Open Journal of Nano
ISSN: 2147-0081
(2022) 7–2
Research Article / Araştırma Makalesi

Use of F-type Fly Ash in Cement Mortar with Alternative Mixing Methods

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Submission Date: 03.01.2022 Acceptation Date: 14.02.2022

Abstract - In this study, it is focused on the use of fly ash, which is one of the industrial wastes, as a partial replacement of cement and fine aggregate in cement mortar. The feasibility of using fly ash as an alternative to cement and fine aggregates in concrete was determined by examining its effect on strength and durability properties in composites. Fly ash was used in the mixtures with three different mixing methods. This is the simple substitution method, addition method and partial substitution method. In each method, 10%, 20% and 30% of the material was removed by weight, and a total of ten different mixtures were prepared by adding fly ash instead. As a result of the experiments to determine the properties of the mixtures in the fresh and hardened state, the addition of fly ash to the mixtures improved the workability and freeze-thaw resistance. When we look at the results in terms of the methods used in the study, it was seen that the addition method gave better results in pressure, water absorption and capillary water absorption experiments than other methods, and according to the bending and cylinder splitting test results, higher values were obtained in the mixtures prepared with the partial substitution method compared to the other mixing methods.

Keywords: Fly ash, simple substitution method, partial substitution method, addition method, mechanical properties, freeze-thaw, permeability properties

Alternatif Karışım Yöntemleri ile F tipi Uçucu Külünün Çimento Harcı İçerisinde Kullanımı

Öz - Bu çalışmada, endüstriyel atıklardan birisi olan uçucu külün çimento harcı içerisindeki çimento ve ince agreganın kısmi ikamesi olarak kullanılmasına odaklanılmıştır. Betonda çimento ve ince agregalara alternatif olarak uçucu kül kullanımının uygulanabilirliği, kompozitlerde dayanım ve dayanıklılık özelliklerine etkisinin incelenmesi ile belirlenmiştir. Uçucu kül, karışımlar içerisinde üç farklı karışım yöntemi ile kullanılmıştır. Bunlar; basit ikame yöntemi, ilave yöntemi ve kısmi ikame yöntemidir. Her bir yöntemde %10, %20 ve %30 oranında ağırlıkça malzeme çıkarılmış, yerine uçucu kül eklenerek toplam on farklı karışım hazırlanmıştır. Karışımların taze ve sertleşmiş haldeki özelliklerinin belirlenmesine yönelik yapılan deneyler neticesinde, uçucu külün karışımlara eklenmesi işlenebilirliği ve donma-çözülme direncini iyileştirmiştir, su emme ve kılcal su emme oranı değerleri ise uçucu kül içeriğinin artmasıyla ilk günlerde artış göstermiş fakat ilerleyen yaşlarda azalmıştır. Çalışmada kullanılan yöntemler açısından sonuçlara bakıldığında basınç, su emme ve kılcal su emme deneylerinde ilave yönteminin, diğer yöntemlere göre daha iyi sonuçlar verdiği görülmüş, eğilme ve silindir yarma deney sonuçlarına göre ise, kısmi ikame yöntemi ile hazırlanan karışımlarda diğer karıştırma yöntemlerine kıyasla daha yüksek değerler elde edilmiştir.

Anahtar kelimeler: Uçucu kül, basit ikame yöntemi, kısmi ikame yöntemi, ilave yöntemi, mekanik özellikler, donma-çözülme, geçirimlilik özellikleri

1. Introduction

Concrete is the most used building material worldwide. The use of cement and aggregate in concrete composition causes rapid depletion of natural resources and environmental pollution. Replacing any of these materials with industrial waste materials has a positive impact on the environment as it reduces the problem of waste disposal, intensive use of energy and natural resources. The durability of concrete is an important consideration to ensure a long service life in aggressive environments. Although Portland cement is one of the main components used in concrete production, it is a relatively high cost material that has no alternative in the construction industry. A

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large amount of cement production causes environmental problems and also consumes a lot of energy. It causes about 7% of the total greenhouse gas emissions in the world [1]. In this situation, engineers and scientists are faced with the crucial decision to either destroy the ecosystem by continuing concrete production or to seek an alternative methodology to conserve natural resources by reducing CO_2 emissions [2]. They can be used as alternative sources in concrete as they can help solve some environmental concerns such as the use of industrial waste materials as recycled materials, the problem of waste disposal, and the intensive use of energy and natural resources. There are many industrial waste products that have the potential to replace aggregate and cement in concrete, such as plastic, fly ash, rubber, steel, and leather waste. Fly ash (FA), which is one of these industrial wastes, can be partially used instead of cement thanks to its pozzolanic structure, thus reducing the carbon emissions and industrial waste amount resulting from cement production. Class F FA contains a small amount of lime. Thus, the increase in the amount of FA in the concrete causes a decrease in the compressive strength. However, the pozzolanic activity of FA increases the compressive strength in advancing curing times [3]. As a result of the pozzolanic reaction, the increase in strength lasts longer than conventional concrete [4].

The voids in the concrete affect the transport of environmental fluids. In their study, Supit and Shaikh observed that with the addition of FA to concrete, the void volume decreased by 6-11% compared to conventional concrete [5]. On the other hand, in the study reported by Mardani-Aghabaglou et al.[6], it was reported that the durability performance was adversely affected as the FA ratio increased with the replacement of FA with cement.

FA can be used in concrete with three different mixing methods [7]. These; simple substitution method, addition method and partial substitution method. In the simple substitution method, a certain amount of cement is removed from the mixture and replaced with the same amount of FA. Concretes produced by this method have low strength at early ages. The main purpose of using the simple substitution method is to reduce the heat of hydration and increase the workability in mass concrete production. In addition, this method can be evaluated environmentally and economically. In the addition method, fine aggregate is removed from the mixture without changing the amount of cement in the mixture and FA is added instead. Thus, the amount of binder in the mixture increases. The main purpose of using this method is to increase the strength of concrete in later ages and to obtain a more impermeable concrete with a denser microstructure. In the partial replacement method, FA is substituted for the cement and fine aggregate removed from the mixture. In this method, it is aimed to provide optimum benefit from the positive features provided by the two methods mentioned above. In this study, three different ratios of FA were added to the mixtures with three different mixing methods and their effects on the fresh and hardened mortar properties were investigated. In the literature, FA is widely used in mortar by replacing cement [8]. In this study, the effects of FA on mixture properties were investigated by substituting both cement and aggregate in equal proportions. Various tests were carried out to determine the consistency and unit weight values of fresh mixtures and the strength, permeability and durability properties of hardened samples. Compressive, flexural and cylinder splitting strength tests in the determination of mechanical properties; water absorption and capillary water absorption in determining permeability properties, in the determination of durability properties, freeze-thaw tests were carried out.

2. Materials and Methods

2.1. Materials

In the study, CEM I 42.5 R type cement, F class FA according to ASTM C618 [9] standard and sand obtained from local sources with 0-4 mm grain size were used. Chemical and physical properties of cement and FA are given in Table 1.

Table 1. Chemical and physical properties of cement and fly ash.

Chemical Composition (%)	Cement (C)	Fly Ash(FA)
SiO_2	20.8	50.98
Al_2O_3	5.42	13.11
Fe_2O_3	2.98	9.74
S+A+F	29.2	73.83
CaO	61.53	11.82
MgO	2.39	3.91
SO_3	2.4	3.94
K_2O	0.75	1.91
Na_2O	0.21	2.71
Physical Properties		
Specific weight (g/cm^3)	3.06	2.36
Fineness (cm^2/g)	3250	2900

2.2. Preparation of Mixtures and Experiments

When designing the mixtures, three different methods were used for incorporating FA into the mixture. In this way, a total of 10 different mixture sets were created, FA was not used for the control mixture(FA(0)). 9 different mixtures were obtained by using 3 different ratios of FA in 3 different methods. Mixing codes and material ratios are given in Table 2.

In the preparation of the mixtures, 25 L capacity planetary mixer is used. First of all, dry materials (aggregates, cement and FA) are processed at 100 rpm. was mixed at speed for 1 minute. Then water was added and 150 rpm. speed for 1 minute, finally 300 rpm. The mixing process was completed by mixing at high speed for 3 minutes (Figure 1). Prepared mixtures were placed in pre-lubricated molds and a vibrator was used for compaction. After 24 hours, the samples were taken out of their molds and placed in a pool filled with lime-saturated water.

(a) (b) (c)

Figure 1. Preparation of mixtures a) Sand addition, b) Cement and fly ash addition, c) Water addition.

One of the tests applied to determine the fresh state properties of the mixtures, the unit weight test was carried out according to the ASTM C138 [9] standard. With this method, it was determined how much the weight of FA, which has a lower unit volume weight than cement, can be reduced compared to the control mixture by using different proportions and different methods in the mixtures. In order to determine the fresh state properties of the mixtures, the spreading table test was carried out in accordance with the ASTM C230[10] standard. The mortar taken from the mixing bowl to the tray was placed in the mold on the spreading plate so that it was half filled, and after it was hit 25 times with the mallet, the other part of the mold was filled and another 25 strokes were applied. After the upper surface of the mold was cleaned and smoothed with a trowel, the handle of the test tool, which was taken by pulling the mold, was rotated 5 times in 15 seconds, the diameter of the spread mixture was measured with the help of a meter in 2 different axes and the average of the readings was recorded (Figure 2).

Figure 2. Spreading table test.

Mechanical and permeability tests were carried out on the hardened samples at the end of the 7, 28 and 90 days following production, and the freeze-thaw test was performed at the end of the 28 day. Compressive strength test was carried out on 50x50x50 mm cube samples in accordance with ASTM C39[11] standard. The flexural strength test was carried out on beam specimens of 40x40x160 mm in 3-point bending model in accordance with ASTM C293[12] Cylinder specimens of Ø100/200 mm size were used in the cylinder splitting tests and the tests were carried out in accordance with ASTM C496. Freeze-thaw test was carried out in accordance with TSE CEN/TR 15177 [13] standard. 40x40x160 mm beam specimens were produced for the experiments, and flexural and compressive strengths were determined by taking the average of the three specimens on the 28 day. In the freeze-thaw test according to the TSE CEN/TR 15177 standard, the samples are frozen at -20 ^{0}C for 18 hours and then left in the air for 30 minutes. Then it is expected to dissolve in water at 20 ^{0}C for 2 hours. In this way, a freeze-thaw cycle is performed. Within the scope of the experimental studies, a total of 30 cycles were applied and the compressive and flexural strengths of the samples were determined after the cycles and the changes that occurred before and after freezing-thawing were examined. Permeability tests are important tests applied to have an idea about the void character and amount of voids of the samples. Significant durability problems arise in materials with permeable voids. In the study, two different test methods were used to determine the permeability properties of the samples. For these experiments, Ø100/200 mm sized cylindrical samples were produced, and the samples extracted from the curing water on the day of the experiment were cut using a diamond saw to obtain Ø100×50 mm sized samples. Water absorption tests were carried out according to ASTM C642[14], capillary water absorption tests were carried out according to ASTM C1585 [15] standards.

Table 2. The amount of material in the mixtures in grams (in grams for 1 dm^3).

Mix. ID	Cement (C)	F-FA	Sand(S)	Water
FA(0)	450	-	1350	225
FA(C10)	405	45	1350	225
FA(C20)	360	90	1350	225
FA(C30)	315	135	1350	225
FA(C5+A5)	427.5	90	1282.5	225
FA(C10+A10)	405	180	1215	225
FA(C15+A15)	382.5	270	1147.5	225
FA(A10)	450	135	1215	225
FA(A20)	450	270	1080	225
FA(A30)	450	405	945	225

3. Results and Discussions

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ISSN: 2147-0081
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3.1. Unit Volume Weight Test

The average unit volume weight values of the fresh mixtures are shown in Figure 3. In the simple substitution method in which FA is replaced by cement, unit weight values were lower than the control mixture. In other methods, it was observed that the unit volume weight was higher, especially at low FA ratios, and the values decreased depending on the increase in FA ratio.

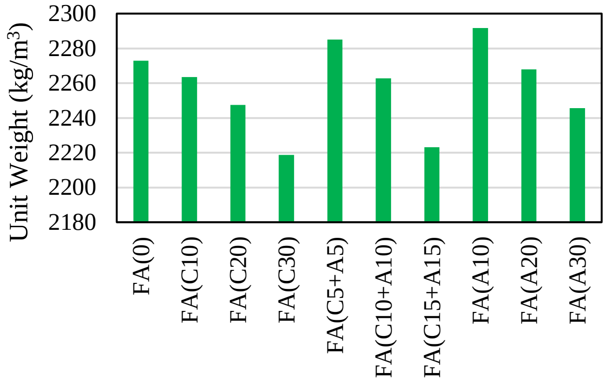

Figure 3. Average unit volume weight values of mixtures.

3.2. Spreading Table Test

The average spreading values of the fresh mixtures are shown in Figure 4. To understand the effect of fly ash on the workability of concrete, the water content was adjusted to be constant for all mixtures. When the spreading test results were examined, the mixture dispersion increased as the fly ash ratio increased. In addition, it is noticed that the mixtures formed by the simple substitution method (using an equal amount of FA instead of cement) are more workable than the mixtures prepared by other methods.

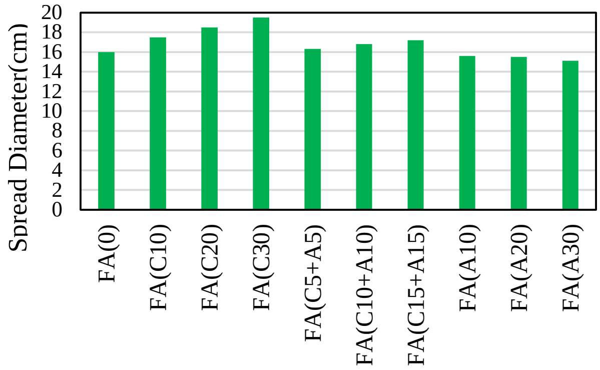

Figure 4. Average spreading diameter values of mixtures.

3.3. Compressive Strength Test

The compressive strength test on the hardened samples was carried out on the 7, 28 and 90 days following and the results are given in Table 3.

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Table 3. 7, 28 and 90-day compressive strengths of the samples.

Mix. ID	Compressive Strength (MPa)		
	7 day	**28 day**	**90 day**
FA(0)	29.88	47.54	55.75
FA(C10)	22.61	44.52	52.01
FA (C20)	16.71	41.39	50.33
FA (C30)	15.61	27.54	49.21
FA (C5+A5)	27.00	50.90	70.18
FA (C10+A10)	23.58	46.48	64.61
FA (C15+A15)	19.61	45.15	60.79
FA (A10)	25.65	54.64	74.37
FA (A20)	21.88	51.47	72.04
FA (A30)	18.82	45.77	69.97

In the simple substitution method, the maximum decrease in compressive strength was 12% in the FA(C30) samples, and the minimum decrease was 7% in the FA(C10) samples compared to the reference samples FA(0).

In the partial substitution method, the maximum increase in compressive strength was 26% in the FA(C5+A5) samples, and the minimum increase was 9% in the FA(C15+A15) samples, compared to the reference samples FA(0).

Similarly, in the addition method, the maximum increase rate was 33% in the FA(A10) samples and the minimum increase rate was 25% in the FA(A30) samples compared to the reference samples FA(0). The graphic representation of the compressive strength comparison of the samples is given in the Figure 5.

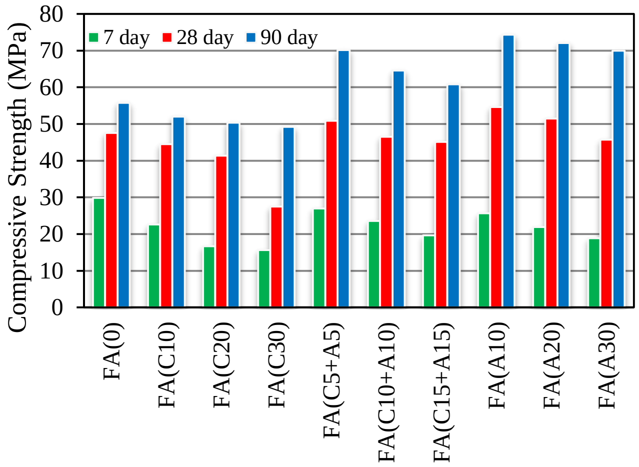

Figure 5. Comparison of compressive strength of samples.

- It was observed that mixtures containing 10% FA at different ages had the highest compressive strength among all FA mixtures. When the existing literature studies are examined, it is seen that the use of FA in concrete reduces the mechanical properties of concrete.
- Increases in compressive strength were observed in all mixtures with advancing age. However, the increase in the 90-day compressive strength of the samples prepared in partial replacement and addition methods is quite evident. The amount of cement removed from the mixtures in these two methods is less than in simple replacement methods. The hydration property of cement is higher than FA. However, the use of FA instead of aggregate caused an increase in the amount of binder in the mixture. Thanks to the pozzolanic character of the FA, the long-term continuation of the

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ISSN: 2147-0081
(2022) 7–2
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hydration event has led to an increase in strength in advancing ages. This can be explained by the positive contribution of pozzolanic activity on compressive strength in later ages.

- When the strength values obtained after the 7, 28 and 90 days curing periods of the mixtures are compared, it is seen that the highest strength values are obtained from the FA(A10) mixture.

3.4. Flexural strength test

The flexural strength test on the hardened samples was carried out on the 7, 28 and 90 days following and the results are given in Table 4.

Table 4. 7, 28 and 90 days flexural strengths of samples.

Mix. ID	Flexural Strength (MPa)		
	7 day	28 day	90 day
FA(0)	6.86	8.42	10.43
FA(C10)	5.62	7.74	9.22
FA(C20)	4.57	7.54	10.27
FA(C30)	4.06	7.33	9.79
FA(C5+A5)	6.00	8.86	11.28
FA(C10+A10)	4.82	7.55	10.63
FA(C15+A15)	4.53	7.36	12.15
FA(A10)	5.58	8.47	10.93
FA(A20)	5.36	7.46	10.90
FA(A30)	5.04	6.77	10.68

In the simple substitution method, the maximum decrease in flexural strength compared to FA(0) was in FA(C10) samples (12%), while the minimum decrease was in FA(C20) samples (2%).

In the partial substitution method, the maximum increase in flexural strength compared to FA(0) was in the FA(C15+A15) samples (17%), while the minimum increase was in the FA(C10+A10) samples (2%).

Similarly, in addition method, the maximum increase rate compared to FA(0) was in FA(A10) samples (5%), and the minimum increase rate was in FA(A30) samples (2%).

The comparison graph of the 7, 28 and 90 days flexural strength values of the samples is given in Figure 6.

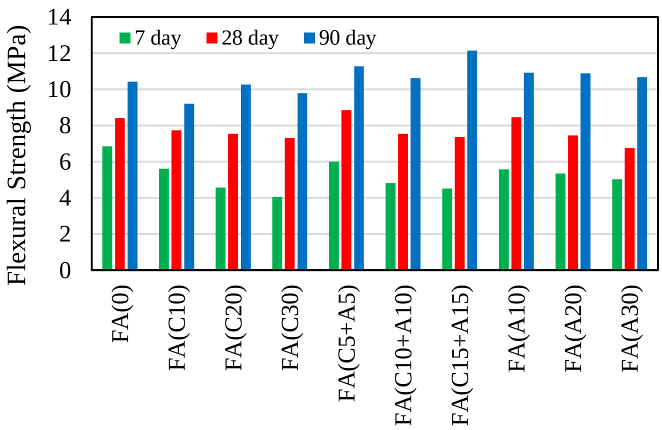

Figure 6. Comparison of flexural strengths of samples.

- The flexural strength of the samples prepared by the simple substitution method at increasing FA ratios was lower than the values obtained from the control samples at different ages. In the samples prepared with the partial replacement method and the addition method, only 7-day flexural strength values were lower than the control samples, and the 28 and 90-day strength values were generally higher than the control sample. According to this result, the replacement of FA with cement only

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ISSN: 2147-0081
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decreases the flexural strength values, partial replacement with cement and aggregate or only with aggregate causes an increase in flexural strengths in advancing ages.

- It has been observed that the increase in flexural strength of FA added samples in advancing ages is less than the increase in compressive strength. At the end of 90 days, the increase in flexural strength was at most 17%, and the increase in compressive strength was 33%.

3.5. Cylinder splitting strength test

The results obtained from the experiments are given in Table 5.

Table 5. 7, 28 and 90 days cylinder splitting strengths of samples.

Mix. ID	Cylinder Splitting Strength (MPa)		
	7 day	28 day	90 day
FA(0)	3.17	3.95	4.10
FA(C10)	2.87	3.45	3.87
FA(C20)	2.56	3.15	3.49
FA(C30)	1.65	2.85	3.28
FA(C5+A5)	3.13	3.53	4.06
FA(C10+A10)	2.76	3.22	3.66
FA(C15+A15)	2.18	3.00	4.21
FA(A10)	3.01	3.63	3.95
FA(A20)	2.68	3.35	3.59
FA(A30)	1.81	3.10	3.36

In the simple substitution method, the maximum decrease in split strength was found in the FA(C30) samples (20%) and the minimum decrease in the FA(C10) samples (5%) compared to the FA(0).

In the partial substitution method, the maximum increase in split strength was found in FA(C15+A15) samples (3%) and the maximum decrease in FA(C10+A10) samples (11%) compared to FA(0).

Similarly, in the addition method, the maximum decrease rate was found in FA(A30) samples (18%) and the minimum decrease rate was 4% in FA(A10) samples compared to FA(0).

The comparison graph of the 7, 28 and 90 days cylinder splitting strength values of the samples is given in Figure 7.

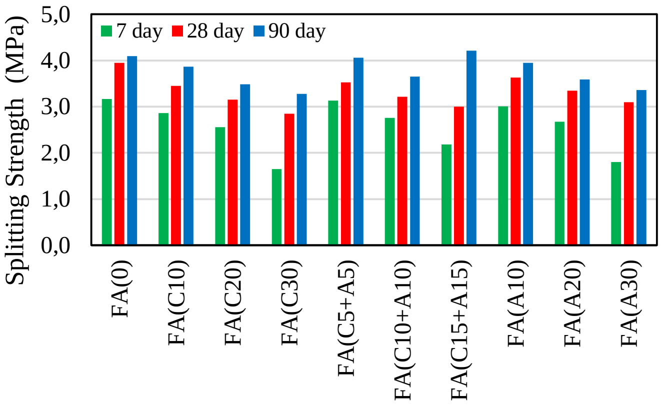

Figure 7. Comparison of cylinder splitting strength of samples.

According to the results of the splitting tensile strength test performed on the cylindrical samples, it was observed that the splitting strength values decreased as the FA content increased. The cylinder splitting strength of the FA added mixtures is lower than the control samples, only the 90-day values of the FA(C15+A15) mixture were found to be greater.

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ISSN: 2147-0081
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3.6. Freeze-Thaw test

The compressive and flexural strength results of the FA substituted and control samples with Freeze-Thaw (F-T) cycle and the comparison samples stored in the standard curing are given in Table 6.

Table 6. Strength drops under Freeze-Thaw effect.

Mixture ID	No Cycle		30 F-T Cycle		Strength Change	
	Compressive strength (MPa)	Flexural strength (MPa)	Compressive strength (MPa)	Flexural strength (MPa)	Compressive strength (%)	Flexural strength (%)
FA(0)	56.65	11.16	52.93	9.83	7	12
FA(C10)	49.27	11.01	46.20	9.95	6	10
FA(C20)	47.16	10.17	44.70	9.60	5	6
FA(C30)	42.38	9.72	40.59	9.44	4	3
FA(C5+A5)	60.54	11.50	57.20	10.58	6	8
FA(C10+A10)	55.55	10.50	53.17	9.86	4	6
FA(C15+A15)	51.17	9.98	49.80	9.68	3	3
FA(A10)	64.51	11.41	61.81	10.79	4	5
FA(A20)	61.76	10.73	60.26	10.25	2	4
FA(A30)	57.87	10.31	57.16	10.20	1	1

When Table 6 is examined, it is seen that the compressive and flexural strength values decrease as the amount of FA increases, similar to the mechanical strength tests. However, when the percentage changes in the strength losses of the samples are examined, it is seen that the decrease in the strength of the control samples without FA is greater than the decrease in the strength of the samples containing FA. The addition method showed less loss in compressive and flexural strengths.

3.7. Water absorption test

The water absorption test was performed on Ø100×50 mm cylindrical samples on the 7th, 28th and 90th days and the percent water absorption values of the samples are given in Figure 8.

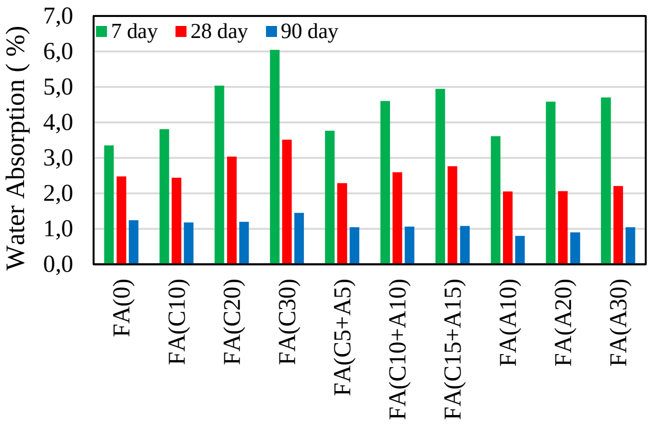

Figure 8. Comparison of the water absorption values of the samples.

It is observed that as the amount of FA replacement increases, the amount of water absorption in the samples also increases. After 28 and 90 days of curing, it was observed that the water absorption values gradually decreased. This shows that the void structures of the samples decrease during curing. According to FA(0), the maximum decrease rate was 4% in the FA(C20) samples, and the maximum increase was 17% in the FA(C30) samples in the simple substitution method.

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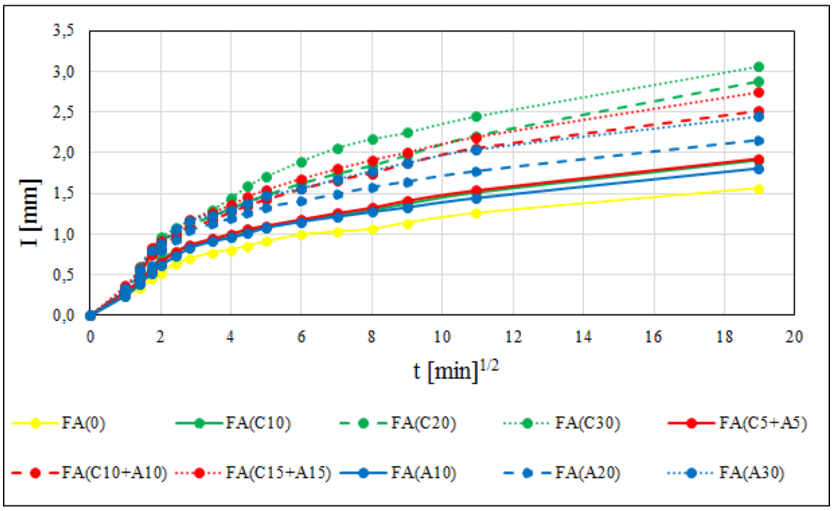
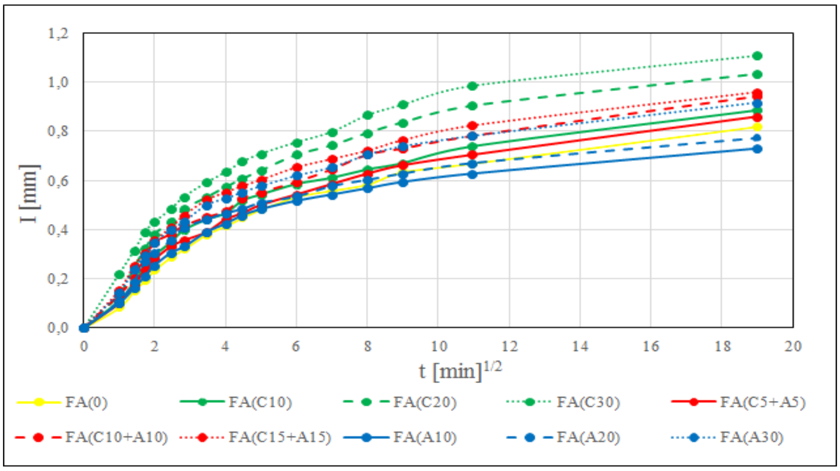
3.8. Capillary water absorption test

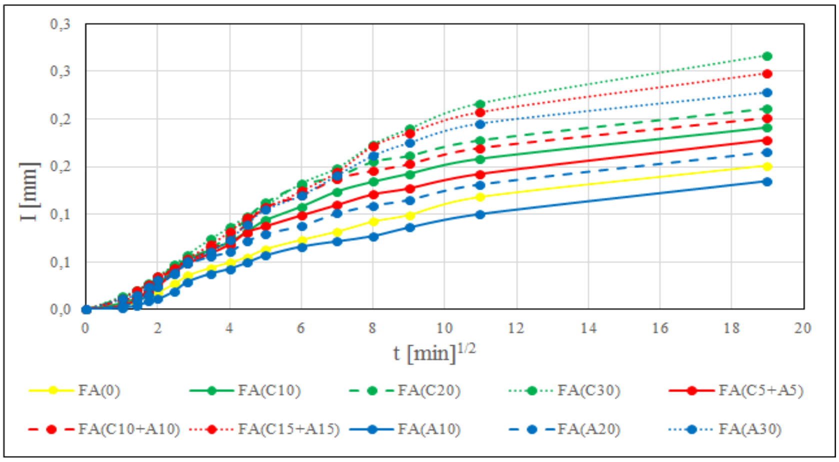
The change in the permeability properties of the samples as a result of the capillary water absorption test is given in Figure 9.



a) 7 days



b) 28 days



c) 90 days

Figure 9. Change in capillary absorption values of samples.

- Similar to the water absorption experiments, it was observed that the capillary water absorption results increased as the amount of FA increased, but this increase gradually decreased with advancing age, especially according to the 7-day test results. One of the most important factors affecting the void amount of the samples is the hydration of the cement. As the hydration progresses, the binder paste formed fills the capillary water absorption gaps and disconnects them. Similarly, additional C-S-H gels are formed as a result of the reaction of FA with $Ca(OH)_2$, which is formed as a result of the hydration of the main components of the cement, and this reduces the amount of capillary space. It was observed that the capillary water absorption values gradually decreased after 28 and 90 days of curing due to the slower hydration reaction of the FA.
- In the experiments performed at different ages, it was observed that the lowest capillary water absorption value was obtained from the FA(A10) samples, and the highest values were obtained from the FA(C30) samples.

4. Conclusions

In this study, FA was used in mixtures with three different mixing methods. Slump and unit weight tests were performed to determine the fresh properties of the mixtures, and mechanical, durability and permeability tests were performed to determine the hardened properties. The results obtained as a result of the experiments carried out are presented below.

1) Regardless of the rate of substitution for all mixes, the inclusion of FA improved the workability of concrete due to the fineness and spherical shape of its particles.
2) It has been observed that the use of large amounts of FA in concrete adversely affects the mechanical properties of the concrete. It is understood that the mechanical properties of mixtures containing 10% FA develop better. However, it was observed that the strength development accelerated in the samples prepared by the addition method or partial replacement method after the advancing curing periods and the FA additive had a positive effect on the behavior.
3) Decreases in flexural and compressive strength values of control samples after freeze-thaw cycles were higher than those of FA substituted samples. Accordingly, it can be said that as the FA content increases, the resistance of the samples to freeze-thaw increases. This can be explained by the fact that FA fills the voids in the sample better and increases the freeze-thaw resistance.
4) As a result of the permeability tests, the permeability properties of the samples prepared by the addition method were generally lower than the other mixing methods. According to this, it is understood that the replacement of FA with aggregate instead of cement has a positive effect in terms of reducing the amount of voids in the samples.

The use of FA as a binder material and reducing the amount of cement has positive results in many ways. By replacing FA with cement, it is possible to obtain more economical and environmentally friendly concrete. In addition, it is thought that the use of some FA instead of fine aggregate used in concrete will contribute to the efficient use of FA, which is a waste material, to the industry, and to reduce its effects on environmental pollution and storage costs.

Peer-review: Externally peer - reviewed.

Author contributions: Concept – A.A., M.A.; Data Collection &/or Processing – M.A.; Literature Search – A.A., M.A.; Writing - A.A.

Conflict of Interest: This work has been partly presented at the ICENTE'21 (International Conference on Engineering Technologies) held in Konya (Turkey), November 18-20, 2021. This study was produced from the Master thesis entitled " Farklı Karışım Yöntemleri İle Kullanılan F Tipi Uçucu Külünün Beton Özelliklerine Etkilerinin İncelenmesi" by Marvan ALITHAWI, which was accepted in 2021.

Financial Disclosure: The authors declared that this study has received no financial support.

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