20% MP were observed compared to the REF sample.
- When the split tensile strengths of 28 days were examined, an increase of 37.89% was observed with the use of 20%FA compared to the REF sample, and an increase of 36.71% with the use of 20% MP.
- It was observed that the compressive and splitting tensile strengths of the samples with FA added as mineral additives were higher than the samples with MP added.
- When the water absorption and porosity values were examined, it was seen that these values decrease with the addition of mineral additives. The lowest water absorption and porosity values were determined by 20% for both minerals.
- As a result of the electrical resistivity measurements taken at 4 different frequency values, it was observed that the electrical resistivity decreased with the increase in frequency and it increased with the increase in age.
- It was determined that ion mobility and electrical resistivity values decreased with the addition of mineral additives.
- When the capillary water absorption coefficients were examined, it was seen that they show parallelism with water absorption and porosity. Both the increase in age and the addition of mineral additives resulted in lower capillary water absorption coefficients by reducing the capillary voids of SSCs.
- Ultrasound pulse velocities increase with both SSC age and the addition of mineral additives. Ultrasound pulse velocities results showed that with the addition of mineral additives to SSC, the void ratio would decrease and a fuller SSC would be obtained.
- It has been concluded that by reducing the amount of cement with the use of mineral additives in SSCs, both environmentally friendly and better physical and mechanical properties can be gained compared to SSCs produced only with cement. It has been determined that the ideal ratio for both mineral additives is 20%.

It has been concluded that the expected physical and mechanical properties are met with the use of waste mineral additives by reducing the amount of cement as intended in the production of SSC. In the use of waste mineral additives up to 20%, better properties have been observed than SSC produced only with cement. Environmentally friendly SSC has been produced, which both emits less CO_2 to the environment and ensures waste disposal.

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