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The Effect of Tunçbilek Thermal Power Plant Waste Fly Ash on Mechanical Properties of Portland Cement

Research Article

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Abstract

Cement production incorporates pozzolanic materials, with fly ash being a common waste utilized for its pozzolanic properties. Using fly ash has positive or negative effects on the cement, especially its physical and mechanical properties. In this study, the effect of substituting fly ash, a waste product from Tunçbilek thermal power plant, one of Turkiye's major power plants, for cement at 5%, 10%, 15%, 30%, and 50% by weight on the 2-, 7-, and 28-days compressive strength, 28-day ultrasonic property, and 150-day porosity of cement has been investigated. As a result, in comparison to the Portland cement, a decrease was observed in unit weight, ultrasonic properties, and 2-, 7- and 28-days compressive strength. Conversely, an increase was observed in porosity. According to the obtained results and EN 197-1 standards, the compressive strength of the samples with 5%, 10%, and 15% fly ash are between standard values.

Keywords: Cement, Fly Ash, Compressive Strength, Porosity.

1. INTRODUCTION

Cement is a fundamental building block of development. It is commonly mixed with concrete, a key material for constructing housing, roads, pipes, airports, and other infrastructures vital for supporting economic growth. Also, cement is used in the construction of factories, dams, hospitals, and schools, which are vital for the well-being, education, and health of society. After drinking water, cement is the second most widely used critical product globally, with over 4 billion tons consumed across various sectors annually. The cement industry, with a broad and multi-hued logistics network, contributes significantly to the global economy, accounting for 5.4% of the global GDP and 7.7% of worldwide employment. Along with its multiple effects on employment and GDP, it plays a considerable role in achieving the United Nations Sustainable Development Goals [1].

Globally, there are more than 1,000 cement producers operating over 2,300 integrated cement manufacturing plants and more than 600 grinding stations. China has the largest cement production share at 57%, followed respectively by India with 7%, Vietnam with approximately 2.2%, and the United States with 2%, which collectively produce around three-quarters of the world's cement. Table 1 displays global cement production from 2010 to 2020 and key countries in global cement production [2].

Table 1. Major countries and production amounts in cement production worldwide from 2010 to 2020 [2]

Country	Production amount in 2010 (Million metric tons)	Production amount in 2015 (Million metric tons)	Production amount in 2019 (Million metric tons)	Production amount in 2020 (Million metric tons)
China	1,880	2,350	2,300	2,200
India	210	270	340	340
Vietnam	50	61	97	96
America	67.2	83.4	89	90
Indonesia	22	65	70	73
Türkiye	62.7	77	57	66
Iran	50	65	60	60
Brazil	59.1	72	54	57
Russia	50.4	69	56	56
Japan	51.5	55	53	53
Egypt	48	55	47	50
South Korea	47.2	63	50	50

According to the United Nations, by 2030, housing and basic urban infrastructure will be needed for 3 billion people, about 40% of the world’s population. Therefore, supporting this sector ensuring the supply of essential materials like cement is crucial for meeting this fundamental need in developing economies. The International Finance Corporation (IFC) is one of the advocates for these sectors, having invested over $3 billion in more than 25 countries over the last 15 years in such projects [3].

According to the materials mentioned in the above section, cement production is very important, so to produce cement, the supply of raw materials is also very important. In recent years, to prevent environmental pollution, also to reduce production costs, and increase economic productivity, cement producers have started incorporating waste materials such as pozzolanic materials. Mostly these pozzolanic materials are produced in other industries. One of these kinds of materials used in cement production is fly ash, a waste byproduct from coal-powered thermal power plants [4].

Coal-fired thermal power plants account for approximately 41% of global electricity production, and in some countries, this percentage may be even higher. Moreover, coal meets around 30% of the world's primary energy consumption [5]. With the increasing global demand for energy, coal consumption is increasing too, leading to a significant increase in the production of fly ash (exceeding 600 million tons annually). The volume of fly ash produced depends on different elements such as the type of power plant, operational methods, type of coal burned, and combustion systems [6].

Generally, fly ash constitutes 10-15% of hard coal and 20-50% of lignite coal burned in thermal power plants. Approximately 75-85% of the fly ash, along with flue gases, exits the boiler, and this ratio may vary from year to year when using different alternative energy production systems. About 25% of the produced fly ash is utilized in various industries, such as construction, agriculture, and chemistry, for recycling purposes, while the remaining 75% is estimated to be disposed of as waste. The construction industry has a principal role in the recycling process of fly ash [7].

In Turkiye, coal-fired thermal power plants play a significant role in electricity production and are prevalent in most regions. These power plants predominantly use low-calorific value lignite coal and to a lesser extent, hard coal as their primary energy source. The ash content in these lignite coals typically ranges from 15% to 35%.

According to data released by the Turkish Statistical Institute, in 2022, thermal power plants in Türkiye produced 27.815548 million tons of waste, of which 10512 tons were hazardous. Of the total waste, 82.6% consisted of ash and slag waste, while 17% consisted of metal, paper, plastic waste, wastewater treatment sludge, and municipal and similar waste. Regarding waste disposal, 87.9% was sent to ash disposal areas/ash dams or controlled landfill sites, 11% was sent to waste management facilities with appropriate licenses and utilized in the backfilling of mines and quarries, and 0.7% was disposed of through other methods [8].

Statistically, a significant portion of the mineral waste produced in thermal power plants is fly ash. In Türkiye, the utilization of fly ash in various sectors and industries has been low. However, in recent years, with the growth of construction industry and the adoption of new cement and concrete standards from Europe, new efforts have emerged to increase the use and valorization of fly ash in the cement and concrete industries.

So far, the Tunçbilek thermal power plant is one of the Turkish very important thermal power plants. The location of Tunçbilek thermal power plant in Turkiye is shown in Figure 1.

Figure 1. Tunçbilek thermal power plant location in Türkiye

Turkiye is one of the leading cement producers in the world, as stated in Table 1. Many cement factories in the country are spread over almost all regions of the country. Considering the location of the-Tunçbilek thermal power plant in the country, it is seen that it is very close to the Marmara Region, where the population density of the country is highest. Fly ash, produced as the waste byproduct of the Tunçbilek thermal power plant, has an important place in terms of reducing environmental damage and sustainable valorization of industrial waste byproducts of the already high net carbon industry.

Some studies have been done in the literature on the Tunçbilek thermal power plant waste fly ash and some studies observing the outcome of using the fly ash on the mechanical properties of Portland cement [9-25]. However, no consensus has been reached regarding the effect of utilizing fly ash in cement and concrete on compressive strength through these studies. In addition to compressive strength parameter, for determining the suitability of cement for use in different construction departments, the porosity at long period, ultrasonic properties of the cement and the correlation between these and comprehensive strength are of great importance, but these parameters and correlations were not taken into account thoroughly in these studies and

When the general scope and experimental details of previous studies are examined, this research stands out by addressing these gaps. In this research, the effect of substituting the Tunçbilek thermal power plant fly ash instead of cement in proportions of 5%, 10%, 15%, 30% and 50% by weight on parameters such as unit weight, 2-, 7- and 28-day compressive strength, ultrasonic properties,150-day porosity of cement, as well as the correlation between these parameters. Furthermore, the fly ash substitution ratios in this study differ from those used in earlier research. Therefore, this study aims to contribute to the development of sustainable materials by filling these gaps in the literature and aid us to figure out how this unwanted industrial by-product affects the performance of construction materials by comprehensively examining the mechanical properties of Portland cement containing fly ash, such as compression strength and related parameters. In doing so, it aims to foster industrial cooperation and facilitate technology transfer, offering new insights into engineering fields such as sustainable material use, waste management, and the enhancement of mechanical performance.

2. MATERIALS AND METHODS

2.1 Raw Materials

Cement holds a significant role in advancing the construction and industrial sectors, which has a noteworthy importance in the development of Turkiye's economy. The same can be said with almost all the other countries of the world. The cement market, which is used as the foundation stone of large-scale construction, infrastructure, and tunnels, especially in Turkiye, is constantly expanding. The continuous increase in demand for cement leads to the employment of thousands of people as facilities to expand to boost cement production.

Additionally, Turkiye is one of the leading cement producers worldwide. Turkiye's prominent position in the international market is due not only to the quantity of its production but also to the quality of its cement. Moreover, the sector significantly contributes to Turkiye's foreign trade volume. In this context, the cement sector makes substantial contributions to Turkiye's industrial development, economic growth, and sustainable construction goals. Cement samples produced in Turkiye are going to be used in this study.

PÇ 42.5 type cement produced in AkçanSA Cement factory, one of the biggest cement manufacturers located in Turkiye, was used in all experiments. The most important feature of PÇ 42.5 type cement is its high strength, making it suitable for structures where strength is the most important requirement, such as bridges and high-rise buildings. Fly ash or other pozzolanic waste materials are not used in the production of this type of cement. So, by adding fly ash to them, we can study its effects on the properties of the cement accurately. The chemical properties of cement, specific gravity, grain density, fineness, and specific surface are presented in Tables 2 and 6.

Table 2. Chemical analysis of PC 42.5 Portland cement

Constituents	Test Result	Unit	Test Method [26]
SO3	3.09	%	TS EN 15309
Al2O3	4.15	%	TS EN 15309
CaO	66.48	%	TS EN 15309
MgO	1.09	%	TS EN 15309
Fe2O3	3.17	%	TS EN 15309
Na2O	0.61	%	TS EN 15309
SiO2	16.26	%	TS EN 15309
SrO	0.066	%	TS EN 15309
BaO	<0.010	%	TS EN 15309
Cr2O3	<0.010	%	TS EN 15309
K2O	0.79	%	TS EN 15309
MnO	0.091	%	TS EN 15309
P2O5	0.28	%	TS EN 15309
TiO2	0.28	%	TS EN 15309

Table 2 (continues)

In this study, there were no changes in the type or granulometry of the aggregate. CEN standard sand, selected according to TS EN 196-1, was supplied by the LIMAK Trakya Cement Factory, which also conducted particle size analysis and measured the moisture content of the sand (Table 3). CEN reference sand is a siliceous, standard sand composed of rounded particles with at least 98% silica content. Therefore, no chemical analysis was performed on the sand [29]. The specific gravity of the sand is shown in Table 3.

Table 3. CEN standard sand grain size distribution and moisture

Square Mesh Size (mm)	Test Results (%)	Moisture (%)
2,00 mm	0.00	0.10
1,6 mm	7.80	
1,00 mm	32.76	
0,05 mm	66.32	
0,16 mm	87.54	
0,08 mm	98.98	

In the experiments, fly ash, a byproduct of the Tunçbilek thermal power plant, was used. This fly ash is classified as Class F according to ASTM C 618 (Table 4). The chemical properties and class of the fly ash are shown in Table 5, while grain density and fineness tests were conducted and summarized in Table 6.

Table 4. Tunçbilek fly ash classification [35]

Fly ash	S+A+F (%)	CaO (%)	Class
Tunçbilek uçucu kül	82.27	<10	F (Düşük Ca)

Table 5. Chemical composition of Tunçbilek fly ash [34]

Oxide (%)	Tunçbilek fly ash
SiO2	54.79
Al2O3	18.58
Fe2O3	8.90
CaO	2.81
MgO	5.90
K2O	1.65
Na2O	0.21
TiO2	0.93
P2O5	0.23
MnO	0.15
Cr2O3	ND
LOI	2.88

Table 6. PC 42.5 Portland cement specific gravity, particle density, fineness, and specific surface, CEN standard sand specific gravity values, and Tunçbilek fly ash grain density and fineness

Material	Parameter	Test Result	Unit	Test Method
PO 42.5 Portland cement	Specific gravity (SGR 03)	2.69	g/cm3	Pycnometric Density Pulp
	Grain density	3.10	g/cm3	TS EN 196-6: 2020 [27]
	Fineness determination Sieve residue (90 µm)	0.5	%	TS EN 450-1: 2015 [31]
	Specific surface: Determination of fineness-Air permeability (Blaine method)	3270	cm2/g	TS EN 196-6: 2020 [27]
CEN Standard sand	Specific gravity (SGR 03)	2.29	g/cm3	Pycnometric Density Pulp
Tunçbilek fly ash	Grain density	2.20	g/cm3	TS EN 196-6: 2020 [27]
	Fineness, Wet sieving method (45 Micron)	19	%	TS EN 450-1: 2015 [31]

For these tests, city water (tap water) has been used to produce samples.

2.2 Preparation and Testing of Cement Samples

In this study, 30 samples were produced in the laboratory. The amount of cement was calculated according to TS EN 196-1, and 0%, 5%, 10%, 15%, 30%, and 50% of Portland cement was replaced with an equivalent weight of fly ash. Water and sand proportions remained constant in compliance with TS EN 196-1 standards [29]. The classification of the samples produced, their mixture ratios, and sizes are shown in Table 7.

In the reference process, the mortar prepared by mechanical mixing was compressed in the mold using a standard shaking machine. The samples in the mold were kept in a humid atmosphere for 24 hours, afterwards, they are pulled out from the mold were held inside water until the specified tests were carried out.

In the experiments, prismatic samples were produced in two different sizes (40 mm x 40 mm x 160 mm and 100 mm x 100 mm) and samples with dimensions of 100x100x100 mm were produced for the ultrasound velocity experiment [32].

Table 7. Nomenclature of produced samples, mixture ratios, and sizes

Sample Name	% Cement + %Fly ash (% by weight) (gr)	Sand (Fixed amount by weight) (gr)	Water (Fixed amount by weight) (gr)	Sample Size (mm)
CUKD0	% 100 Cement (150 gr) + % 0 Fly ash	450	75	40x40x160
CUKD5	% 95 Cement (142.5 gr) + % 5 Fly ash (7.5 gr)	450	75	40x40x160
CUKD10	% 90 Cement (140 gr) + % 10 Fly ash (10 gr)	450	75	40x40x160
CUKD15	% 85 Cement (127.5 gr) + % 15 Fly ash (22.5 gr)	450	75	40x40x160
CUKD30	% 70 Cement (105 gr) + % 30 Fly ash (45 gr)	450	75	40x40x160
CUKD50	% 50 Cement (75 gr) + % 50 Fly ash (75 gr)	450	75	40x40x160
CUKK0	% 100 Cement (586 gr) + % 0 Fly ash	1758	293	100x100x100
CUKK5	% 95 Cement (556.7 gr) + % 5 Fly ash (29.3 gr)	1758	293	100x100x100
CUKK10	% 90 Cement (527.4 gr) + % 10 Fly ash (58.6 gr)	1758	293	100x100x100
CUKK15	% 85 Cement (498 gr) + % 15 Fly ash (88 gr)	1758	293	100x100x100
CUKK30	% 70 Cement (410.2 gr) + % 30 Fly ash (175.8 gr)	1758	293	100x100x100

Table 7 (continues)

CUKK50	% 50 Cement (293 gr) + % 50 Fly ash (293 gr)	1758	293	100x100x100

3. RESULTS AND DISCUSSION

3.1 Fresh Mortar Test

Unit Weight Test [28]:

A unit weight test was conducted on the fresh mortar. Since the unit weight of fresh mortar is not dependent on size, the test was applied to a cast mortar with dimensions of 100x100x100 mm. The results of the unit weight test are shown in Table 8.

Table 8. Fresh mortar unit weight test results

Sample Name	Unit Weight (N/m3)
CUKK0	21378.5
CUKK5	21143.13
CUKK10	21035.26
CUKK15	20996.03
CUKK30	20917.58
CUKK50	20790.09

In the study involving weight substitution between cement and fly ash, the lower specific gravity of fly ash leads to an increase in the volume of the binding material. As the volume of the binder increases, there's a decrease in the unit weight of the fresh concrete mix. The correlation between unit weight and fly ash content can be seen in Figure 2. As illustrated, while the use of fly ash increases, the unit weight decreases.

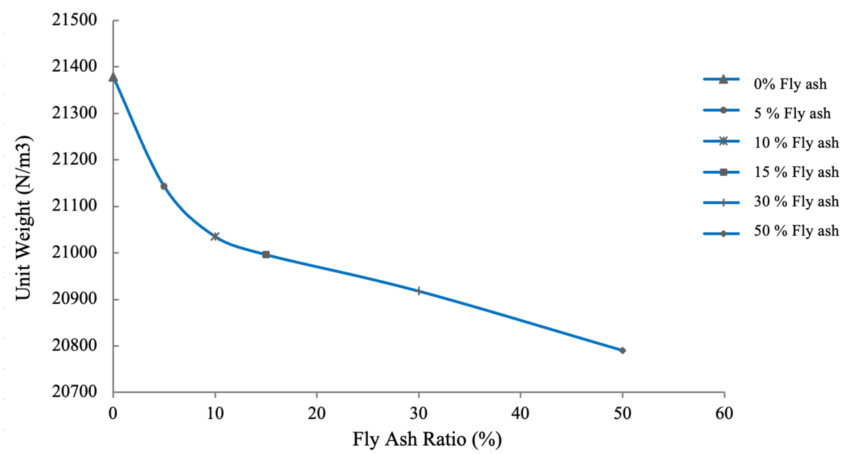

Figure 2. Correlation between unit weight and fly ash ratio

3.2. Hardened Concrete Test

Compression Strength Test:

The compression strength values of the samples were determined using the UTEST Compression Testing machine. In Table 9 the averages of the experiment results for all specimens are presented. Also, the percentages in parentheses, which are listed vertically beside the compression strength test results in this table, assume that the compression strength of the sample without fly ash (control concrete) is 100%. The other variables in the column are evaluated according to the percentage ratios of the test results of this sample. In Table 10, the test results for all samples on the 28th day are assumed to be 100 MPa, and the percentage difference created by the time each sample was kept until testing is investigated for each test result.

Table 9. Average results of compression strength experiments conducted on all specimens and the comparison of the percentage values of compression in comparison with the control concrete sample (*)

Sample Name	2 Day Average Results (MPa)	7 Day Average Results (MPa)	28 Day Average Results (MPa)
CUKK0	32.1 (100%)	41.4 (100%)	53.0 (100%)
CUKK5	28.9 (90%)	38.4 (92%)	50.3 (95%)
CUKK10	25.4 (79%)	36.0 (87%)	48.9 (92%)
CUKK15	23.6 (73%)	33.0 (80%)	47.1 (89%)
CUKK30	15.7 (49%)	27.4 (66%)	40.9 (77%)
CUKK50	9.5 (29%)	17.3 (41%)	27.9 (53%)

*The table displays the average values of 18 specimens.

Table 10. Comparison of the percentage values of compression strength obtained from the test results with obtained from the test results with respect to the 28-day concrete (*)

Sample Name	2 Day Average Results (MPa)	7 Day Average Results (MPa)	28 Day Average Results (MPa)
CUKK0	60	78	100
CUKK5	57	76	100
CUKK10	52	73	100
CUKK15	50	70	100
CUKK30	38	67	100
CUKK50	35	62	100

Table 10 (continues)

*The table displays the average values of 18 specimens.

The interpretation of the Table 9 results reveals a negative correlation between fly ash to concrete percentage in the sample and the compression strength in concrete. Additionally, as the fly ash ratio increases, it positively correlates with proportionally higher compression strength results in concrete samples cured for an extended period. The reduction in compression is linked to a reduction in the ratio of fly ash mass increase, resulting from a reduction in cement content. Despite the expected decrease in strength due to the reduced cement, the faster hydration of lime in the cement content plays a contributing role. The pozzolanic reaction of fly ash taking longer than lime results in a decrease in lime content as the fly ash ratio increases. Consequently, samples with higher fly ash ratios, exposed to the same conditions for the same duration, exhibit lower compression strengths compared to the 28-day concrete.

In Table 10, the values of compression strength test results on the 28th day are assumed to be 100 MPa for each column, and the averages of strengths on the 2nd and 7th days are processed as percentage ratios. Considering the findings on the table, it can be seen as the curing days increase homogeneously, the strength values in the test results also increase. Aside from this, as the fly ash ratio increases, a greater percentage increase in compression strengths with more days of curing in comparison with the samples with smaller fly ash content is inspected. The reason for this is anticipated to be because the hydration time of fly ash is longer than that of cement. In samples where cement is relatively less, it can be interpreted that to achieve maximum strength efficiency in concrete with higher fly ash content, it will need to be cured for a longer period due to the lower hydration and lime transformation capabilities of the contents of cement. The correlations between compression strength, curing days, fly ash content, and unit weight are illustrated in Figures 3 to 5.

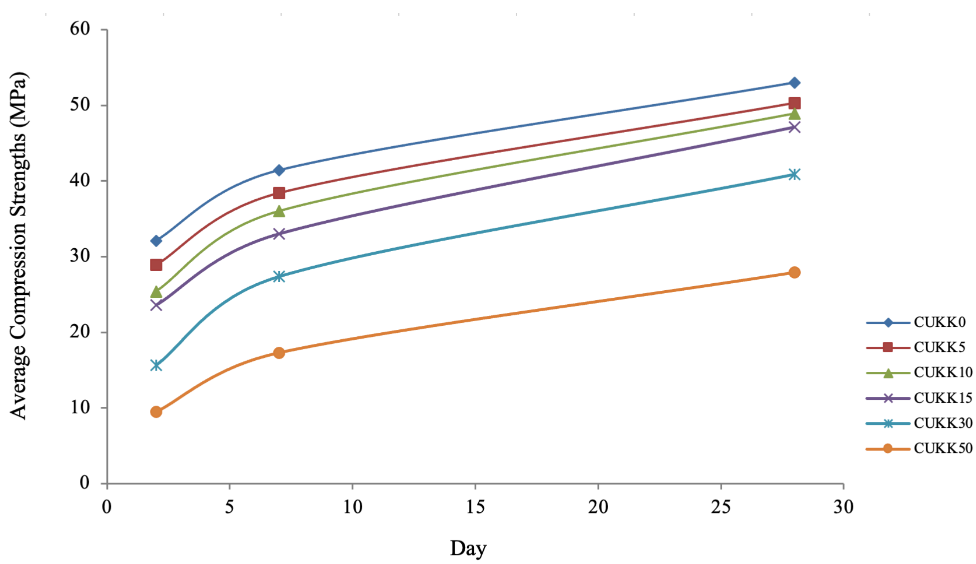

Figure 3. Average compression strengths of samples for various curing times

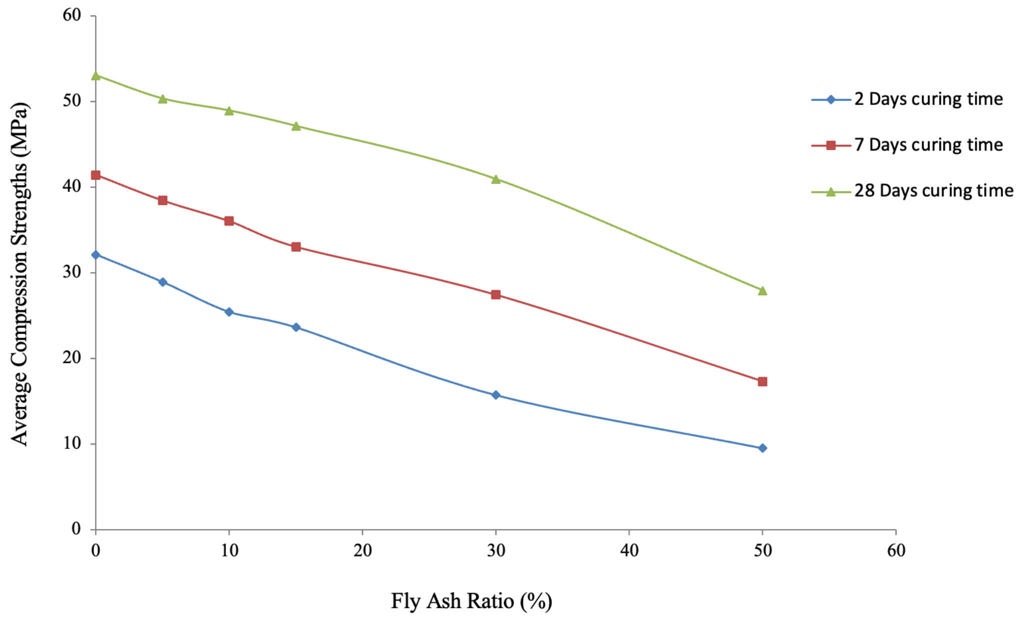

Figure 4. Correlation between average compressive strength and fly ash ratio at different curing times

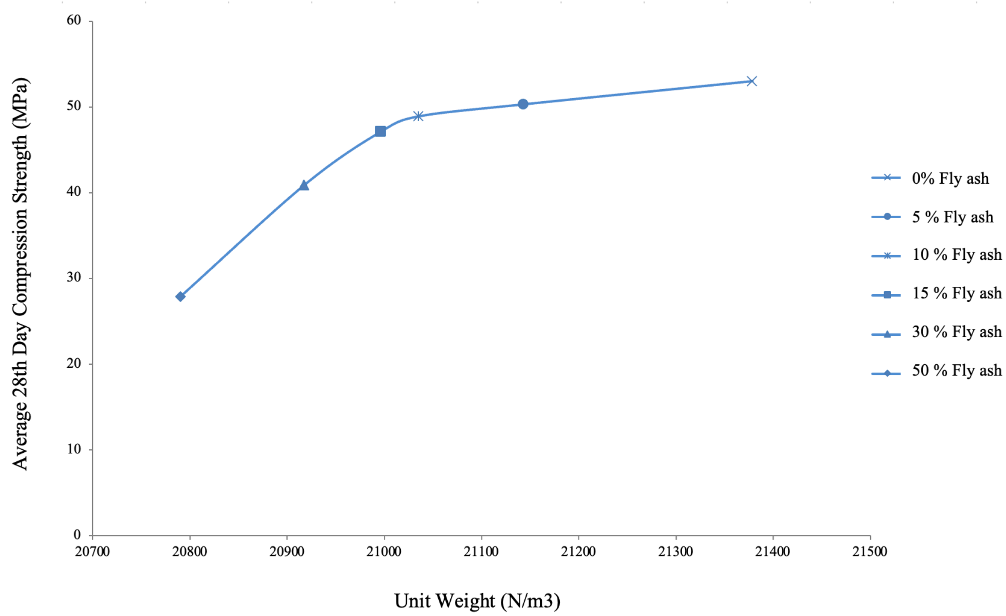

Figure 5. Correlation between unit weight and average 28th-day compression strength

Ultrasonic Velocity Test:

According to the TS EN 12504-4 standard [32], Ultrasonic velocity tests were conducted on six cube-shaped samples with dimensions of 100x100x100 mm after 28 days of production. Proceq Pundit Lab+UTC-3050 Ultrasonic Wave Velocity Testing Device was used for measurements. The findings of the tests conducted on all samples can be seen below in Table 11.

Table 11. Samples of ultrasonic velocity test results

Sample Name	Ultrasonic Velocity m/s
CUKK0	4367
CUKK5	4365
CUKK10	4348
CUKK15	4292
CUKK30	4202
CUKK50	4032

Based on the percentage of fly ash, it has been examined over time that samples with lower void content allow ultrasonic waves to pass more quickly. An increase in ultrasonic velocity is positively correlated with higher compressive strength and the favorable effect of fly ash on void content in humid surroundings [34, 36].

Table 11 shows that concrete with fly ash has lower ultrasonic velocity values at 28 days compared to control mortar (0% fly ash). This suggests that samples with high fly ash content may not be as durable under environmental conditions at early ages. It can be stated that high fly ash content negatively affects the ultrasonic velocity values of hardened mortar.

Upon examining the ultrasonic tests in previous studies, it is observed that the ultrasonic velocity of fly ash samples increases with age. This is caused by the pozzolanic reaction slowing down the occurrence of lime [34, 36].

It has been seen that fly ash has a positive effect on void content in moist environments in advancing ages. When considering that lime is released as a result of cement hydration and then dissolves in water, leaving voids in the concrete, the reduction in void content associated with lime can be explained during the pozzolanic reaction of fly ashes. The positive effect of fly ashes on void content can be related to this way and considering that void content is closely related to durability under environmental conditions, it can be anticipated that the utilization of fly ash in small percentages is expected to have a positive impact on durability. The correlations between ultrasonic velocity and fly ash ratio, unit weight, and compression strength, are to be found in the figures below (6-7-8).

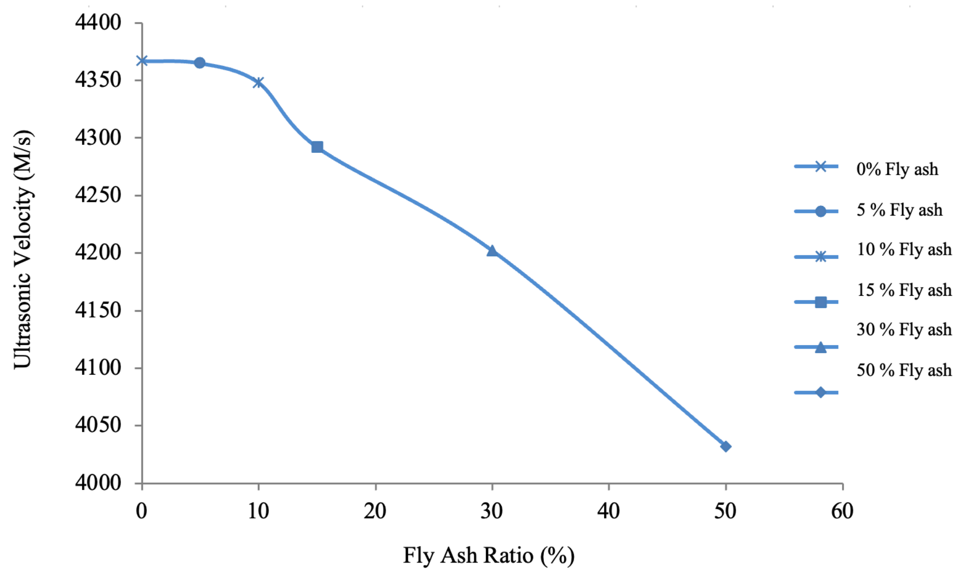

Figure 6. Correlation between ultrasonic velocity and fly ash ratio

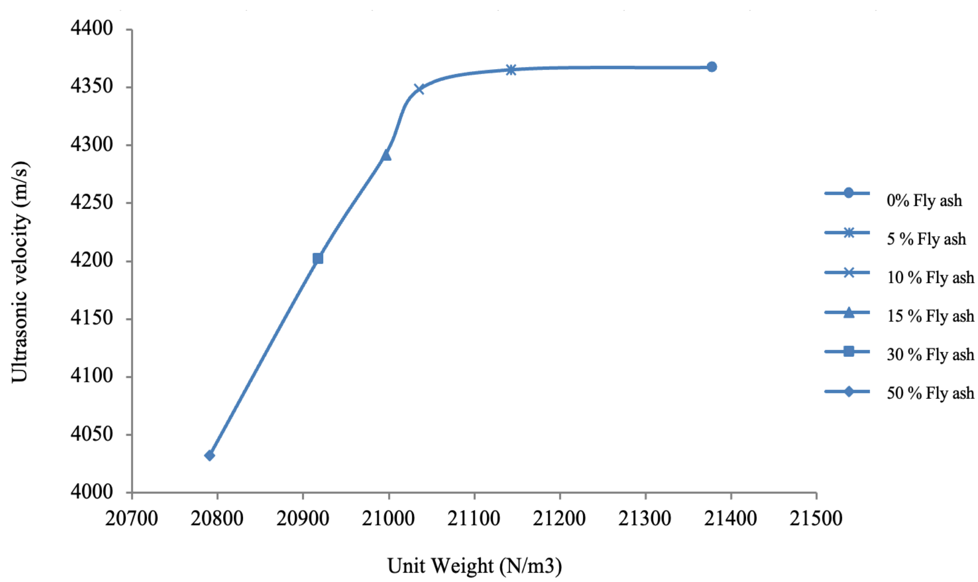

Figure 7. Correlation between ultrasonic velocity and unit weight

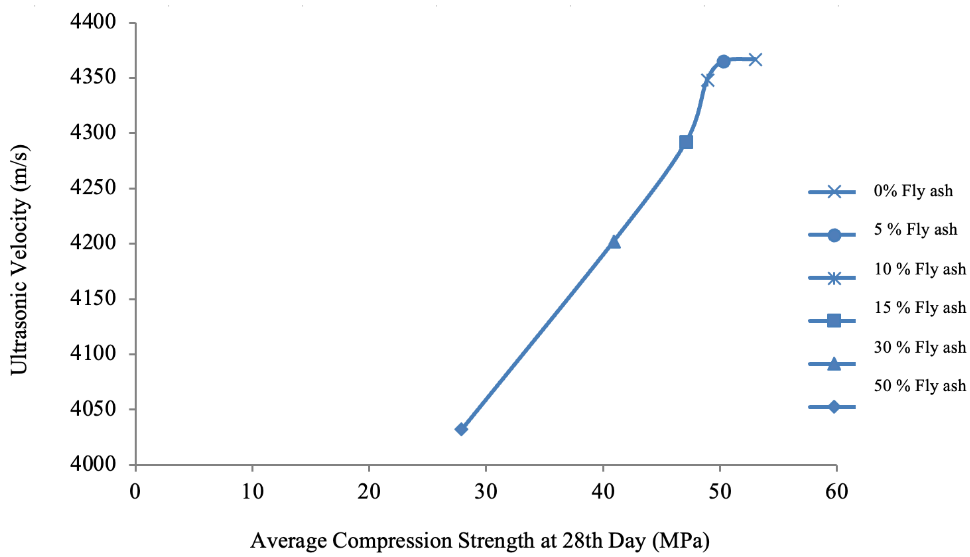

Figure 8. Correlation between ultrasonic velocity and average compression strength at the 28th day

Porosity Test:

According to the TS 9179 standard [33], porosity tests were conducted on six samples with dimensions of 160x40x4 mm after 150 days of curing. For this test, the samples in the mold were kept in a humid setting for 24 hours, and then the samples pulled out of the mold were kept in water for 28 days. Again, these samples have been taken out of the water and stored in a normal environment for 132 days. The Auto Pore Test Device was used for the measurements. Table 12 demonstrates the findings of the tests conducted on all samples.

Table 12. Sample porosity test results

Sample Name	Total Intrusion Volume (mL/g)	Total Pore Area (m²/g)	Median Pore Diameter (Volume) (nm)	Median Pore Diameter (Area) (nm)	Average Pore Diameter (4V/A) (nm)	Bulk Density at 0.52 psia (g/mL)	Apparent (skeletal) Density (g/mL)	Porosity (%)	Stem Volume Used (%)
CUKK0	0.0664	5.825	102.3	14.7	45.6	2.1448	2.5008	14.2340	39
CUKK5	0.0679	7.019	101.0	8	38.7	2.1351	2.4973	14.5021	38
CUKK10	0.0809	8.610	95.8	8.9	37.6	2.0704	2.4871	16.7552	48
CUKK15	0.0854	8.984	188.4	6.6	38	2.0632	2.5046	17.6223	48
CUKK30	0.0905	10.559	243.3	5.9	34.3	2.0441	2.5083	18.5075	50
CUKK50	0.1005	10.481	380.7	5.4	38.4	2.0113	2.5211	20.2217	53

Hardened concrete's crucial characteristics are tied to pores and hydration products, influencing strength, shrinkage, swelling, and permeability. Examining concrete's pore structure and mineral composition is beneficial.

Fresh concrete pores are filled with water or gas. In initial mixing, water separates cement particles and gravel, creating water-filled spaces. This space allows for cement hydration product formation. As hydration advances, the void volume, larger than the original unhydrated cement, decreases as hydration products form a continuous matrix, binding residual cement particles in time. The original water-filled area not covered by hydration products contributes to the cement paste's pore system, typically with the biggest pores. Hydration decreases the dimensions and volume of capillary voids; if small, the gel's bulk volume eventually fills the void, producing a paste without capillary voids [36].

The volume of water-filled voids in fresh cement paste must surpass the total volume of cement or leave a portion of the original cement without water. Consequently, even after complete cement hydration, hydration products are insufficient to occupy the original water space, resulting in pastes with relatively large capillary pores.

Researches on hardened cement pastes reveal that the size of the largest pores is primarily related to the level of moisture. For young cement pastes with minimal hydration, the size is approximately 1 micrometer, decreasing to around 0.1 micrometers in fully hydrated mature pastes [34, 36]. During ongoing curing, as voids are filled with hydration products, most capillary voids become isolated, and separated by the gel, provided the initial water/cement ratio is sufficiently low. This gel is primarily calcium silicate hydrate with a non-solid part, forming a porous solid [34, 36].

In compliance with the findings in Table 12, as the volume of fly ash added instead of cement increases, Total Pore Area, Total Intrusion Volume, Average Pore Diameter (4V/A), Median Pore Diameter (Volume) Visible (skeletal) Density, and Porosity increase, while at 0.52 psia Median Pore Diameter (Area) and Mass Density decrease.

The correlations between Porosity, fly ash ratio, unit weight, compression strength on the 28th day, and ultrasonic velocity can be observed in the Figures below (9 to 13).

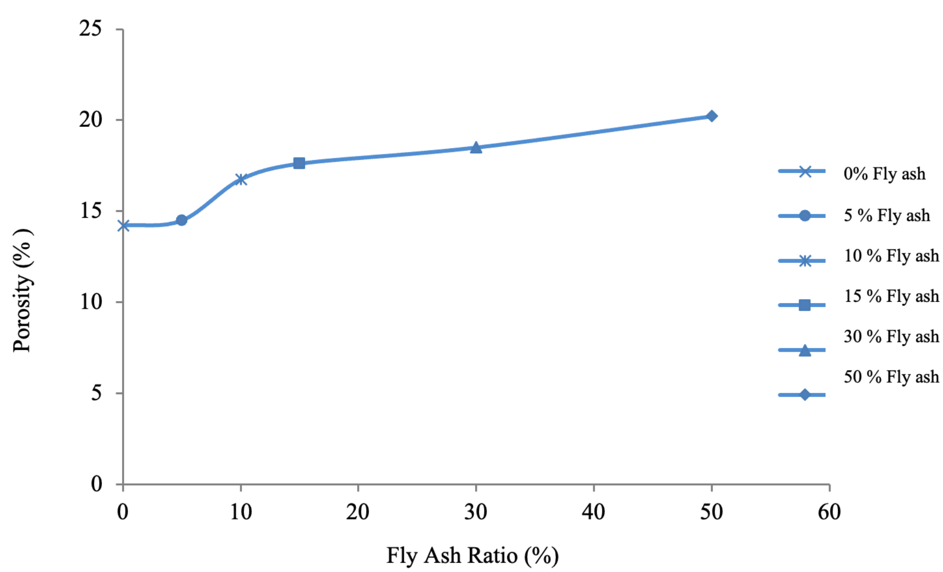

Figure 9. Correlation between porosity and fly ash ratio

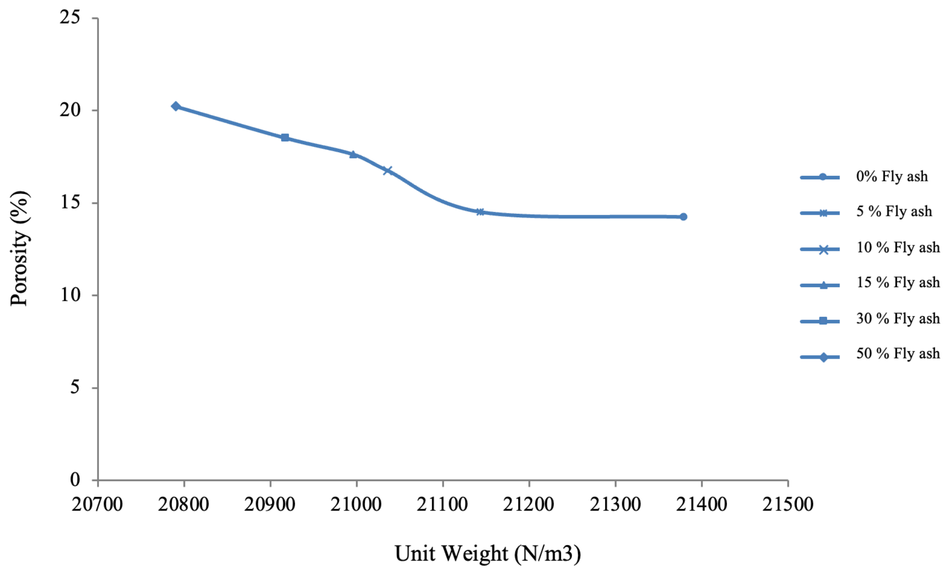

Figure 10. Correlation between porosity and unit weight

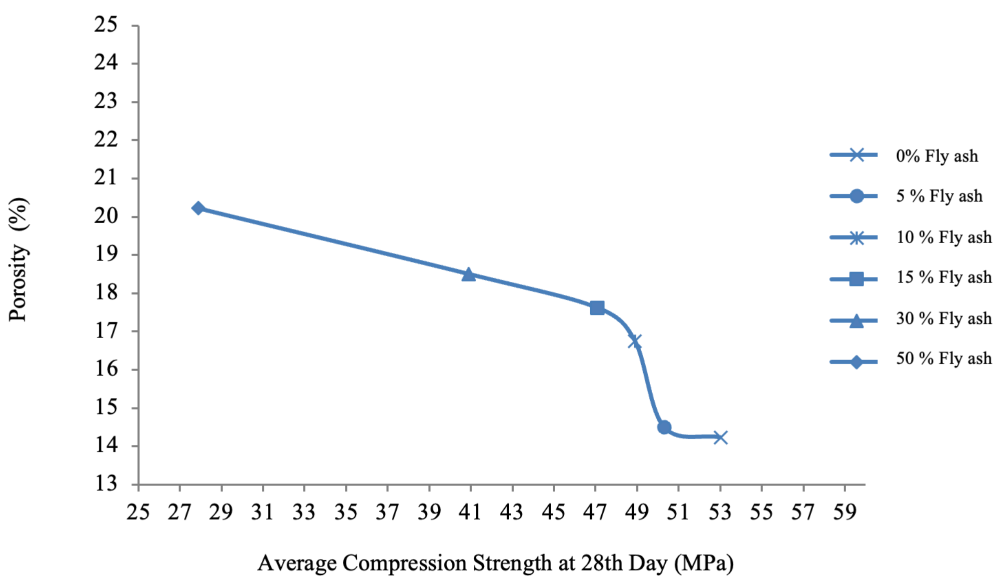

Figure 11. Correlation between porosity and compression strength on the 28th day

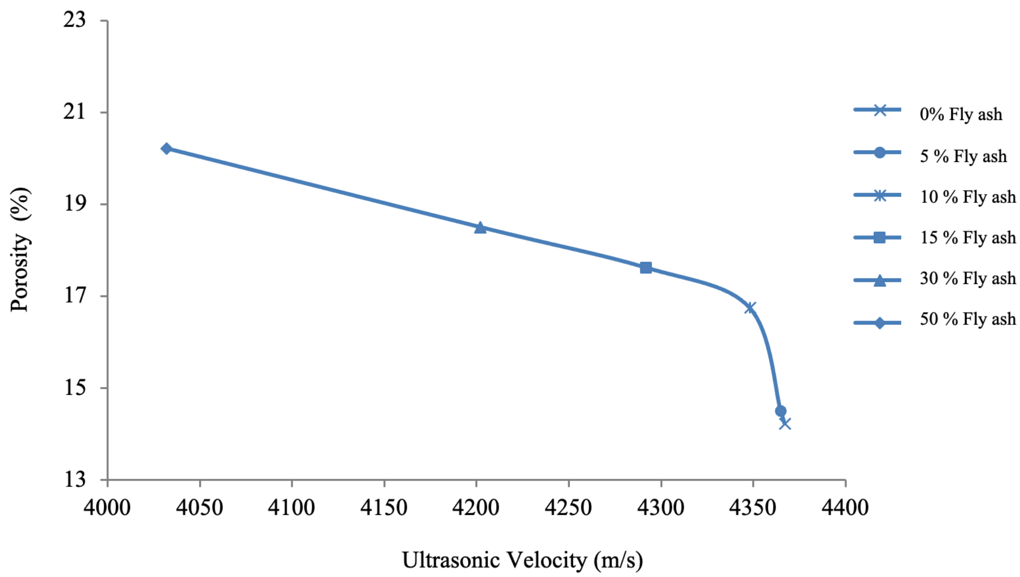

Figure 12. Correlation between porosity and ultrasonic velocity

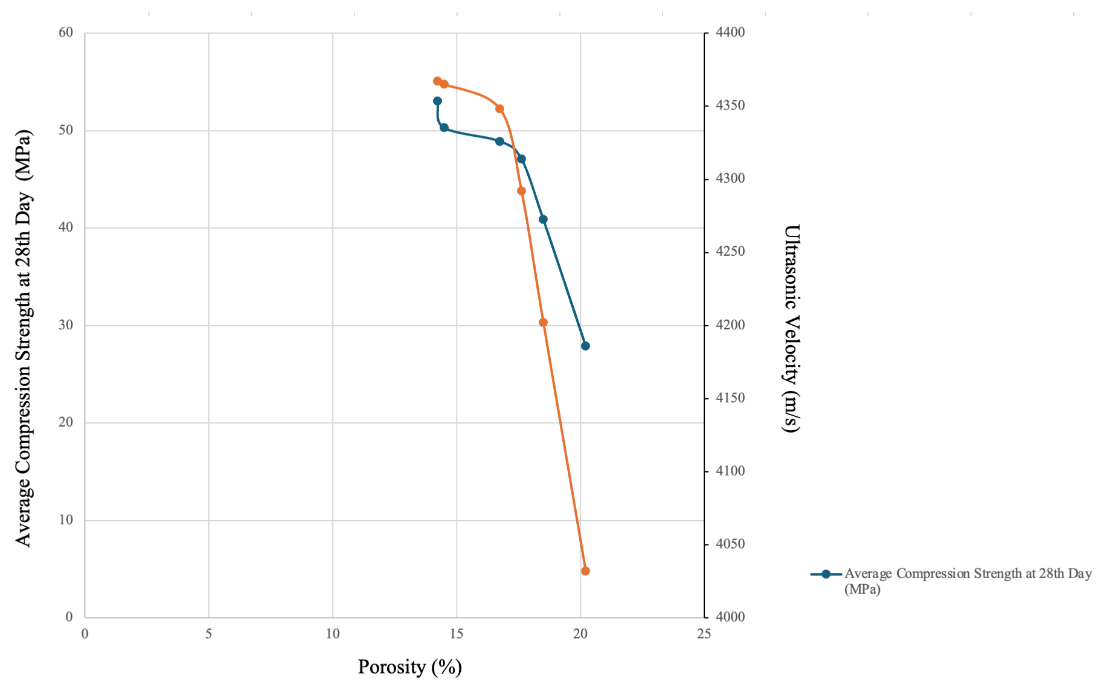

Figure 13. Correlation between porosity, average compression strength on the 28th day, and ultrasonic velocity

In the preceding part, it was explained that the pozzolanic reaction of fly ash increases with age because of delays in lime formation. Fly ash positively influences void content, vital for durability under environmental conditions, and curing time significantly affects porosity. Therefore, to simulate real construction environments and obtain more precise results, the samples were cured at 25 degrees Celsius outside water under normal conditions for 132 days more, and then porosity tests were performed.

The results, after 150 days of curing and hydration, compared to the control mortar (0% Fly ash), indicate that porosity increases with higher fly ash ratios. This shows that samples with high fly ash content may be less durable and mechanically strong under environmental conditions, as elevated fly ash content adversely affects porosity values in hardened mortar.

Conversely, using fly ash in low percentages is deemed beneficial for compression strength and durability, so moderation in fly ash content is of great importance.

4. CONCLUSION

This study reveals the following conclusions regarding the substitution of cement with Tunçbilek fly ash:

- According to the relation between specific gravity and volume, the lower specific gravity of fly ash leads to an increased volume of the binding material, and the result is a lower unit weight in the fresh concrete mix as the binder's volume expands.
- A negative correlation exists between the fly ash-to-cement ratio and compressive strength in concrete samples cured for short periods. The reduction in compressive strength is attributed to the lower cement content as fly ash replaces cement. Despite this, the faster hydration of lime in the cement contributes to early strength. Samples with higher fly ash content exhibit greater percentage increases in compressive strength with extended curing, emphasizing the need for longer curing periods due to the slower hydration of fly ash compared to cement.
- Ultrasonic Velocity tests indicated that the examines with lower void content allow ultrasonic waves to pass more quickly. The increase in ultrasonic velocity positively correlates with higher compressive strength and the favorable effect of fly ash on void content in a moist environment and concrete with high fly ash content shows lower ultrasonic velocity values at 28 days, suggesting potential durability concerns in certain surrounding conditions, especially at early ages.
- In this study the crucial role of pore structure and hydration products in influencing concrete properties such as strength is emphasized. Generally, fly ash has a positive effect on void content in a moist environment, reducing voids associated with lime during the pozzolanic reaction of fly ashes over an extended period. According to the 28th-day compressive strength test results, the samples with 5%, 10%, and 15% fly ash are between standard values. Therefore, it can be inferred that the valorization of fly ash at low percentages has the potential to further improve the compressive strength within a longer period, signifying its improving effect on concrete properties.
- Curing time significantly impacts porosity, and samples cured for 150 days in this study demonstrate increased porosity with higher fly ash ratios, suggesting potential durability concerns.
- In conclusion, based on the comprehensive results acquired with this research, utilizing low percentages of fly ash is deemed advantageous for enhancing concrete properties. This underscores the significance of maintaining moderation in fly ash content to achieve optimal performance in real-world construction applications.

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