J Inno Sci Eng, 2025, 9(2):191-204

DOI:https://doi.org/ 10.38088/jise.1593473

Research Article

Evaluation of paper factory screen underflow sludge and power plant fly ash in concrete block production: Improvement of mechanical and physical properties

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ARTICLE INFO

Received Date: 3/12/2024
Accepted Date: 21/06/2025

Cite this paper as:
Topyüz, B., Yaşar, M. & Karademir, A. (2025). Evaluation of paper factory screen underflow sludge and power plant fly ash in concrete block production: Improvement of mechanical and physical properties. *Journal of Innovative Science and Engineering.* 9(2), 191-204.

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Keywords:
Waste material
Concrete block
Fly ash
Waste paper sludge
Strength
Water permeability

ABSTRACT

This study investigates the utilization of paper mill sludge (PS) and non-standard fly ash (FA) from power plants in the production of concrete blocks. Test specimens were produced by incorporating varying proportions of PS and FA into standard concrete block mixtures. The specimens were cured, using standard methods and tested at various intervals. The analysis results indicate that PS and FA, which are difficult to dispose of, can be used in structural elements at certain proportions. Additionally, FA incorporation improved the strength and workability of the concrete, and the water permeability remained within the targeted values with the inclusion of PS and FA. In conclusion, PS and FA provide acceptable properties for concrete block production, with the chemical and physical characteristics of the waste materials, mix ratios, and production parameters significantly affecting the outcomes. However, to increase the proportion of these wastes and enhance their positive contributions, further detailed studies are required, particularly focusing on mixing techniques and homogeneous formation.

1. Introduction

Concrete, widely utilized in the construction sector, is a critical building material whose properties can be enhanced through various admixtures. Traditional concrete mixtures consist of cement, water, fine, and coarse aggregates. However, modern concrete technology employs a variety of mineral and chemical additives to improve the performance and durability of concrete. In contemporary urban life, transportation, and industrial infrastructure, concrete has become indispensable, bringing transformative changes to human existence.

As with any material and technology, the construction sector and concrete industry continue to experience progress, research, and innovation. Efforts are being made to enhance the strength properties of concrete-based structural elements, reduce production costs, and integrate alternative components into standard concrete mixtures. Studies have demonstrated that the inclusion of straight and hooked steel fibers improves the mechanical properties of normal-strength concrete, such as compressive, flexural, and splitting tensile strength [11]. Another study highlighted the effects of ultra-high-performance fiber-reinforced concrete (UHPFRC) on the flexural and shear behavior of I-beam reinforced concrete [10]. The addition of steel fibers significantly enhances the cracking resistance and toughness of concrete [13]. Research continues to explore a wide range of additives aimed at improving the properties of concrete.

The growing global population and the consumption-driven economy have led to an inevitable increase in the generation of diverse and massive volumes of waste, posing significant disposal challenges. Studies have investigated the potential of incorporating some of these wastes into concrete production to address disposal issues while enhancing material properties. For instance, detailed studies have examined the effects of incorporating PET bottle waste into cement mortar and concrete properties [12]. It has been shown that polypropylene fiber increases tensile strength and prevents microcrack formation in concrete [3]. Further research on steel, glass, and polypropylene fibers has concluded that these fibers significantly improve the flexural strength of concrete [1]. Investigations into using cable waste mixed with fly ash in concrete have also been conducted [5].

Fly ash has been extensively studied as well. A detailed study explored the utilization of fly ash, collected through cyclone filters in coal-fired power plants, in concrete production [4]. Fly ash has been observed to enhance the long-term durability of concrete and slow down the hydration process [7]. Concrete mixtures containing up to 20% fly ash were reported to exhibit higher late-age strength compared to traditional concrete mixtures [2]. Furthermore, fly ash reduces the permeability of concrete, thereby improving its corrosion resistance [14].

Research on the combined use of fiber reinforcements and fly ash has also yielded promising results. Concrete mixtures containing steel fibers and fly ash have demonstrated superior strength and durability characteristics [6]. Combinations of polypropylene fibers and fly ash have been noted to reduce water permeability, thereby increasing corrosion resistance [8]. Synthetic fiber and fly ash additives have significantly improved both the mechanical properties and long-term durability of concrete [9].

Varaka Kağıt Sanayi A.Ş. (Varaka) generates substantial amounts of under-screen sludge (USS), composed of short fibers and fillers, as a by-product of its daily production process. Additionally, significant quantities of fly ash (FA) and bed ash (BA) are produced at the on-site power plant from coal combustion. The sustainable, environmentally friendly, and economically viable utilization of these two high-volume wastes in concrete production is a matter of critical importance. To this end, numerous concrete blocks have been produced under laboratory conditions, tests have been conducted, and the results have been analyzed and interpreted.

2. Methodology

2.1. Materials

Cement (CEM-I 42.5): According to the standard definition, this cement type is produced by grinding Portland cement clinker with a certain amount of gypsum ($CaSO_4 \cdot 2H_2O$). Its composition typically includes 95% Portland cement clinker and 5% minor components, along with an additional 5% gypsum. The product is certified under CE number 1784-CPR-DI53. In terms of its standard chemical properties, the loss on ignition is less than 5%, the insoluble residue is below 5%, the sulfur trioxide (SO_3) content is under 4.0%, and the chloride (Cl^-) content is maintained at levels lower than 0.1%.

Water: Clean water with a pH range of 7–8.5, suitable for drinking and agricultural irrigation

Under-Screen Sludge (USS): During the paper production process at the paper mill, the sludge formed from cellulose fibers retained below the screen, referred to as under-screen sludge, was utilized in this study. A visual representation of this waste material is presented in Figure 1.

Figure 1: Under-Screen Sludge (USS).

Fly Ash (FA): Fly ash, a significant waste material generated by the power plant operating within the premises of Varaka, was utilized in this study. A visual representation of the fly ash is provided in Figure 2, while its fundamental chemical composition is presented in Table 1.

Figure 2: Fly Ash (FA).

Table 1: The chemical composition of fly ash.

Composition	%
SiO_2	42,49
CaO	15,93
Fe_2O_3	8,840
Al_2O_3	20,21
Na_2O	0,741
SO_3	4,790
K_2O	1,189
MgO	3,482

In the study, cement, fly ash (FA), and under-screen sludge (USS) were utilized in their air-dry weights for experimental trials. The bulk densities of Varaka's USS and FA were determined as 360 kg/m³ and 665 kg/m³, respectively. The moisture contents of the cement, USS, and FA used in the experimental work were measured as 0.6%, 15%, and 2%, respectively. The relevant standard test methods applied for determining these properties are presented in Table 2.

2.2. Method

For a concrete mixture with a volume of 20 dm³, a total of 18 different specimens were prepared, excluding the control sample, using the materials specified in the materials section. During the preparation of these specimens, relevant standard methods were meticulously followed (Table 3). Various proportions of under-screen sludge (USS) and fly ash (FA) were used in the prepared specimens, and the mix designs for each composition were carefully implemented. The mix designs were structured based on the material ratios and properties. Maintaining a constant total volume is an important practical consideration for the feasibility of the experimental study. However, due to the non-standard and high water absorption capacity of the fly ash used in this study, as well as the water retention properties of cellulose fibers derived from paper waste, it is practically impossible to keep the water-to-cement ratio constant experimentally. In mixtures containing such high water absorption materials, maintaining a constant water-to-cement ratio typically requires the addition of significant amounts of chemical admixtures. Nevertheless, this study focuses on traditional concrete applications rather than modern concrete technologies. Therefore, the inability to fully stabilize the water-to-cement ratio is consistent with the scope and objectives of the research. Consequently, the observed natural variations in the water-to-cement ratio arise from the inherent water absorption characteristics of the materials, and this factor should be taken into account in the experimental design and interpretation of the results. The primary objective of this experimental study was to evaluate the effects of different USS and FA proportions on the mechanical and physical properties of the concrete mixtures.

2.3. Abstract and Keywords

The standard numbers followed for the tests conducted are provided (i.e., Table 4).

In this context, cube specimens were cast and subsequently converted into cylindrical form in accordance with the requirements of the splitting tensile strength test. The necessary conversion factors were applied to ensure that the results obtained from the cylindrical specimens could be accurately derived from the originally cast cube samples. (i.e., Table 5).

3. RESULTS AND DISCUSSION

Concrete samples with dimensions of 15x15x15 cm were prepared in accordance with the standards. Initially, the concrete mixture was blended homogeneously in the mixer according to the specified material proportions. The mixture was poured into molds in layers, and each layer was compacted by using a vibrator to eliminate air voids. The molds were then subjected to a curing process under appropriate conditions to allow the concrete to set. The casting and curing processes were carried out according to standard procedures to ensure the accurate determination of the mechanical properties of the samples (i.e. Figure 3).

Figure 3: Appearance of the specimens after casting.

Figure 4: Specimens removed from the mold after a certain waiting period.

Table 2: The components used in concrete mix and some of their properties.

Property	Standard	Unit	Coarse Aggregate	Fine Aggregate	Varaka Fly Ash	Varaka Cellulose Fiber Reinforcement
Loose Bulk Density	ASTM C29 / TS EN 1097-3.	kg/m³	1850	1930	550-700 kg/m³	300-400 kg/m³
Compacted Bulk Density	ASTM C29 / TS EN 1097-3.	kg/m³	1910	1950	800-1400 kg/m³	540-720 kg/m³
Specific Gravity	ASTM C127 (Coarse aggregate), ASTM C128 (Fine aggregate) / TS EN 1097-6.	-	2,64	2,68	2,2-2,6	1,3-1,5
Water Absorption Rate	ASTM C127 (Coarse aggregate), ASTM C128 (Fine aggregate) / TS EN 1097-6.	%	2,80	11,30	%10-20	%200-400
Abrasion	ASTM C131 (Los Angeles Abrasion test) / TS EN 1097-2.	%	26,00	-	%20-30	-
Crushing	ASTM D7428 / TS EN 933-9.	%	9,10	-	%15-25	May enhance resistance.
Clay Content	ASTM C142 / TS EN 933-8.	%	0,24	7,00	-	>%20
Combustible Matter	ASTM D3174 / TS EN 13820.	%	5,20	5,00	Non-flammable.	Flammable.
Fines Content	ASTM C117 / TS EN 933-1.	%	2,00	4,00	Low Quantity ≤%5	Does not contain
Organic Matter	ASTM C40 / TS EN 1744-1.	color	-	Light Yellow	Does not contain	High
Loose Bulk Density (repeated)	ASTM C29 / TS EN 1097-3.	kg/m³	1850	1930	550-700 kg/m³	300-400 kg/m³
Compacted Bulk Density (repeated)	ASTM C29 / TS EN 1097-3.	kg/m³	1910	1950	800-1400 kg/m³	540-720 kg/m³

Figure 5: 15x15x15 cm cube specimen sample

Figure 6: Curing of the specimens

Table 3: Mix designs for concrete produced with waste paper sludge and fly ash blends.

		Crushed Stone (%)	0-4 mm Fine Aggregate	Cement CEM I 42.5 R	Fly Ash	Fiber Reinforcement	Water (%)	Total (%)
Control		46,2	30,8	15,4	0	0	7,7	100
%5 FA Substitution	1	46,2	30,8	14,6	0,8	0	7,7	100
	2	46,2	30,8	14,2	0,8	0,4	7,7	100
	3	46,2	30,8	13,7	0,8	0,9	7,7	100
% 10 FA Substitution	4	46,2	30,8	13,8	1,5	0	7,7	100
	5	46,2	30,8	13,4	1,5	0,4	7,7	100
	6	46,2	30,8	13	1,5	0,9	7,7	100
% 20 FA Substitution	7	46,2	30,8	12,3	3,1	0	7,7	100
	8	46,2	30,8	11,9	3,1	0,4	7,7	100
	9	46,2	30,8	11,4	3,1	0,9	7,7	100
% 30 FA Substitution	10	46,2	30,8	10,8	4,6	0	7,7	100
	11	46,2	30,8	10,3	4,6	0,4	7,7	100
	12	46,2	30,8	9,9	4,6	0,9	7,7	100
% 40 FA Substitution	13	46,2	30,8	9,2	6,2	0	7,7	100
	14	46,2	30,8	8,8	6,2	0,4	7,7	100
	15	46,2	30,8	8,4	6,2	0,9	7,7	100
% 50 FA Substitution	16	46,2	30,8	7,7	7,7	0	7,7	100
	17	46,2	30,8	7,3	7,7	0,4	7,7	100
	18	46,2	30,8	14,6	7,7	0,9	7,7	100

The samples removed from the molds were carefully separated from the molds (i.e., Figure 4). This process was performed by applying pressurized air through the air inlet points at the bottom of the molds, ensuring that no damage occurred to the samples. Afterward, the removed samples were prepared to be placed in the curing tank, where they would be kept under appropriate conditions for the curing process.

Table 4: The chemical composition of fly ash.

Tests	Standard	Curing Durations
Compressive Strength Test	TS EN 12390-3	7/14/28
Splitting Tensile Strength Test	TS EN 12390-6	7/14/28
Water Absorption Test	TS EN 12390-7	28

3.1. Test Results and Analyses

Compressive Strength

Specimen Type: The samples were cast in the form of cubes (150 mm x 150 mm x 150 mm), and the cylindrical compressive strength and splitting tensile strength results were obtained by using the UNESCO conversion factors (i.e. Figure 5).

Curing Periods: The samples were cured by immersing them in water for curing periods of 7, 14, and 28 days (i.e. Figure 6).

N Number of Samples: Three samples were taken for each curing period. Method: The cured samples were tested at the end of 7, 14, and 28 days (i.e. Figure 7).

Table 5: UNESCO Conversion Factors.

Specimen Shape	Specimen Size (mm)	Conversion Factor
Cylinder	150 x 300	1,00
	100 x 200	0,97
	250 x500	1,05
Cube	100 x 100 x 100	0,80
	150 x 150 x 150	0,80
	200 x 200 x 200	0,83
	300 x 300 x 300	0,90
Prism	150 x 150 x 450	1,05
	200 x 200 x600	1,05

When examining the differences in compressive strength between the control and fiber-reinforced samples (Figure 8), it was observed that, contrary to initial expectations, the inclusion of fibers led to a reduction in strength due to the adopted mix design methodology. On the other hand, the incorporation of fly ash within the concrete mixture was found to enhance workability. Although no specific experiment was conducted to measure this effect the created networks. This does not guarantee that the solution found is the best solution; in other words internal friction and improve flowability (Mehta & Monteiro, 2014; Siddique, 2004). Furthermore, the pozzolanic fineness of fly ash compensates for the lack of fine material in the mix, particularly when adequate water content is maintained. These properties, as confirmed in the literature, were consistent with the empirical observations in this study.

Figure 7: Compression test preparation stage of the specimen

The graph (Figure 9) indicates a decrease in compressive strength at 7, 14, and 28 days as the fly ash content increases. Up to 20% replacement, the reduction is moderate, while more pronounced drops are observed at replacement levels of 30% and above. The 28-day strength is the highest, whereas the 7-day strength is the lowest, highlighting that fly ash substitution negatively impacts early strength but contributes to improved strength over time.

Figure 8: Compression test during and after the experiment on the specimen.

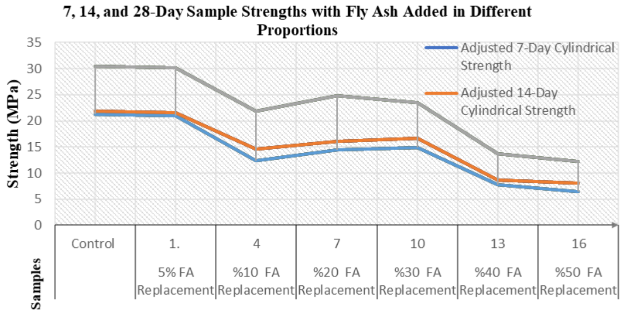

Figure 9: Strength versus time graph of ash content

The graph (Figure 10) demonstrates a reduction in compressive strength in samples containing 0.4% fiber reinforcement as the fly ash replacement ratio increases. While there is slight recovery at 20% and 30% replacement levels, a significant drop in strength is observed at 40% and 50%. Although fiber reinforcement enhances the 28-day compressive strength, its influence on early-age strength remains limited.

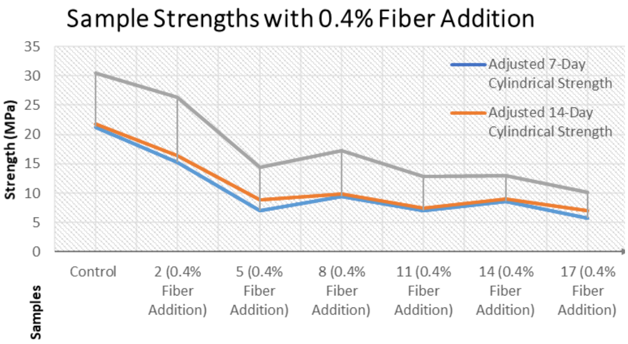

Figure 10: Strength graph of specimens with 0.4% fiber reinforcement.

The graph (Figure 11) examines the compressive strengths at 7, 14, and 28 days for samples containing 0.9% fiber reinforcement with varying fly ash replacement levels. A noticeable strength loss is observed at 5% replacement, followed by partial recovery at 10% and 20%, and a subsequent decline at 30% and higher replacement levels. While fiber reinforcement positively influences the 28-day strength, its effect on early-age strengths remains limited. The results indicate that 0.9% fiber reinforcement does not fully offset the adverse effects of fly ash replacement but partially improves overall strength.

In this graph (Figure 12), the effects of different fly ash (FA) replacement ratios and fiber reinforcement levels on the compressive strengths of concrete samples at 7, 14, and 28 days are analyzed. Strength results were obtained for all three age groups, highlighting variations due to fly ash replacement and fiber content.

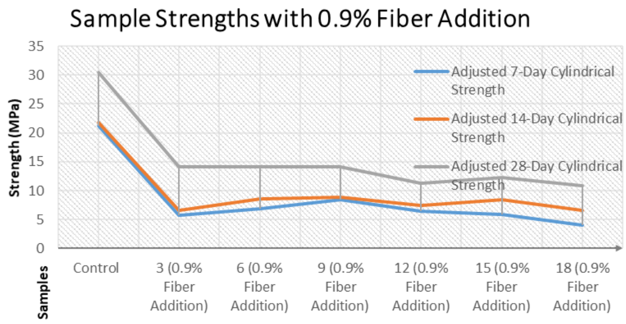

Figure 11: Strength graph of specimens with 0.9% fiber reinforcement.

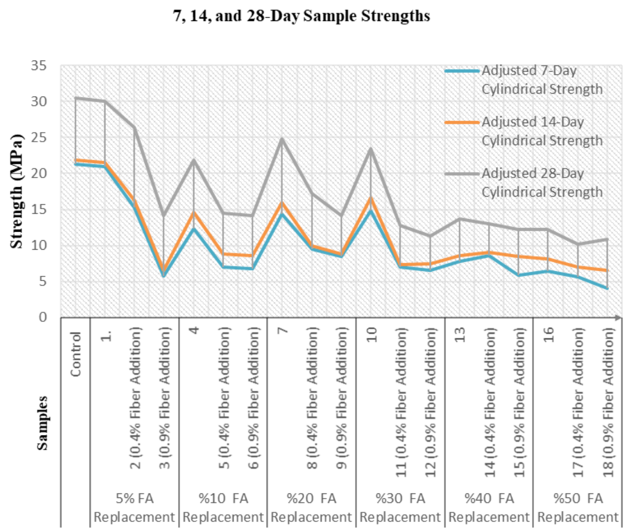

Figure 12: Strength versus time graph of all specimens.

General Trends and Evaluation

The control sample depicted in the graph represents the standard mix, with no fly ash replacement or fiber reinforcement. This sample achieves the highest compressive strength values at both 7 and 28 days. These results illustrate the reference strength obtained without the influence of additional modifications or additives.

Fly Ash (FA) Replacement Ratios

FA 5% and 10%: At these replacement levels, compressive strength at 7 days shows a significant decline in mixes with fiber reinforcement. However, strength values at 14 and 28 days are slightly higher. This suggests that FA negatively impacts early-age strength but contributes to partial recovery in later stages due to pozzolanic reactions.

FA 20%: When FA replacement increases to 20%, both early- and late-age compressive strength exhibit a noticeable reduction. The effect of fiber reinforcement remains limited, indicating that at this level, FA negatively affects the concrete microstructure, and the reinforcing fibers are insufficient to mitigate this effect.

FA 30% and Above: At replacement ratios of 30% and higher, compressive strength shows a marked decrease. Both 7- and 28-day strengths remain low, and the inclusion of fibers fails to compensate for the loss. These findings highlight that high levels of FA replacement can have a detrimental effect on concrete strength, and this adverse impact cannot be adequately balanced by fiber reinforcement.

Effect of Fiber Reinforcement

The ratio and type of fiber reinforcement influence the strength values of concrete. In this study, cellulose fibers were first dispersed in water to separate and fibrillate the strands, which were then drained to reduce excess free water before being incorporated into the mix at the final stage of preparation. This method was adopted to improve uniform distribution and mitigate the potential for fiber agglomeration. Generally, mixtures containing 0.4% fiber content exhibited lower compressive strength compared to those with 0.9%, suggesting that higher fiber ratios can contribute to crack bridging and strength enhancement. However, at high levels of fly ash (FA) replacement, particularly at 30% and above, the ability of fiber reinforcement to improve compressive strength diminishes. Therefore, optimizing both the FA replacement ratio and the fiber content is essential to achieve an effective balance between mechanical performance and sustainability.

Split Tensile Strength

The split tensile strength test was conducted on cylindrical concrete specimens to determine the tensile strength of the concrete. However, in this particular test, cube specimens were used, and the relevant conversion factors were applied for the experiments. In this test, the cube specimen was placed on its horizontal axis, and the loading was applied between two steel plates (i.e., Figure 13). The applied compressive force generates tensile stress within the specimen, causing it to split along its center. The split tensile strength value was calculated by using the maximum load at the moment of failure, and it is used to assess the tensile properties of the concrete.

Figure 13: Splitting tensile strength test

Sample Type: Prismatic (15x15x15 cm)

Curing Periods: 7, 14, and 28 days

Number of Samples: 3 samples for each curing period

Method: The samples were tested in the split tensile test apparatus at the end of the specified curing periods (i.e., Figure 14).

Figure 14: Final condition of specimens after the splitting tensile strength test.

In the graph obtained from the test results (i.e., Figure 15), the variation in split tensile strength of concrete samples with 0.4% fiber addition is examined based on different fly ash (FA) replacement ratios.

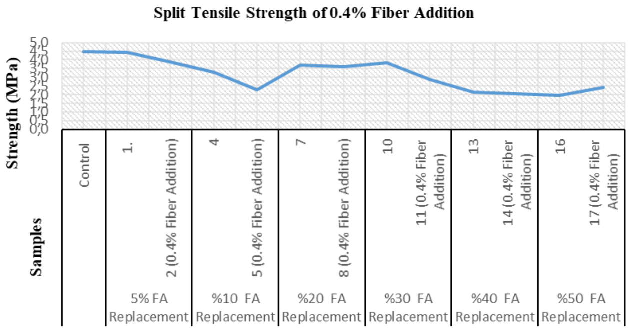

Figure 15: Splitting tensile strength test graph for specimens with 0.4% fiber reinforcement.

Compared to the control samples, a significant decrease in split tensile strength was observed with 5% and 10% fly ash (FA) replacement. With 20% FA replacement, strength showed slight recovery, but at replacement ratios of 30% and above, strength decreased again. At 40% and 50% FA replacement, the tensile strength dropped to its lowest levels. These results indicate that the 0.4% fiber addition is not sufficient to counterbalance the negative effects of FA replacement, and higher FA contents significantly weaken the concrete's tensile strength. In Figure 16, the variation in split tensile strength of concrete samples with 0.9% fiber content based on different FA replacement ratios is shown. Compared to the control sample, a decrease in strength is observed with 5% FA replacement, and this reduction becomes more pronounced as the FA replacement ratio increases.

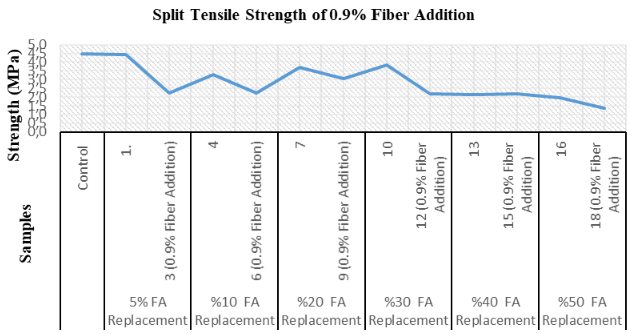

Figure 16: Splitting tensile strength test graph for specimens with 0.9% fiber reinforcement.

Similar to the 0.4% fiber addition, a downward trend in strength is also observed with the 0.9% fiber addition. • At 10% and 20% fly ash (FA) replacement ratios, a slight recovery in strength is observed; however, after 30% replacement, the strength continues to decrease. The lowest split tensile strength is reached with 50% FA replacement.

In the graph (Figure 17), the split tensile strengths (in MPa) of the samples prepared with varying fly ash (FA) replacement ratios and fiber additions are shown. Compared to the control sample (Sample 1), a general decrease in split tensile strength is observed as the fly ash replacement increases. However, this decrease does not occur in a linear fashion for all samples. While there are some fluctuations with 5% FA replacement and low fiber contents, the overall trend shows a decline in strength until the 50% FA replacement level.

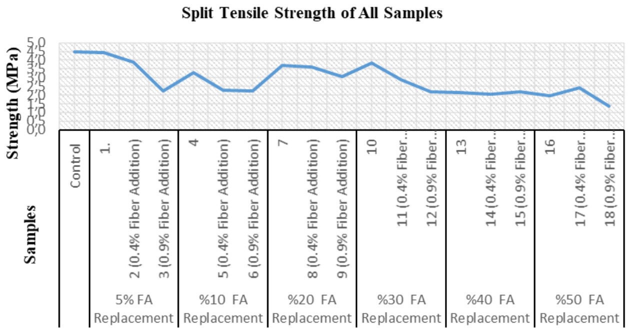

Figure 17: Splitting tensile strength test graph for all specimens.

Especially in experiments with 5% and 10% fly ash (FA) replacement (Samples 2-6), a more noticeable decrease in strength is observed, whereas with 20% FA replacement (Samples 7-9), a slight recovery is seen. However, for samples with 30%, 40%, and 50% FA replacement (Samples 10-18), a significant reduction in strength is evident.

These results indicate that as the fly ash replacement increases, the material's split tensile strength decreases. However, the addition of fibers can partially balance out this decline. Nonetheless, when the replacement ratio exceeds 20%, the effect of the fibers diminishes, leading to a significant reduction in strength.

Water Absorption

In the graph (i.e., Figure 18), the changes in the water absorption percentages of samples with fly ash substitution are analyzed. Starting from the reference sample, it can be observed that the water absorption rates of the samples with fly ash substitution ranging from 5% to 50% have increased. The graph indicates that the water absorption amount shows a linear increase with the fly ash substitution ratio, and it is noted to have a high coefficient of determination (R^2 = 0.9655).

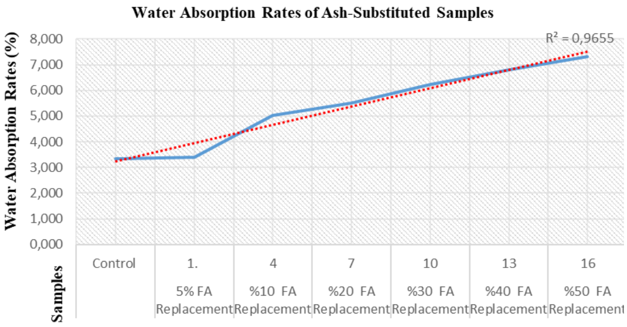

Figure 18: Water absorption graph of ash-containing specimens.

This situation demonstrates that the effect of fly ash substitution on water absorption capacity is quite consistent and predictable. In the graph (i.e., Figure 19), the change in water absorption amounts of samples with 0.4% fiber content is shown according to the substitution ratio. A general increasing trend is observed, which can be associated with the structural changes induced by the fiber addition in the concrete. Specifically, as the substitution ratio increases, the number and volume of capillary voids created by the fibers within the concrete also increase. These voids allow water to penetrate more easily into the concrete, leading to higher water absorption values.

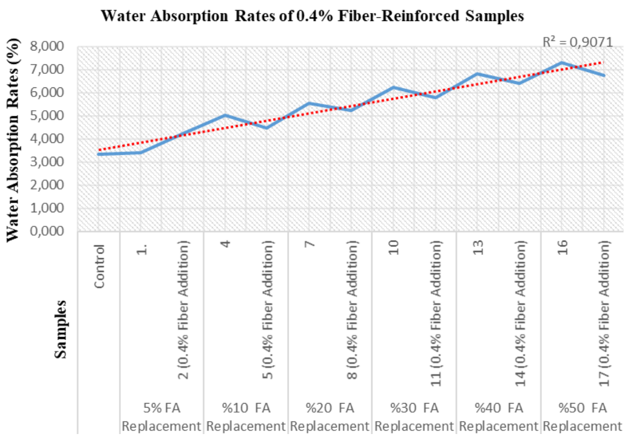

Figure 19: Water absorption graph of specimens with 0.4% fiber reinforcement.

The use of fibers in concrete is typically preferred to improve mechanical properties; however, unexpectedly, it also leads to an increase in water absorption capacity. This can be explained by the fibers creating micro-level voids in the concrete, which in turn increases the capacity to retain water. Additionally, the fly ash used as a substitute material may not completely fill the voids between cement particles, and when combined with fiber additives, it can be a factor that further increases the concrete's tendency to absorb water.

The linear regression curve presented in the graph (red dashed line) and its R^2 value (0.9071) demonstrate a strong positive relationship between water absorption amounts, substitution ratio, and fiber content. This high R^2 value indicates that the model explains the data very well and highlights the significant impact of substitution ratio and fiber content on water absorption values. This finding suggests that the effect of fiber additives on the increasing water absorption trend, in conjunction with the substitution ratio, needs to be optimized. Considering the fiber's enhancing effect on the concrete's ability to retain water, careful selection of substitution ratios and balanced use of fiber additives are necessary.

In Figure 20, the changes in water absorption amounts of samples with 0.9% fiber content are detailed based on the substitution material ratios used. The graph shows a general upward trend in water absorption as the substitution ratio increases. This trend can be directly related to the changes in the microstructure of the concrete induced by the fiber content.

The addition of Varaka fiber to the concrete leads to the formation of new capillary voids in the concrete matrix. These voids increase the concrete's ability to allow water to penetrate. Fiber content changes the permeability characteristics of the concrete, causing higher-than-expected water absorption values. This can be attributed to the fibers' ability to absorb water and leave permanent voids in the concrete as the absorbed water evaporates.

Furthermore, since the fly ash used as a substitute material cannot completely fill the voids between cement particles in the concrete, the presence of these voids has a further increasing effect on water absorption. Particularly when high amounts of substitution material are used, these voids become more pronounced, and the concrete's water absorption capacity increases as a result. The inability of fly ash, as a fine material, to fully close these voids is another factor that increases the concrete's water permeability. The linear regression curve in Figure 18 and the high R^2 value (0.9596) show a strong relationship between water absorption values, substitution ratios, and fiber content. The 0.9% fiber content and substitution ratios notably differ from the 0.4% fiber content samples in terms of their impact on water absorption performance. The high R^2 value reflects that the model accurately captures the influence of variables on water absorption, emphasizing the critical role of substitution ratios and fiber content.

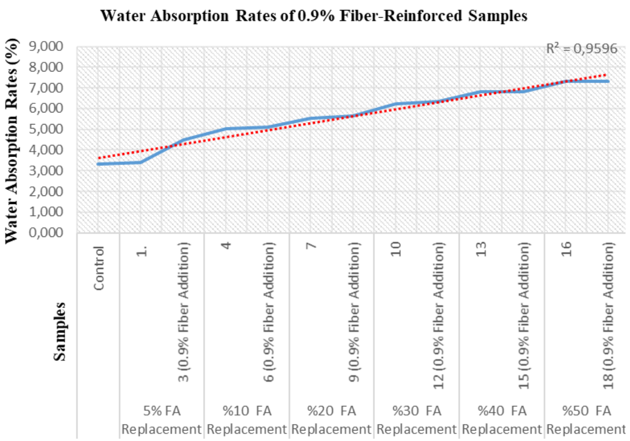

Figure 20: Water absorption graph of specimens with 0.9% fiber reinforcement.

These findings highlight the necessity of carefully considering fiber additives and replacement materials in concrete design. An increase in fiber content can enhance water absorption capacity, as it may create more voids in the microstructure of the concrete. Additionally, high fly ash substitution rates can negatively affect water impermeability, as they may not adequately fill the voids in the cement matrix. Therefore, it is crucial to balance the fiber content and substitution ratios to optimize the concrete's water permeability and durability.

Figures 19 and 20 demonstrate that both fiber content and substitution ratios significantly influence the water absorption properties of concrete. While fibers alter the void structure of the concrete, the limited filling capacity of the replacement material plays a crucial role. These changes are associated with an increase in capillary voids in the concrete, emphasizing the need to optimize fiber content and substitution ratios to improve concrete durability.

In the graph (i.e., Figure 21), the water absorption values (%) of samples with 0.4% and 0.9% fiber content and varying fly ash (UK) substitution ratios are presented.

The water absorption amount shows a consistent increase as the fly ash replacement ratio increases. The linear trend line in the graph (R^2 = 0.9743) indicates that this increase follows a highly accurate linear pattern. This suggests a strong correlation between fly ash replacement and water absorption. Compared to the control sample, a gradual increase in water absorption is observed across all replacement and fiber content ratios.

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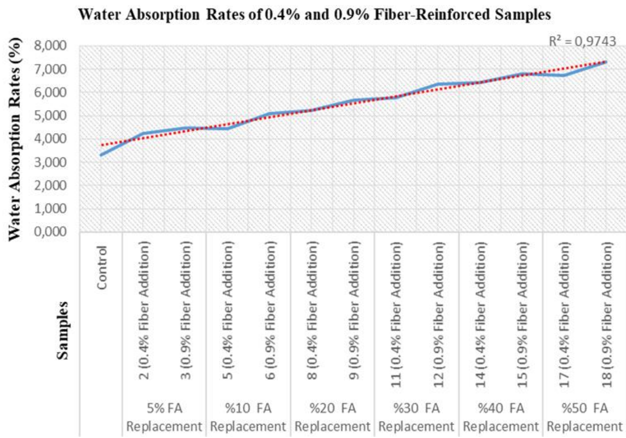

Figure 21: Water absorption relationship graph between specimens with 0.4% and 0.9% fiber reinforcement.

In the graph (i.e., Figure 22), the changes in water absorption amounts for different samples based on fly ash (UK) and fiber content ratios are shown. The trend observed in the graph reveals that as both the replacement ratio and fiber content increase, the water absorption amount also increases significantly. This can be attributed to the increase in capillary voids, which in turn enhances the material's water retention capacity.

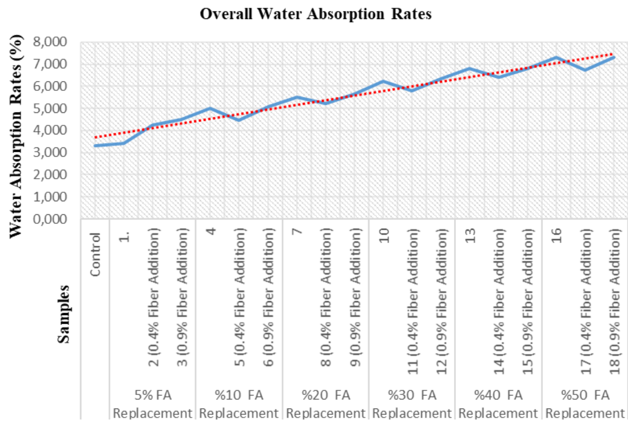

Figure 22: General water absorption variation graph.

The linear regression curve and high R^2 value (0.936) in the figure indicate a strong relationship between water absorption and the replacement and fiber addition ratios. These results emphasize that the replacement ratios and fiber additions must be carefully balanced to optimize the permeability of concrete. In the graph (i.e., Figure 23), the 28-day cylindrical compressive strength (in MPa) and water absorption test results (expressed as percentages) of samples prepared with different proportions of fly ash (FA) replacement and fiber additions are presented.

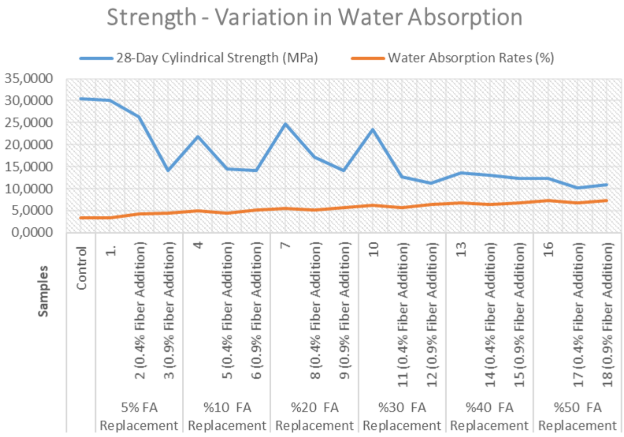

Figure 23: Graph showing the relationship between strength and water absorption.

Compared to the control sample, the 28-day compressive strength of the samples prepared with fly ash replacement ranging from 5% to 50% significantly decreased. While there were noticeable fluctuations in strength values, the overall trend was a decrease. A marked reduction in strength was particularly observed for fly ash replacement ratios of 30% and above. The water absorption rate remained around 5% for all samples, with a slight increase in water absorption as the fly ash replacement ratio increased. However, this increase was more limited in comparison to the decrease in compressive strength.

4. Conclusions

Graphical analyses reveal the complex effects of fiber reinforcement and fly ash (FA) substitution on the water absorption capacity and compressive strength of concrete. Fiber reinforcement increases the porosity and water absorption capacity by creating capillary voids in the concrete's microstructure. Although direct porosity or microstructural analyses were not performed in this study, the observed increase in water absorption in fiber-reinforced specimens suggests that fiber addition may lead to the formation of additional capillary voids within the concrete matrix. This inference is supported by previous studies reporting that fiber incorporation can increase porosity and water absorption in concrete. At high FA substitution rates, the ability of fiber reinforcement to counterbalance this increase is limited, potentially leading to negative impacts on the long-term durability of the concrete.

When examining the relationship between compressive strength and water absorption capacity, a negative correlation is observed, where compressive strength increases as water absorption decreases. While this negative correlation highlights the potential of fiber reinforcement to enhance the strength properties, it is noted that when combined with high FA substitution rates, the positive effects of fiber reinforcement become limited. Specifically, at FA substitution rates exceeding 20%, the beneficial impact of fiber reinforcement on compressive strength diminishes, resulting in a notable decrease in the concrete's strength.

These findings underscore the necessity of carefully determining fiber reinforcement and substitution rates to optimize the strength and sustainability performance of concrete. An FA substitution rate of 5% and a fiber content of 0.4% yield the most favorable results in terms of strength characteristics. It is recommended to optimize these proportions through extensive experiments under prolonged curing periods and various environmental conditions. Additionally, the use of advanced mixing techniques and equipment to ensure the homogeneous distribution of fibers within the concrete is crucial. Microscopic analyses would further enhance the understanding of the microstructural properties of concrete and the effects of fiber reinforcement. Long-term performance assessments through tests conducted under diverse environmental conditions are essential for evaluating the durability of the concrete.

The data presented in Figures 18 and 19 clearly demonstrate the dynamic effects of fiber reinforcement and FA substitution on the strength and water absorption properties of concrete. While fiber reinforcement can improve strength at certain levels, it is unable to fully mitigate the adverse effects of high FA substitution rates. Therefore, the careful optimization of fiber reinforcement and FA substitution ratios is of critical importance in concrete mix designs.

The negative correlation between water absorption capacity and strength characteristics emerges as a key parameter that must be optimized in concrete design. Enhancing the microstructural properties of concrete will improve both its impermeability and durability. In this context, ensuring the homogeneous distribution of fibers and identifying appropriate FA substitution rates will enhance the long-term performance of concrete.

In conclusion, further research and experiments are necessary to better understand the effects of fiber reinforcement and FA substitution. Such studies will provide the necessary insights and data to optimize the strength and permeability of concrete. Determining the correct fiber reinforcement and substitution ratios is crucial for the long-term durability and performance of concrete.

5. Thanks

We extend our sincere gratitude to Assoc. Prof. Dr. Altuğ Yavaş for granting access to the Construction Materials Laboratory at Balıkesir University, and to Prof. Dr. Arın Yılmaz, Head of the Department of Civil Engineering at Balıkesir University, for his support. We also thank Serhat Kaya, a Civil Engineering student at Balıkesir University, for his contributions to this study. Special thanks are due to Prof. Dr. Arif Karademir for his invaluable support during the article writing process, and to Mesut Yaşar for his unwavering assistance and contributions. Furthermore, we are grateful to Muzaffer Can Aydın for his help in procuring the raw material samples.

Article Information

Financial Disclosure: The author (s) has no received any financial support for the research, authorship or publication of this study.

Authors' Contrtibution: Concept: A.K.; Design: B.T.; Supervision: A.K.; Resources: A.K., M.Y.; Data Collection: B.T., M.Y.; Analysis: B.T.; Literature Search: B.T.; Writing Manuscript: B.T., A.K., M.Y.; Critical Review: A.K., M.Y.

Conflict of Interest/Common Interest: No conflict of interest or common interest has been declared by the authors.

Ethics Committee Approval: This study does not require ethics committee permission or any special permission.

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