Mechanical Properties of OPC-Fly Ash Blended Cement Mortar Samples Utilizing Fly Ash from Sri Lankan Power Plants

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ABSTRACT

This paper presents findings of an investigation of the compressive strength and water absorption of fly ash blended cement mortar samples made using fly ash (FA) generated in power plants in Sri Lanka. Ordinary Portland Cement (OPC) was substituted partially by 10%, 20%, 30% and, 40% of FA by weight. The control mixture was made up entirely of 100% OPC. The ratio of Cement is to sand was 1:2.75 by volume. Three water to binder ratios were used in preparing mortar samples as 0.375, 0.4, and 0.425. A total of 180 mortar cubes of 50mm x 50 mm x 50mm were prepared and the mortar cubes were water cured. The mortar samples were tested for water absorption at age of 28 days and compressive strength at the ages of 3, 7, and 28 days. The test results show that water absorption increased with FA content, while compressive strength decreased slightly at early ages but remained within an acceptable range. At 28 days, FA replacement had no significant negative impact on strength, and the water absorption was inversely related to compressive strength and density. These findings indicate that OPC can be partially replaced by up to 40% FA without compromising mechanical performance, offering benefits in reducing CO_2 emissions, conserving energy, and promoting sustainable construction materials.

KEYWORDS: *High Energy Costs, CO2 Emission, Fly-Ash, Compressive Strength, Water Absorption, Sustainable Construction Material*

INTRODUCTION

Increasing levels of greenhouse gases in the environment are a significant reason for both global warming and climate change. Human activity is almost certainly responsible for the increase in global greenhouse gasses (GHG) and it is mainly due to industrial development and transportation [1]. Among the industrial sectors, the cement industry is responsible for a huge segment of GHG emissions. The emission of CO_2 from the production of cement lies in between 5-7% of the emission of CO_2 globally [2]. Each and every ton of cement which is produced will emit one ton of CO_2 into the atmosphere [3]. Production of Ordinary Portland Cement (OPC) requires a rigorous energy process; and from the total demand for the energy industry, it consumes about 15% [4]. On average, the nuclear power required is 3.4 GJ (in the dry process) and the required electrical energy is 110 kWh to produce one ton of cement. As a result, there is an urgent need to develop sustainable cement with a reduced environmental impact. Social research has shown that there are also social concerns about sustainable cement production [5]. In response, extensive research has been conducted to find alternative solutions that lower OPC consumption while preserving or even improving the performance of construction materials. One promising approach is partially replacing OPC with supplementary cementitious materials (SCMs). Commonly used supplementary cementitious materials include pozzolans such as fly ash, silica fume, ground granulated blast-furnace slag, red mud, rice husk ash, and sugarcane bagasse ash. [6, 7].
Fly ash (FA) is selected for this study over other pozzolanic materials because it is the most common pozzolanic material in Sri Lanka and also it is one of the by-product which is generated from the coal combustion process. According to the Coalition against coal (CAC), Lakvijaya Coal Power Station, Norochcholai, Sri Lanka will approximately generate 1000 tons of FA per day [8]. More than 400 tons

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of FA are dumped daily into the nearby dumping yard. Spreading it along with the wind, causing significant environmental and community pollution. By increasing the use of FA for cement production these harms can be minimized.
Pedraza, Pineda, and Gutiérrez investigate the effect of unburned impurities in FA additions on the mechanical properties of cement mortars by partially replacing mortar cement cubes with FA fractions of 20, 40, 60, and 80% [3]. This research study mainly focused on the variation in compressive strength of mortar when FA added to the mix. According to the findings of this research, it revealed that 20% of cement can be replaced with FA without compromising quality. According to the research, combinations with a high percentage of FA are incompatible with the strength of 100% cement mortar. The compressive strength of FA incorporated cement mortar was examined by Kondraivendhan & Bhattacharjee, by replacing OPC in 10% increments from 0% to 40% [9]. Compressive strength of the FA blended cement mortar has been increased with age in all water to binder ratios and FA replacement levels, according to the study. In comparison to the control specimens, the strength of the specimens steadily decreased due to an increase in FA replacement. Properties of the mortar improves due to the pozzolanic reaction. Calcium Silicate Hydrates (CSH) produced during the pozzolanic reaction is primarily responsible for the strength of the cement and it reduces the size of the capillarity pores in the hardened cement paste [10, 11]. FA's pozzolanic action aids in the development of strength in later ages. According to a study conducted by Kondraivendhan and Bhattacharjee, up to 28 days of curing, the compressive strength of OPC-FA blended cement mortar declines with an increase in FA replacement level but, when compared to the control specimen, the compressive strength of OPC-FA blended cement mortar increases at 90 days of curing [9]. Cho, Jung, and Choi investigated the impact of the chemical composition of FA on the mechanical properties of FA blended cement mortar using 16 distinct types of FA present in South Korean ready-mixed concrete production plants as raw material [12]. They emphasized in their study that, while FA is a very beneficial cement additive, it has the disadvantage of performance of blended cement which is highly dependent on quality of the FA used.
Although extensive experiments and research have been conducted in this field, significant gaps remain, particularly in the Sri Lankan context, where such studies are limited. FA has a wide range of qualities, depending on the coal combustion process. As a result, this research study aimed to look into the mechanical properties of OPC-FA blended mortar prepared from FA generated in Sri Lankan power plants.

The objectives of this research are:

- To investigate the variation in compressive strength of mortar samples when ordinary Portland cement is partially replaced with fly ash.
- To examine the changes in water absorption of mortar samples with partial replacement of ordinary Portland cement by fly ash.
- To establish the relationship between density, water absorption, and unconfined compressive strength in mortar samples incorporating fly ash as a partial replacement for ordinary Portland cement.

The scope of this research may be limited to OPC–fly ash blended cement mortar samples made with fly ash that has similar properties to the one used in this study, which was obtained from power plants in Sri Lanka.

MATERIALS AND METHODOLOGY

To accomplish the study's objectives, an experimental methodology was adopted.

Materials Used

During the investigation, the materials which were used are given below;

- Cement – Ordinary Portland Cement, strength class 42.5 N, produced by Ultratech Cement Lanka (Pvt) Ltd, complying with SLS 107:2015 and BS EN 196-6:2010 standards [13, 14]

- Fly Ash - Class F fly ash obtained from Lakvijaya Coal Power Plant, Norocholai, Sri Lanka. The particle size distribution of the FA and its chemical composition was obtained from the sample and analysis certificate issued by SGS South Africa (Proprietary) Limited and are shown in Tables 1 and 2 respectively.

- Fine aggregate – Washed and sieved offshore sea sand obtained from Sri Lanka Land Development Corporation.

- Water – Clean, fresh, and potable tap water

Rationale of Selecting Materials

Ultratech OPC is the most widely used cement in Sri Lanka. Therefore, Ultratech OPC was used for the experimental program. Lakvijaya Coal Power Plant, Norocholai is the only coal power plant in Sri Lanka. Therefore, FA obtained from Lakvijaya Coal Power Plant, Norocholai was used for the experimental works. In Sri Lanka, sand obtained from different areas are different in quality and prices are also very different. But offshore sea sand which is obtained from Sri Lanka Land Development Corporation has a fixed price and quality. In addition, sea sand is kind of consistent material. Table 1 and Table 2 provide particle size distribution and chemical composition of fly ash specified by ASTM standards [15].

Table 1. Particle Size Distribution of the Fly Ash

Size Distribution		**Fractional Mass (%)**	**ASTM Standards**
-mm	+mm		D 4749
	50.00	1.5	
2.00	0.00	12.6	

Table 2. Chemical Composition of the Fly Ash

Mineral Ash Analysis (Dry Basis)	**Unit**	**Result**	**ASTM Standards**
Silicon as SiO_2	%	48.66	D 4326
Aluminum as Al_2O_3	%	27.99	D 4326
Iron as Fe_2O_3	%	3.41	D 4326
Calcium as CaO	%	9.15	D 4326
Magnesium as MgO	%	2.49	D 4326
Sodium as Na_2O	%	0.57	D 4326
Potassium as K_2O	%	0.66	D 4326
Phosphorous as P_2O_5	%	1.91	D 4326
Titanium as TiO_2	%	1.57	D 4326
Manganese Dioxide as Mn_3O_4	%	0.09	D 4326
Sulphur as SO_3	%	3.00	D 1757
Undermined	%	0.50	-
Total	%	100.00	-

Mix Proportions and Experimental Factors

According to ASTM C-109, the control mix for this study is 1:2.75 cement to sand by volume. To determine which mixture with FA additions exhibits greater compressive strength and other mechanical properties, a percentage of 10%, 20%, 30%, and 40% of FA is utilized as partial cement replacement. The experimental works included three water to binder ratios of 0.375, 0.4, and 0.425. Table 3 shows the proportions of FA blended cement mortar.

Table 3. Mix Proportions of Fly Ash Blended Cement Mortar

No. of cubes	w/c Ratio	FA (%)	OPC (%)	Cement (g)	FA (g)	Sand (g)	Water (ml)
12	0.375	0	100	1916	0	2476	719
12		10	90	1724	192	2476	719
12		20	80	1533	383	2476	719
12		30	70	1341	575	2476	719
12		40	60	1150	766	2476	719
12	0.4	0	100	1886	0	2437	754
12		10	90	1697	189	2437	754
12		20	80	1509	377	2437	754
12		30	70	1320	566	2437	754
12		40	60	1132	754	2437	754
12	0.425	0	100	1857	0	2399	789
12		10	90	1671	186	2399	789
12		20	80	1486	371	2399	789
12		30	70	1300	557	2399	789
12		40	60	1114	743	2399	789

Preparation of Mortar Cubes

Three water to binder ratios, three different curing ages, and five FA replacement levels were cast in 180 samples of 50 mm cubical cement mortar. The test specimens were cast in fiber molds with foam oil applied to the mold's inner side for easy removal. First, FA and cement were mixed well in a dry form, and then sand was added. After that water was added and mixed thoroughly using a mortar mixer until a uniform mixture is formed. It was then placed in molds and compacted thoroughly with a steel rod. The specimens were demolded and submerged in a water bath for 24 hours before being tested for cure.

Figure 1. Hardened mortar samples

Compressive Strength Test

ASTM C-109 is used to conduct the mortar compressive strength test. The cubes were tested at three different ages: 3, 7, and 28 days using three cubes per FA replacement. They were tested on a universal testing machine, as shown in Figure 2. The load is applied at a constant rate of 4.50 kN/s until the specimen failed. The representative compressive strength of each mortar mix was calculated using the average failure stress of three cubes.

Figure 2. Standard compressive strength apparatus

Water Absorption Test

At the age of 28 days, three cubes of each mixture were tested. The water absorption test process begins with the water curing mortar specimens being dried at 105°C in an oven for not less than 24 hours, till the weight does not drop more than 0.2% in 2 hours, as illustrated in figure 3. The mass of dried mortar specimens (W_d) is weighed. Subsequently, the dried mortar specimens were immersed in water, and readings were taken at 10, 20, 30, 60, 120, 180, and 240 minutes, as proposed by previous researchers [16] and shown in Figure 4. The specimens were placed on a cane net to ensure that all the faces were in contact with water. The mass of wet mortar specimens (W_s) is weighed based on the testing period and the percentage of water absorption is determined as follows:

$$\text{Water Absorption (\%)} = \frac{(W_s - W_d)}{W_d} \text{ x } 100\%$$

The water absorption of each three specimens was determined and the mean water absorption was computed.

Figure 3. Drying of Samples

Figure 4. Immersion of Samples in Water

RESULTS AND DISCUSSION

Compressive strength

The cubes were tested for compressive strength at the age of 3,7 and 28 days using three cubes per FA replacement and then the average compressive strength value for each FA replacement was calculated.

Figure 5 depicts the variation in the compressive strength of OPC-FA blended cement mortar samples with respect to the water to cement ratios of 0.375, 0.4, and 0.425. Compressive strength of the OPC-FA blended cement mortars increases from 3 to 28 days in all water to binder ratios and FA replacement levels, according to the findings. The continuation of cement hydration is responsible for the increase in compressive strength with age. When Portland cement is mixed with water, the initial reactions are mainly involved with the silicates contained in the cement. During their reaction with water both tricalcium silicate and dicalcium silicate produce a hard paste – gel made up of Calcium Silicate Hydrates (CSH). CSH is the major contributor to the strength of cement. It is known that compressive strength increases rapidly in the early stages and slowly in later stages [17]. Although the compressive strength of mortar specimens increases with age, it is observed that the compressive strength of the specimens decreased gradually as the amount of FA replaced increased as compared to the control specimens. The sluggish pozzolanic process is mostly responsible for the decrease in compressive strength. Silicates are reacting with water during the cement hydration process to produce CSH as well as at the same time it forms Calcium hydroxide. The amorphous silica in FA reacts with this excess Calcium hydroxide to reproduce CSH which forms further strength in cement. The reduction in free Calcium hydroxide makes the mixture chemically more stable. So, it also increases strength. During their research study Ahmed, 2019 revealed that, due to the secondary reactions, most pozzolanic cements develop strength beyond 28 days. The result obtained from the study is in line with that obtained by Kondraivendhan & Bhattacharjee [9].

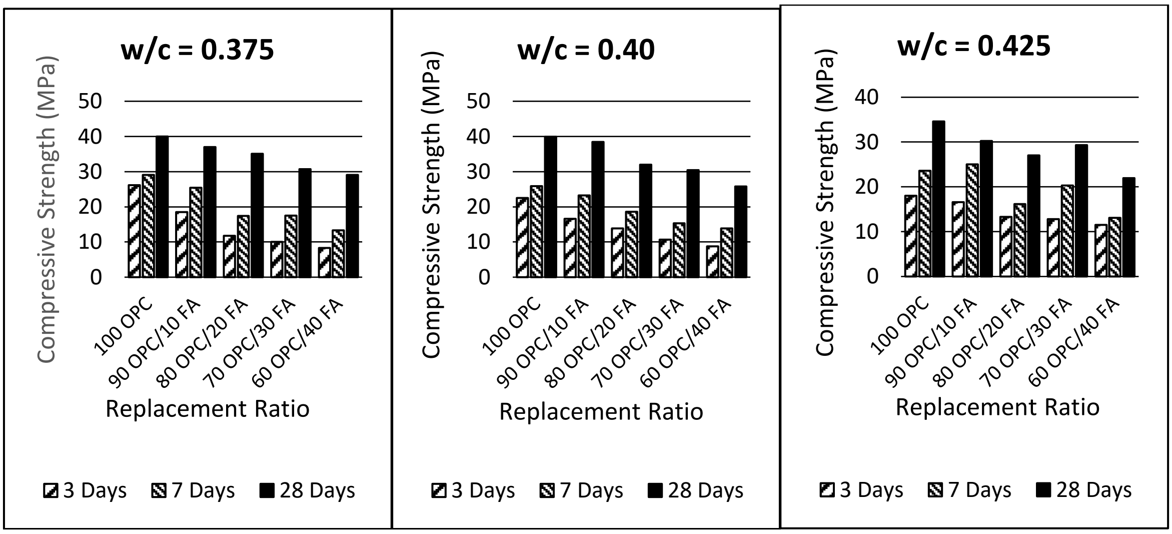

Figure 5. *Compressive* strength of OPC-FA blended cement mortar

3.1.1 Sensitivity to water to binder condition on strength

The sensitivity of compressive strength to the water-to-binder ratio was investigated using the 'Sensitivity Index' concept for samples cured in water for 28 days, as adopted by previous researchers [18].

Sensitivity Index (SI) = $\frac{f_{test} - f_{ref}}{f_{ref}} = \frac{f_{test}}{f_{ref}} - 1$

Where, f_{test} = Strength of the test mix
f_{ref} = Strength of the corresponding mix with reference water to binder ratio

The 'Sensitivity Index' can be defined as the difference of strength between the test mix and the reference mix as a ratio of the reference mix. The central water to binder ratio of the experimental program was 0.4. Therefore, to test sensitivity to water to binder ratio on compressive strength, a mixture with water to binder ratio of 0.4 was used as a reference. The mixtures with a w/binder ratio of 0.375 and 0.425 were taken as test mixtures for the analysis. If the sensitivity index is '0' it indicates that there is no sensitivity. The positive value of the sensitivity index indicates that the strength has been increased, while the negative value indicates the strength has been decreased. Figures 6 and 7 present sensitivity to w/binder ratio of 0.375 and 0.425 respectively. In Figure 6, all values except the 10% FA replacement level are positive; indicating that all mixtures are sensitive to water to binder ratio and that the strength increases as the water to binder ratio decreases from the datum. According to Figure 7, all the sensitivity index values are negative; and it indicates that all the mixtures are sensitive, and also strengths are decreased with the increase of water to cement ratio from 0.4 to 0.425.

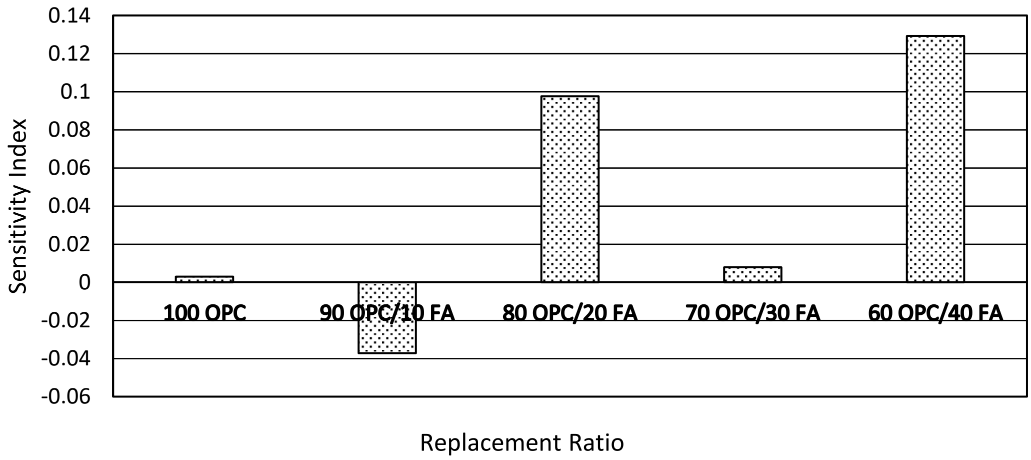

Figure 6. Sensitivity to w/c ratio on strength (w/c = 0.4 to 0.375)

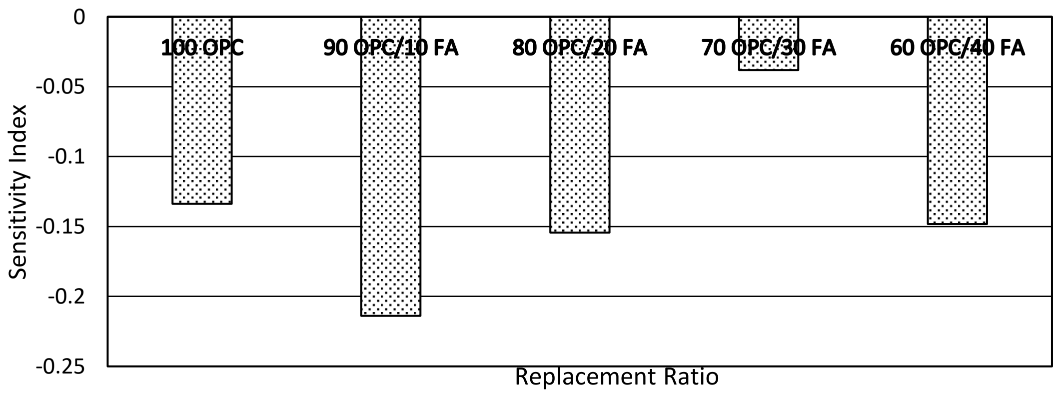

Figure 7. Sensitivity to w/c ratio on strength (w/c = 0.4 to 0.425)

Water Absorption

Figure 8 depicts the variation in water absorption of the FA blended cement mortar samples with the water to binder ratios of 0.375, 0.4, and 0.425. The water absorption of the FA blended cement mortar increases as FA replacement level increases in all water to binder ratios, according to the trendline of the results. The silica which is in the FA, reacts with excess free calcium hydroxide in the pozzolanic reaction to form CSH, which reduces the size of the capillarity pores. However, due to the insufficient CSH in the early ages of cement hydration, these capillary pores may not be filled. The results revealed that as the water to binder ratio increases, water absorption of the FA mixed cement mortar will also be increase. After obtaining the required amount of water for cement hydration, if any excess water remains in the mix, they remain as water in the sample. The results of this study are aligned with that obtained by Hatungimana, Taşköprü, İçhedef, Saç & Yazıcı [19]. With the increasing of the fraction of FA replacement, the values of water absorption of FA mortar mixtures will also be increased, according to the authors. Although the method proposed by Jung, Siang, Kwong & Boon [16] to determine water absorption was used for this study, the chemical composition of the mortar sample may change as the FA blended samples are heated in the oven at 105 °C. Therefore, it has the potential to affect the final results. So, it is recommended for future researchers to get the saturated weight first and then put it in the oven to take the dry weight.

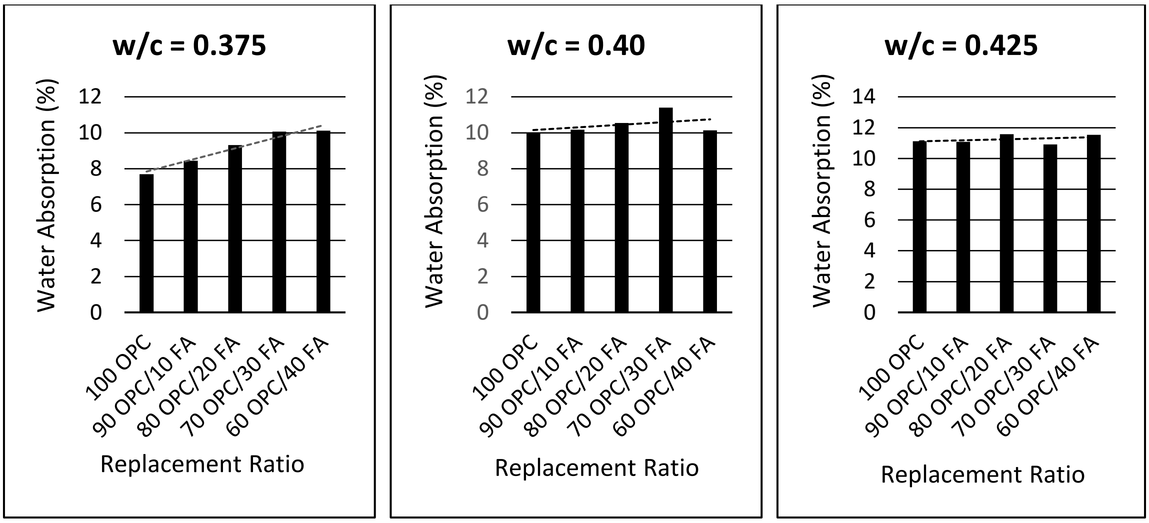

Figure 8. Water absorption of OPC-fly ash blended cement mortar

Density

The density variance of FA blended cement mortar samples with water to binder ratios of 0.375, 0.4, and 0.425, respectively, is shown in Figure 9.

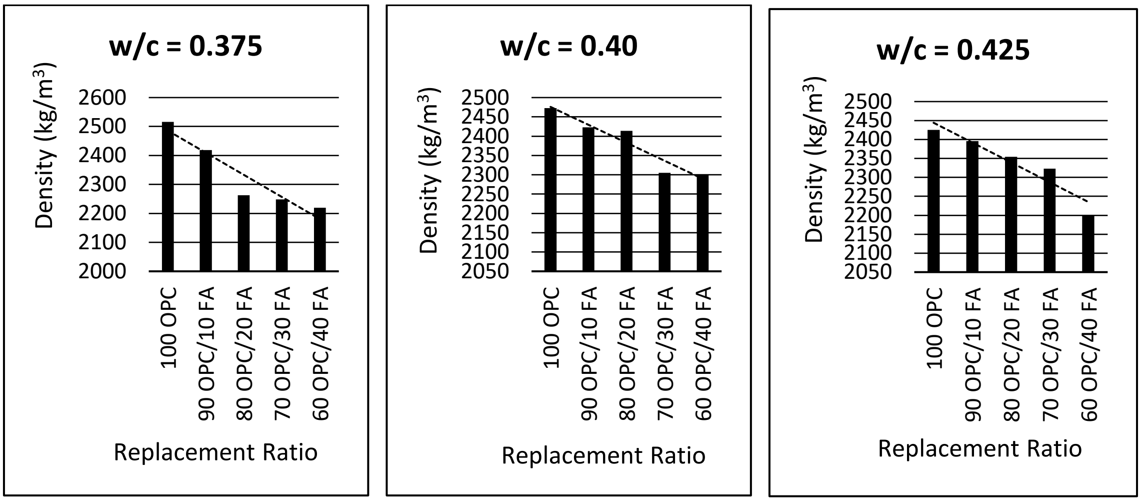

Figure 9. Density of OPC-fly ash blended cement mortar

According to the findings, the density of the FA blended cement mortar reduces as the FA replacement amount increases in all water to binder ratios. 28 days of cure is insufficient to complete the pozzolanic process. As a result, the CSH may not be sufficient to fill the capillary pores in the specimen at the age of 28 days. In comparison to the control sample, the number of pores in the specimen increases as the FA replacement level increases. As a result, when the FA level increases, the weight of the sample decreases, and then the density also increases.

The Relationship of Compressive Strength, Water Absorption and Density of Mortar

When water absorption decreases, the compressive strength and density of specimens increase. According to the results, the control sample which has 100% OPC shows the least water absorption. This is because the control sample has a larger concentration of CSH. The larger the quantity of CSH, the smaller the capillary pores in the specimen. Therefore, less water is absorbed into the specimen. Due to the lesser number of pores in the specimen, the compressive strength increases as the percentage of water absorption decreases.

CONCLUSION

The experimental results and analysis presented in this paper lead to the following conclusions;

1. At 28 days, compressive strength decreased slightly with higher FA content due to lower early-age CSH formation, but remained within acceptable limits.
2. The water absorption is inversely proportional to compressive strength and density at age of 28 days.
3. Due to the pozzolanic reactions induced by the presence of FA in the mixture, CSH is formed and thereby capillary pores in the specimen are reduced, resulting in increased compressive strength and durability.
4. Up to 40% OPC can be replaced with FA without significantly reducing strength, contributing to energy savings, lower CO_2 emissions, and sustainable material use.

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