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THE INFLUENCE OF CHEMICAL ADMIXTURE TYPES ON THE MECHANICAL PROPERTIES OF CONCRETE WITH 100% FLY ASH SUBSTITUTION

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ABSTRACT: Concrete is a fundamental construction material, with production processes, particularly cement manufacturing, posing significant environmental challenges due to high CO_2 emissions. To address these challenges, fly ash, a by-product of coal combustion, presents a sustainable alternative by partially or completely replacing cement in concrete to reduce CO_2 emissions. Despite the potential, previous research reported that concrete with 100% fly ash substitution faced issues in achieving adequate workability and initial strength. The strategic use of chemical admixtures can mitigate these issues, but further investigation is required to optimize the mix proportioning effectively. Therefore, this research aimed to evaluate the influence of various chemical admixtures on the mechanical properties of concrete using 100% fly ash as a binder. The experiment included comprehensive testing of raw material properties, designing mix formulations with different chemical admixtures, and conducting laboratory tests on both fresh and hardened concrete. Fresh concrete was assessed for workability, while hardened concrete was tested for dry density, compressive strength, and split tensile strength at 3, 7, 28, and 56 days. The specimens used will be cylindrical, measuring 100 mm x 200 mm, and cured by water immersion. The study indicated that using Class C fly ash for 100% fly ash concrete, combined with chemical admixtures, resulted in compressive strength and split tensile strength that increased from 28 to 56 days. Chemical admixtures combination enhanced the concrete's density, while superplasticizers improved the slump value, creating self-compacting concrete (SCC). Notably, a 60:40 ratio of superplasticizer to accelerator (MD2) was most effective in enhancing strength.

Keywords: Fly ash, Chemical Admixture, Workability, Mechanical property, Sustainable concrete.

1. INTRODUCTION

Concrete is among the most extensively utilized construction materials globally, attributed to its strength, durability, and availability. Nevertheless, the production of cement, a key component of concrete, is notably detrimental to the environment, requiring substantial energy and generating significant CO_2 emissions. Current estimates suggest that cement production accounts for approximately 7% of global greenhouse gas emissions. Consequently, the identification and development of more environmentally sustainable binder alternatives is imperative to mitigate the environmental impact associated with cement production [1-7].

In this context, fly ash, a by-product of coal combustion, has shown significant potential in concrete applications. Particularly, high-volume fly ash concrete (50-70%) has been widely adopted because of its ability to enhance certain properties of concrete, such as strength and durability. The use of large amounts of fly ash or complete replacement of cement is becoming popular due to the potential environmental benefits and mechanical performance. Concrete made with 100% fly ash can achieve compressive strength comparable to conventional type [8]. Furthermore, the high-volume use of fly ash offers environmental benefits, such as reducing carbon emissions and using industrial waste in line with sustainable development concepts [9-10].

Concrete with 100% fly ash presents both advantages and disadvantages in application. The advantages include significant reductions in CO_2 emissions and energy consumption during production, as well as improved durability against chemical attacks and freeze-thaw cycles. Typically, Type C fly ash with high CaO content is used [8,11], but the main drawbacks include difficulties in controlling setting time and reduced tensile strength of concrete. Additionally, 100% fly ash concrete faces challenges in achieving the early strength required for certain structural applications.

The use of 100% fly ash concrete in the construction industry faces several major challenges, such as adjusting batching methods and the need for special set retarders to prevent flash setting.

Strategies to overcome these challenges include training and educating batch plant operators, and construction workers, as well as developing simpler and more consistent batching procedures. Trial batches and educational meetings are essential to ensure the successful large-scale implementation of this concrete. With appropriate handling, 100% fly ash concrete has the potential to serve as a sustainable and environmentally friendly alternative in the construction industry, offering performance comparable to traditional concrete across various structural applications, provided that its mix design is meticulously engineered and the curing process is carefully optimized [12].

In recent years, further research on 100% fly ash concrete have focused on using various types of chemical admixtures to address these challenges. Admixtures such as superplasticizers and retarders have proven effective in improving workability and controlling setting time in concrete. However, many variables still need to be explored to optimize the mechanical performance of 100% fly ash concrete with different admixtures.

To address the challenges of rapid setting time and low workability in 100% fly ash concrete, various types of chemical admixtures have been used. Chemical admixtures in high-volume fly ash concrete (HVFAC) primarily function to enhance properties such as workability, setting time, and compressive strength, in accordance with ASTM C494 standards. Various chemicals, including calcium chloride, calcium sulfate, sodium sulfate, and sucrose, are used to improve geopolymer properties. Research shows that calcium chloride accelerates the setting time, while sucrose causes delays. The addition of chemical admixtures to HVFAC and geopolymer concrete has shown significant improvements in setting time, compressive strength, and workability. Calcium chloride, sodium sulfate, and sucrose play essential roles in modifying these properties, with each chemical providing specific effects based on the dosage [13-16]. Superplasticizers and accelerators have also proven highly effective in enhancing the early strength of concrete, serving as potential solutions for construction applications requiring high-strength concrete in a short time. Therefore, the main drawbacks due to the high-volume use of fly ash can be mitigated by the addition of chemical admixtures such as superplasticizers and accelerators [17-19]. The appropriate use of these admixtures is capable of enhancing the mechanical properties of concrete using 100% fly ash as a binder.

Based on the description, this research aimed to determine the optimal mixture formulation and evaluate the impact of different types of chemical admixtures on the mechanical properties of concrete using 100% fly ash as a binder. The experiment was carried out in several stages including testing the characteristics of the materials, mixture proportioning with variations of different types of chemical admixtures, followed by evaluation of fresh and hardened concrete in the laboratory. Types of chemical admixtures used were superplasticizers, accelerators, and their combinations. Fresh concrete was tested for workability, while hardened concrete was evaluated for dry density, compressive strength and split tensile strength at ages 3, 7, 28, and 56 days. The tests were performed using cylindrical specimens measuring 100 mm x 200 mm cured with a water immersion method. The analysis of the test data was conducted to examine the correlations between density, compressive strength, and split tensile strength of 100% fly ash concrete, incorporating the specified variations.

2. RESEARCH SIGNIFICANCE

This research aimed to significantly contribute to the development of concrete technology using 100% fly ash, offering a cost-effective and environmentally friendly alternative with optimal mechanical performance. By evaluating the impact of various chemical admixtures on concrete properties and determining optimal mixture formulations, the results provided valuable contributions to advance the practical application of 100% fly ash concrete in the construction industry, promoting sustainable development and reducing carbon emissions.

3. MATERIAL AND METHODS

The flow chart in Figure 1 shows the stages of laboratory research titled "The Influence of Chemical Admixture Types on the Mechanical Properties of Concrete with 100% Fly Ash Substitution."

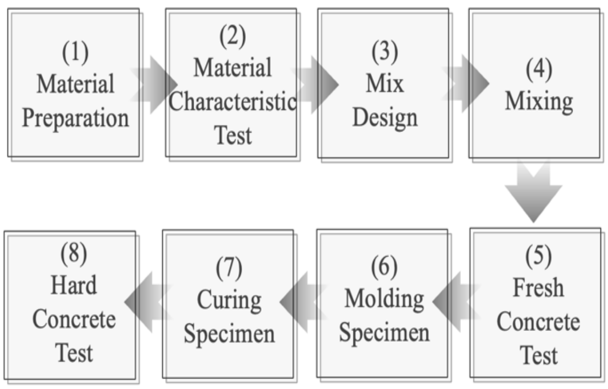


Fig.1 Research flow chart

The research process is presented sequentially, encompassing each step from goal setting, material characterization, mix design proportion, testing of fresh and hardened concrete, data analysis, and concluding findings, to provide a comprehensive and systematic overview.

3.1 Material Characteristic

3.1.1. Fly Ash Characteristic

The physical and chemical characteristics of fly ash as a binder in concrete mixtures were determined to ensure quality and compatibility in enhancing concrete performance. Specifically, physical characteristics were assessed through particle size analysis using sieving or laser diffraction. Density and specific surface area measurements were conducted using the Blaine method. Chemical characteristics were analyzed by determining the primary oxide composition, such as SiO_2, Al_2O_3, and Fe_2O_3, through X-ray fluorescence (XRF), followed by assessing organic material content through loss on ignition (LOI). These tests ensure that fly ash meets the required standards, namely ASTM C618, for use as concrete binder, thereby improving concrete's strength, durability, and environmental resistance. Table 1 shows the characteristics of fly ash sourced from a local power plant in Makassar, South Sulawesi, Indonesia. Based on ASTM C618, with a combined content of SiO_2 with Al_2O_3 and Fe_2O_3 of 63.77% and a CaO content of 15.69%, fly ash used in this research was categorized as Class C or high-calcium fly ash.

Table 1 Fly ash characteristic

Test Description	Result, %
SiO_2	39.15
Al_2SO_3	13.69
Fe_2O_3	10.92
CaO	15.69
MgO	4.01
K_2O	0.77
Na_2O	0.66
H_2O	0.48
$SiO_2+Al_2SO_3+Fe_2O_3$	63.77

3.1.2. Aggregate Characteristic

The aggregates used in this research comprised coarse (crushed stone 10/20) and fine aggregates (sand), which were sourced from local raw materials in Gowa, South Sulawesi, Indonesia. The physical characteristics of the coarse and fine aggregates for concrete mixture were tested in line with ASTM C33 standards. This testing included several stages, namely sample collection, particle size analysis (gradation), cleanliness testing (including silt and organic content), as well as the assessment of strength and durability (compressive strength and abrasion resistance tests). The purpose of these characteristic tests was to ensure that the aggregates met quality specifications and were compatible with producing strong as well as durable concrete. This process is essential to ensure the quality and consistency of concrete in construction. Based on the data presented in Table 2, the aggregates used in this study were evaluated against the standards specified in ASTM C33 and were found to meet all the requirements. This compliance indicates that the aggregates are suitable for use in concrete production, ensuring consistent quality and performance in line with established industry standards.

Table 2 Aggregate characteristic

Properties	Coarse Agg.	Fine Agg.
SSD Specific Gravity	2.64	2.56
Clay Content, %	0.20	2.95
Water absorption, %	0.54	3.05
Finest Modulus	8.94	2.74
Moisture Content, %	0.00	2.01

3.1.3. Chemical Admixture Characteristic

The characteristics of chemical admixtures used served as differentiating factors among the various mixture proportions of the specimens to be tested. Type and dosage of these admixtures could significantly alter or enhance the performance of the produced concrete. Table 3 shows the characteristics of chemical used, namely Polycarboxylate superplasticizer and accelerator, which are classified as Type F and Type C chemical admixtures, respectively, according to ASTM C494. In the mixture proportioning variations designed, these two chemicals were used independently as well as a combination of superplasticizer and accelerator with a predetermined composition. Chemical admixtures used in this research were obtained from local products in Indonesia.

Table 3 Chemical admixture characteristic

Properties	Superplasticizer	Accelerator
Density, kg/l	1.10 ± 0.05	1.46 - 1.48
Purpose	Slump keeper agent, workability, strength improvement, pumping aid	Accelerating agent formulation, Chloride free, rapid hardening
Dosage of binder, %	0.8 - 2.0	0.5 – 3.0
Appearance	Turbid yellowish liquid	Brownish clear liquid

3.2 Mixture Proportion of 100% Fly Ash Concrete

Mixture proportion of 100% fly ash concrete was developed based on the availability of local materials as the primary components of concrete. The proportion used the same material composition, except for type and dosage of chemical admixtures (Adm). Adm1 consisted of 100% superplasticizer, Adm2 was a mixture of 60% superplasticizer and 40% accelerator, Adm3 contained 50% superplasticizer and 50% accelerator, and Adm4 comprised 40% polycarboxylate and 60% accelerator. The variations in the mixture were denoted as MD0, MD1, MD2, MD3, and MD4. MD0 served as the control specimen, consisting of a 100% fly ash concrete mixture without admixtures. MD1 incorporated Adm1, MD2 contained Adm1 with the addition of Adm2, MD3 used Adm3, and MD4 applied Adm4. Moreover, the specific composition of each mixture proportion is shown in Table 4.

Table 4 Material composition of mixture proportion (m^3)

Material	Mix Code				
	MD0	MD1	MD2	MD3	MD4
Fly ash, kg	532	532	532	532	532
Stone, kg	750	750	750	750	750
Sand, kg	870	870	870	870	870
Water, l	140	50	43	43	43
Adm1, l	-	7.98	-	-	-
Adm2, l	-	-	7.98	-	-
Adm3, l	-	-	-	7.98	-
Adm4, l	-	-	-	-	7.98

3.3 Concrete Testing

3.3.1. Fresh Concrete

The workability test for fresh concrete, as specified by ASTM C143, was carried out to measure the slump of concrete to determine its consistency. The equipment required included an Abrams cone, a tamping rod, and a non-absorbent base plate. The testing procedure started by placing the Abrams cone on the base plate and filling with fresh concrete in three layers, each was compacted with 25 strokes of the tamping rod. After the cone was completely filled, the surface was leveled, and the cone was lifted vertically. The slump was measured from the top of concrete after slumping to the original top of the cone. For Self-Compacting Concrete (SCC), the slump value is determined by measuring the average length of two perpendicular diameters of the spread concrete using a ruler or other measuring device. This measurement is conducted on a horizontal surface after the concrete has been poured and allowed to flow freely without external vibration, reflecting its ability to spread and fill molds independently. The recorded slump value indicates the workability of the concrete, with higher values representing greater flowability. This test is critical for ensuring that SCC exhibits the required flow characteristics while maintaining material homogeneity and preventing segregation

The measured slump value showed the workability of concrete, as presented in Figure 2.

Fig.2 Workability testing of fresh concrete

3.3.2. Hardened Concrete

In hardened concrete testing, dry density, compressive strength, and split tensile strength were assessed on cylindrical specimens at 3, 7, 28, and 56 days, with 3 samples tested at each age. The density test, following ASTM C642, was conducted to measure concrete's density, porosity, and water absorption, factors that significantly influenced durability. The procedure included weighing concrete in 3 conditions, namely dry, submerged in water, and after boiling.

The compressive strength test, as stated in ASTM C39, evaluated the maximum load concrete could withstand before failure. The compressive strength test for hardened concrete included the use of standard cylindrical specimens (150 mm in diameter and 300 mm in height) cured under moist conditions following proper curing procedures. The equipment used included a compression testing machine, rigid and level-bearing plates, and instruments to measure the maximum load. Before testing, the surface of the specimens was thoroughly cleaned, and placed vertically between the bearing plates of a compression testing machine, ensuring central orientation. A gradually increasing load was applied at a constant rate of 0.15–0.35 MPa/s until the specimen failed. The maximum load at failure was recorded and the compressive strength (fc) was determined:

$$fc = P/A \quad (1)$$

Where:
P = represents the maximum load in Newtons, and
A = cross-sectional area of the specimen (πr^2) in mm^2

Split tensile strength testing was conducted in line with ASTM C496M to determine the tensile strength of concrete indirectly. This test included applying a compressive load centrally along the length of a cylindrical specimen (150 mm in diameter and 300 mm in height) stored under damp conditions and cleaned before testing. Subsequently, specimen was positioned horizontally in a compression testing machine, with metal bearing plates placed on its top and bottom to convert the compressive force into tensile stress. The load was applied at a constant rate of 689–1380 N/s until the specimen failed and the maximum load at failure was recorded to calculate the split tensile strength. The equipment used included a compression testing machine, bearing plates, and a load measurement device. The formula for calculating the split tensile strength (ft) is expressed as follows:

$$ft = \frac{2P}{\pi LD} \quad (2)$$

With:
ft = represents the split tensile strength (MPa),
P = the maximum applied load leading to failure (Newton),
L = denotes the length of the specimen (mm)
D = signifies the diameter of the specimen (mm).

Tests on hardened concrete consisting of dry density and compressive strength can be seen in Figure 3.

Fig.3 Dry density and compressive strength testing

4. RESULTS AND DISCUSSION

4.1 Fresh Concrete Test Result

According to Table 5, the average slump value for MD0 was found to be 11.0 cm, while for MD1, MD2, MD3, and MD4, the values were 70, 70, 65, and 55 cm, respectively. The addition of chemical admixtures, whether superplasticizer only or in combination with an accelerator, increased the slump value and transformed the behavior of fresh concrete from normal concrete to SCC. As the proportion of accelerator in chemical admixtures increased, a corresponding decrease was observed in the average slump value [16, 20, 21].

Table 5 Slump test results

Mix Code	Slump (Cm)		
	Max	Min	Average
MD0	11.8	10.2	11.0
MD1	71.5	68.5	70.0
MD2	70.3	69.7	70.0
MD3	65.9	64.1	65.0
MD4	55.5	54.5	55.0

4.2. Hardened concrete test result

4.2.1. Density Test

The results of the density tests for 100% fly ash concrete are presented in Figure 2. The results showed the correlation between concrete density and different specimens (MD0, MD1, MD2, MD3, and MD4) according to the age of concrete at 3, 7, 28, and 56 days. The data showed that the density of concrete generally increased with age. On 3rd day, concrete densities ranged from 2313 kg/m³ (MD0) to 2356 kg/m³ (MD1), and continued to increase until the 56th day, reaching between 2390 kg/m³ (MD0) and 2429 kg/m³ (MD1). This showed that concrete experienced continuous hardening and densification over time. The continuous hydration process, evaporation of free water, consolidation of the microstructure, and carbonation process further reduced porosity but increased density.

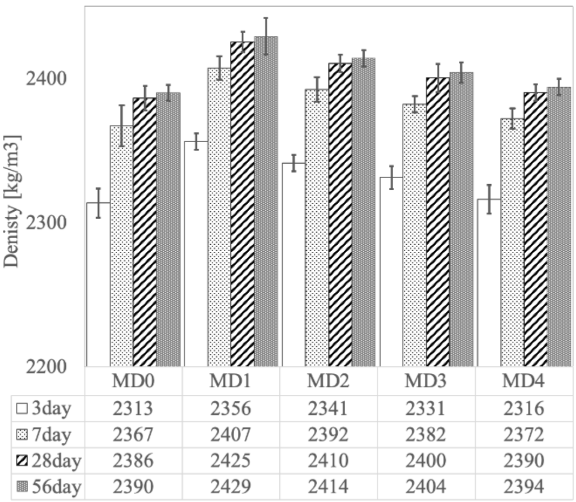
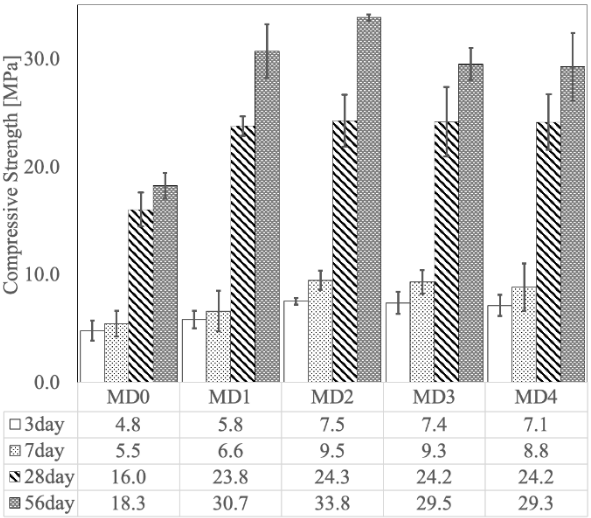


Fig.4 Density test result

As presented in Figure 4, the MD1 specimen consistently showed the highest density at each measurement period, namely 2356 kg/m³, 2407 kg/m³, 2425 kg/m³, and 2429 kg/m³ at 3, 7, 28, and 56 days, respectively. Other specimens, such as MD0, MD2, MD3, and MD4, showed similar increasing trends but with slightly lower densities compared to MD1. Therefore, the use of chemical admixtures enhanced concrete density. Superplasticizers increased density by reducing water requirements and improving workability, allowing for better compaction of concrete. Accelerators also increased density by speeding up the hydration reaction, reducing porosity, and accelerating the achievement of early strength, thereby producing denser and stronger concrete. In comparison, superplasticizers tended to have a more direct and significant impact on increasing concrete density compared to accelerators [22, 23].

4.2.2. Compressive Strength Test

Figure 5 shows the relationship between the compressive strength of MD0, MD1, MD2, MD3, and MD4 at 3, 7, 28, and 56 days. The results showed that the compressive strength increased as concrete ages. At 3 days, MD2 showed the highest compressive strength at 7.5 MPa, followed by MD3 (7.4 MPa), MD4 (7.1 MPa), MD1 (5.8 MPa), and MD0 (4.8 MPa). The increase in compressive strength continued at 7 days, with MD2 maintaining the highest compressive strength (9.5 MPa), followed by MD3 (9.3 MPa), MD4 (8.8 MPa), MD1 (6.6 MPa), and MD0 (5.5 MPa).



	MD0	MD1	MD2	MD3	MD4
3day	4.8	5.8	7.5	7.4	7.1
7day	5.5	6.6	9.5	9.3	8.8
28day	16.0	23.8	24.3	24.2	24.2
56day	18.3	30.7	33.8	29.5	29.3

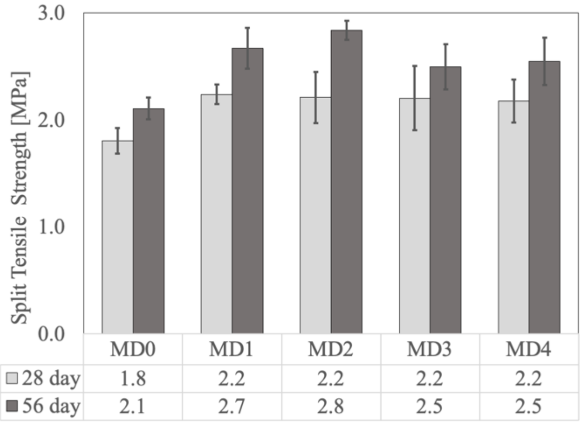
Fig. 5 Compressive strength result

At 28 days, all specimens showed a significant increase in compressive strength. MD2 remained the highest with a compressive strength of 24.3 MPa, slightly higher than MD3 and MD4, each at 24.2 MPa. This was followed by MD1 and MD0 with compressive strengths of 23.8 MPa and 16.0 MPa, respectively. At 56 days, MD2 reached the highest at 33.8 MPa, followed by MD1 (30.7 MPa), MD3 (29.5 MPa), MD4 (29.3 MPa), and MD0 (18.3 MPa).

The use of 100% fly ash concrete offered significant practical advantages in enhancing concrete performance as well as providing a more economical and environmentally friendly solution. The incorporation of chemical admixtures, such as superplasticizers and accelerators, in the appropriate proportions showed the potential to facilitate the mixing and pouring processes, thereby improving the applicability of concrete in various construction projects. 100% fly ash concrete also showed advantages over geopolymer, particularly in terms of the broader availability of raw materials, simpler production processes, and lower production costs. However, several challenges must be addressed including inconsistent quality of fly ash, which can affect the final concrete outcome. The initial compressive strength of fly ash concrete tends to develop more slowly compared to conventional concrete. Therefore, ensuring uniform distribution of fly ash and maintaining consistency during the production process is essential to meet the desired strength and durability standards of the final product.

4.2.3. Split Tensile Strength Test

Figure 6 depicts the variation in split tensile strength for five concrete specimens (MD0, MD1, MD2, MD3, and MD4) at four different curing ages: 28 and 56 days.



	MD0	MD1	MD2	MD3	MD4
28 day	1.8	2.2	2.2	2.2	2.2
56 day	2.1	2.7	2.8	2.5	2.5

Fig. 6 Split tensile strength result

Figure 6 shows the variation in split tensile strength for MD0, MD1, MD2, MD3, and MD4 at 28, and 56 days. Based on Figure 6, the split tensile strength of the specimens MD0, MD1, MD2, MD3, and MD4 shows a significant increase as the concrete age progresses. MD0 exhibited the lowest split tensile strength, starting at 1.8 MPa at 28 days and reaching 2.1 MPa at 56 days. MD1 demonstrated a better performance, with a split tensile strength of 2.2 MPa at 28 days and 2.7 MPa at 56 days. MD2 showed the best performance, starting at 2.2 MPa at 28 days and achieving 2.8 MPa at 56 days. MD3 and MD4, although showing an increase over time, had lower split tensile strength compared to MD2, with MD3 reaching 2.5 MPa and MD4 2.5 MPa at 56 days. Overall, MD2 achieved the highest values, followed by MD1, MD3, MD4, and lastly MD0. The trend observed in the split tensile strength closely follows that of the compressive strength test results.

The correlation between the split tensile strength and compressive strength of Portland cement concrete is described by the American Concrete Institute (ACI). According to the equation in ACI 318 [24], the ratio of split tensile strength to compressive strength of Portland cement concrete at 28 days can be estimated within the range of 10 to 11%. This ratio decreases as compressive strength increases. Table 6 presents the ratio of split tensile strength to compressive strength for 100% fly ash concrete.

Table 6 Ratio of split tensile strength to compressive strength.

Age	Mix Code				
	MD0	MD1	MD2	MD3	MD4
28 days	0.113	0.092	0.091	0.091	0.091

As illustrated in Figure 6, the ratio of split tensile strength to compressive strength for 100% fly ash concrete at 28 days for samples MD0, MD1, MD2, and MD3 are reported as 0.113, 0.092, 0.091, 0.091, 0.091, and 0.091, respectively. These findings are consistent with previous studies, which indicate that the ratio of splitting tensile strength to compressive strength for 100% fly ash concrete is lower than the values predicted by the ACI 318 equation originally developed for Portland cement concrete [8].

5. CONCLUSIONS

Based on the data analysis, results, and discussion, the following conclusions can be drawn:

1. The addition of superplasticizers and accelerators enhances the workability of fresh concrete, enabling transformation into self-compacting concrete (SCC).
2. Incorporating chemical admixtures contributes to increased density in 100% fly ash concrete.
3. The application of C-grade fly ash in 100% fly ash concrete, combined with chemical admixtures, has been shown to achieve compressive strengths of up to 33.8 MPa and split tensile strengths of up to 2.8 MPa at 56 days
4. The compressive and split tensile strengths of 100% fly ash concrete showed a progressive increase between 28 and 56 days, with the potential for further improvement over time.
5. Among various admixture combinations, a 60:40 ratio of superplasticizer to accelerator (MD2) has been identified as the most effective in enhancing the compressive and split tensile strengths of 100% fly ash concrete.

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