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Optimization of Type C Fly Ash Utilization on the Mechanical Properties of Eco-Friendly Concrete

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Abstract

This study investigates the use of Class C fly ash (FA-C) as a partial replacement for Ordinary Portland Cement (OPC) in concrete mixtures to enhance its mechanical properties and environmental sustainability. FA-C, a by-product of coal combustion with a high calcium oxide (CaO) content, is known for its self-cementing properties, which contribute to improved hydration products, such as calcium silicate hydrate (C-S-H). The experiment involves varying FA-C replacement levels 10%, 20%, and 30% in concrete mixtures while maintaining a constant water-to-cement (w/c) ratio of 0.5. The effects of FA-C substitution on workability, compressive strength, flexural strength, water absorption, and porosity were analyzed at 7, 14, and 28 days of curing. Results show that FA-C significantly improved workability, reduced water absorption, and enhanced concrete durability by reducing porosity. The optimal FA-C substitution of 20% led to the highest improvements in compressive and flexural strengths, particularly at 28 days. However, higher FA-C contents 30% slightly decreased early-age strength, highlighting the need for careful control of hydration and curing conditions. This study demonstrates that FA-C can be effectively utilized in eco-friendly concrete applications, contributing to reduced carbon emissions while maintaining desired structural performance.

Keywords : *Fly Ash, Concrete Sustainability, Compressive Strength, Environmental Impact.*

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I. INTRODUCTION

The increasing demand for infrastructure development and ambitious emission-reduction targets are driving the construction industry to develop low–carbon concrete without compromising mechanical performance. One of the most promising approaches is the partial replacement of Portland cement with supplementary cementitious materials (SCMs), such as fly ash. Globally, cement production contributes approximately 0.65–0.85 tons of CO_2 per ton of cement produced; therefore, every percentage reduction in clinker content through the utilization of SCMs has a direct and measurable impact on reducing emissions from the construction sector (Pamenter et al., 2021).

Numerous life cycle assessment (LCA) studies demonstrate that the incorporation of fly ash can significantly reduce the carbon footprint of concrete. In low-emission mixture designs, partial substitution of cement with fly ash and/or other mineral fillers consistently lowers greenhouse gas emissions, although mixture proportions must be carefully controlled to prevent emission reductions from being accompanied by unacceptable losses in mechanical strength (Wang et al., 2025). Similar findings have been reported in LCA studies conducted in Indonesia, which indicate substantial emission-reduction potential in ready-mixed concrete when fly ash is strategically utilized in mixture formulations (Khalil et al., 2023).

With respect to fly ash typology, Class C fly ash originates from the combustion of lignite or sub-bituminous coal and is characterized by a higher calcium oxide (CaO) content compared to Class F fly ash. This high calcium content imparts “self-cementing” properties and relatively high early-age reactivity. These characteristics contribute to the formation of additional hydration products primarily calcium silicate hydrate (C–S–H) and ettringite which densify the microstructure, reduce porosity, and, under certain conditions, enhance compressive strength and overall durability of concrete (Zhang et al., 2022).

From a mechanistic perspective, calcium content significantly influences hydration kinetics and microstructural evolution. Several studies report that fly ash addition may reduce early-age hydration heat and early strength; however, it generally improves medium- to long-term strength development and refines pore structure, with the magnitude of these effects strongly dependent on the CaO content of the fly ash employed (Yang et al., 2023).

In Indonesia, the availability of high-calcium fly ash is relatively abundant as a by-product of coal-fired power plants and has been utilized in both Portland cement–based systems and geopolymer concretes. In geopolymer systems, the high reactivity of Class C fly ash may even induce rapid setting, necessitating careful control through admixtures and curing regimes to maintain workability and long-term durability performance (Moolchandani et al., 2025).

Despite its strong potential, optimization of Class C fly ash dosage cannot be treated generically, as the mechanical performance of concrete depends on complex multi-parameter interactions, including the water-to-binder (w/b) ratio, particle fineness and size distribution, compatibility with superplasticizers, curing conditions, testing age, and synergistic effects with other SCMs such as slag or limestone fillers. Syntheses of recent evidence highlight differences in the contributions of Class F and Class C fly ash to compressive strength; nevertheless, both types can enhance strength and durability when properly proportioned. For Class C fly ash, the self-cementing behavior supports early- to medium-age strength development while still providing long-term benefits in terms of permeability reduction and paste densification (Mondal et al., 2023).

In alternative binder environments, such as calcium sulfoaluminate (CSA) cement systems, both Class C and Class F fly ash tend to reduce one-day compressive strength while improving 28-day strength, with Class C fly ash exhibiting slightly superior strength development characteristics (Mondal et al., 2023).

Consistent with these findings, several recent reviews and experimental studies report that a “safe” substitution range for maintaining compressive strength in conventional concrete lies between approximately 10–25%, whereas in ultra-high-performance concrete (UHPC), substitution levels of 20–35% can deliver competitive performance, provided that the w/b ratio is tightly controlled (Suwanmaneechot et al., 2025; Feng et al., 2024).

In specific mixture cases such as 15% Class C fly ash replacement improvements in flexural performance and ductility have been observed, although initial stiffness may decrease. This underscores the importance of performance-based optimization that explicitly considers strength–stiffness–ductility trade-offs rather than relying on a single substitution percentage (Flores et al, 2025).

Supply-chain considerations are becoming increasingly critical. The gradual phase-out of coal-fired power generation in many regions is

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reducing the availability of "fresh" fly ash, necessitating more efficient utilization strategies and consideration of alternative sources such as beneficiated landfilled or ponded ash (Shukla et al, 2023).

Within the ASEAN region, energy transition policies place coal on a complex phase-down trajectory, affecting fly ash supply chains and encouraging innovation in low-emission mixture design that does not rely on a single SCM (ASEAN Centre for Energy, 2024).

Accordingly, optimization of Class C fly ash use represents not only a technical mandate to maximize performance but also a material resilience strategy during a period of supply transition. From a mechanical performance standpoint, the most commonly referenced indicators include compressive strength (f'c), splitting tensile strength, flexural strength, and modulus of elasticity. Microstructural improvements through filler effects and pozzolanic–cementitious reactions generally correlate with increased compressive strength at ages ≥28 days and reduced permeability coefficients. However, excessively high substitution levels or poorly controlled w/b ratios can result in dilution effects that diminish strength and durability (Zhang et al., 2024).

Recent studies further integrate sustainability considerations into optimization frameworks by linking strength gains to reductions in Global Warming Potential (GWP). As a result, Class C fly ash dosage decisions are increasingly guided by multi-objective functions encompassing strength, durability, workability, cost, and emissions rather than a single performance metric (Akbulut et al., 2024).

In the Indonesian context, the opportunity to utilize Class C fly ash in environmentally friendly concrete is substantial due to the availability of high-calcium ash and the urgent need for accelerated infrastructure development. Local studies indicate that Class C fly ash can be effectively used in both cement-based and geopolymer systems, with specific technical challenges such as rapid setting control, sulfate resistance, and mass stability in aggressive environments (Yang et al., 2022; Liu et al., 2021).

Simultaneously, regional energy policy directions imply the need for medium-term strategies to ensure consistent SCM quality and supply. These strategies include optimizing Class C fly ash dosage within realistic ranges, combining it with other SCMs (e.g., slag), and adopting performance-based design approaches verified through mechanical and durability testing (ASEAN Centre for Energy, 2024; NACOE, 2025).

Against this background, the present research entitled "Optimization of Class C Fly Ash Utilization on the Mechanical Properties of Environmentally Friendly Concrete" is designed to map the optimal dosage domain of Class C fly ash that balances compressive strength, splitting tensile/flexural strength, and elastic modulus with a reduced environmental footprint. The study emphasizes the influence of key variables Class C fly ash substitution ratio, w/b ratio, activator or superplasticizer type, and curing regime on mechanical responses and microstructural indicators. Consequently, the outcomes will not only address "how much" Class C fly ash is optimal but also "under which processing conditions" it delivers maximum benefits for low-carbon concrete within local material availability and climatic conditions. With this design, the research is expected to yield data-driven practical recommendations for industry while contributing scientifically to the literature on Class C fly ash optimization in low-emission concrete during the energy transition era (Akbulut et al., 2024; Duan et al., 2025; Jiang et al., 2024).

II. METHODOLOGY AND MATERIALS

An experimental laboratory study was conducted to evaluate the influence of Class C fly ash on the mechanical properties of concrete with a target compressive strength of f'c = 25 MPa. The research methodology was designed to systematically assess the effects of partial cement replacement by Class C fly ash through a structured sequence of material preparation, mixture proportioning, specimen production, mechanical testing, and data analysis. The overall experimental workflow is schematically presented in Figure 1.

The study began with the preparation and characterization of constituent materials, including ordinary Portland cement, Class C fly ash, fine aggregate, coarse aggregate, water, and chemical admixtures where applicable. Cement and fly ash were characterized in terms of physical properties such as specific gravity and fineness, while aggregates were tested for gradation, bulk density, water absorption, and cleanliness to ensure compliance with relevant standards. Particular attention was given to the chemical and physical characteristics of Class C fly ash, especially its calcium oxide content, due to its potential self-cementing behavior and influence on early-age strength development.

Following material characterization, concrete mixture designs were developed for a reference mix targeting f'c = 25 MPa and for several modified mixes incorporating Class C fly ash as a partial replacement of cement by mass. The replacement levels were selected to represent practical substitution ranges commonly reported in the literature, while maintaining a constant water-to-binder ratio to isolate the effect of fly ash content. Adjustments to admixture dosage were made as necessary to achieve comparable workability across all mixtures, ensuring that differences in mechanical performance could be attributed primarily to binder composition rather than fresh concrete variability.

Concrete specimens were then prepared in the laboratory using standardized mixing, casting, and compaction procedures. Fresh concrete was mixed until a homogeneous consistency was achieved, after which workability was assessed using slump testing. The concrete was cast into molds corresponding to the intended mechanical tests, including cylindrical specimens for compressive strength and splitting tensile strength tests, and prismatic specimens for flexural strength evaluation. All specimens were compacted adequately to minimize entrapped air and then covered to prevent moisture loss during the initial setting period.

After demolding, specimens were subjected to controlled curing conditions, typically through water curing at room temperature, to ensure consistent hydration development. Mechanical testing was conducted at designated ages, commonly including early-age and 28-day testing, to capture both the initial and later-stage strength development influenced by Class C fly ash. The primary mechanical properties evaluated included compressive strength, splitting tensile strength, flexural strength, and, where applicable, modulus of elasticity.

The final stage of the study involved systematic data analysis to quantify the effects of Class C fly ash substitution on the mechanical performance of concrete. Test results were statistically evaluated and compared against the reference mixture to identify trends related to strength enhancement or reduction. The analysis also considered the balance between mechanical performance and material efficiency, highlighting substitution levels that maintained or improved strength relative to the control mix. Through this structured experimental approach, the study aimed to provide a clear and reproducible assessment of how Class C fly ash influences the mechanical behavior of environmentally friendly concrete designed for a characteristic strength of 25 MPa.

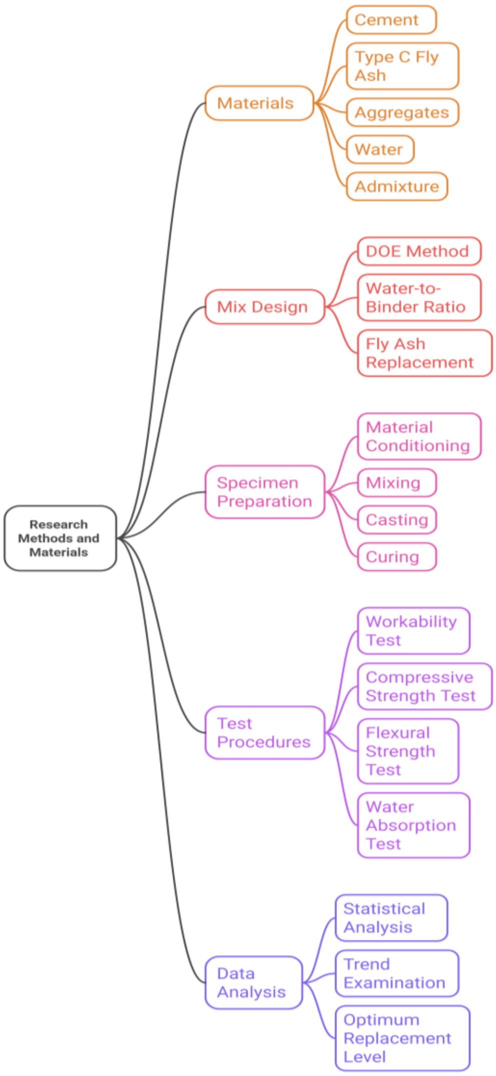

Figure 1. Research Grooves and Concrete Materials with Type C Fly Ash Substitution.

2.1. Material

2.1.1. Cement: Ordinary Portland Cement (OPC) type I as per ASTM C150 standard as the main binding material.

2.1.2. Fly Ash Type C: Fly ash waste from the remaining coal combustion at Steam Power Plants (PLTU), with high CaO levels (>20%) that function as a substitute for part of cement (substitution of 10–30% by weight of cement).

2.1.3. Fine Aggregate: Natural sand comes from local rivers with a maximum size of 4.75 mm and meets the ASTM C33 gradation standard.

2.1.4. Coarse Aggregate: Gravel with a maximum size of 19 mm, hard, clean, and silt-free.

2.1.5. Water: Clean water that qualifies potable

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water used for mixing and curing.

2.1.6. Admixture: Polycarboxylate (PCE)-based superplasticizers are used to improve workability and reduce water requirements without degrading concrete strength.

The selection of type C fly ash is based on its chemical characteristics which are rich in CaO, Al_2O_3, and SiO_2, so that it is able to act as an active pozzolan material that increases the density of concrete microstructures and decreases porosity and permeability.

2.2. Mix Design

The concrete mixture design was determined to achieve a target compressive strength of 25 MPa at 28 days of age by the DOE (Department of Environment Method) method. The water-cement ratio (w/c) was kept constant at 0.5 for all variations. The material composition for 1 m³ of normal concrete (control) is as follows in Table 1.

Table 1. Mix Design Concrete

Materials	Quantity per m³ Concrete
Ordinary Portland Cement	350 kg
Fine Aggregate	750 kg
Coarse Aggregate	1200 kg
Water	175 liters

In this study, type C fly ash replaced some cement in three percentage variations, namely 10%, 20%, and 30% of the cement weight. A mixture without fly ash is used as a control mixture. Substitutions are made based on weight ratios to maintain the consistency of the total binding material.

2.3. Sample Preparation

2.3.1. Preparation of Ingredients: All materials are dried in advance to avoid excess moisture. Fly ash is sifted with a 75 µm sieve to homogenize it.

2.3.2. Mixing: The mixing process is carried out using a mechanical mixer. Fine aggregate, coarse aggregate, and some cement are mixed dry first, then water and superplasticizer are added little by little until homogeneous.

2.3.3. Molding: The mixture is poured into the mold of the cylinder (150 × 300 mm) for the pressure test and the beam (150 × 150 × 600 mm) for the bending test. Compaction is carried out manually as many as 25 times per layer to remove trapped air.

2.3.4. Curing: After 24 hours, the test specimen is removed from the mold and immersed in water at 23 ± 2°C for 28 days to ensure perfect hydration.

2.4. Testing Procedure

2.4.1. Workability Test (Slump Test)

The slump test is carried out based on the ASTM C143 standard to determine the level of workability of fresh concrete at each variation in fly ash content. The decrease in slump value compared to normal concrete shows the effect of fine fly ash particles on the consistency of the mixture.

2.4.2. Compressive Strength Test

Compressive strength tests were performed on 150 mm cube test pieces using a pressure testing machine in accordance with ASTM C39 at 7, 14, and 28 days of age. The compressive strength value is calculated by the formula:

$$f_c' = \frac{P}{A}$$

where:

- f_c' = compressive strength (MPa),
- P = maximum load at the time of failure (N),
- A = Test Strip Cross-Section Area (mm²).

2.4.3. Flexural Strength Test

The bending test was carried out on concrete blocks measuring 150 × 150 × 600 mm using the two-point loading method following ASTM C293. The bending strength is calculated using the equation:

$$f_r = \frac{PL}{bh^2}$$

where:

- f_r = flexural strength (MPa),
- P = applied load at failure (N),
- L = span length (mm),
- b = beam width (mm),
- h = beam height (mm).

2.4.4. Water Absorption and Porosity Test

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To evaluate the level of durability, a water absorption test based on ASTM C642 is carried out. Fly ash is expected to fill micro-pores in concrete, thereby reducing water absorption and increasing resistance to chemical attacks.

2.5. Data Analysis

Data from the test results of compressive strength, flexural strength, and water absorption were statistically processed to compare the effect of variations in fly ash content on the mechanical performance and durability of concrete. The analysis was carried out with:

2.5.1. Compare the mean values between variations against the control,
2.5.2. Calculate performance gains or decreases in percent,
2.5.3. Analyzing the relationship between fly ash content and concrete strength with regression graphs.

IV. RESULTS AND DISCUSSION

4.1. Workability Test

In a study that tested the effect of type C (FA-C) fly ash as a partial cement substitute on the mechanical properties of concrete, one of the tests carried out was slump testing to measure the consistency or softness of the fresh mixture of concrete. In this study, cement was replaced with type C fly ash at various percentages (0%, 10%, 20%, and 30%) with a constant cement moisture content of 0.5. The results of the slump test showed a gradual increase from the control (without substitution) which had a slump value of 90 mm, to a 30% substitution of 105 mm.

This phenomenon illustrates the increase in the softness of the fresh mixture of concrete along with the increase in the substitution rate of type C fly ash. Fly ash, especially type C, is known to have properties that can increase the softness of fresh concrete. This can be explained by the physical characteristics of fly ash which has a smooth, spherical particle shape, which functions as a filler in concrete mixtures. As a filler, type C fly ash fills the empty space in the concrete mixture, reduces friction between aggregate particles and cement, and improves the ease of mixing.

Table 2. The following shows the effect of type C fly ash substitution on slump values at various percentages of substitution. Slump testing is performed on concrete mixtures with a fixed water-cement factor of 0.5 to ensure consistency in testing.

Table 2. Concrete Slump Values with Type C Fly Ash Substitution at Various Percentages

Fly Ash Type C Substitution Percentage (%)	Slump Value (mm)
0%	90
10%	95
20%	100
30%	105

Source : Analysis Results

From the table above, it can be seen that the higher the percentage of type C fly ash substitution, the higher the slump value produced. At the control (without fly ash substitution), the slump value was recorded at 90 mm, which indicates that the concrete mixture is sufficiently viscous and not too soft. This shows that the controlled concrete mixture (without fly ash) has a fairly dense consistency and is not easy to process. However, by replacing some of the cement with type C fly ash, the slump value increases gradually, which reflects the increased softness or workability of the concrete. At 30% substitution, the slump value was recorded at 105 mm, which indicates that the concrete mixture becomes softer and easier to process, thus providing ease in casting and compaction. This increase shows the significant contribution of type C fly ash to the increased ease of processing fresh concrete.

Type C fly ash, which has a smooth and rounded particle shape, plays an important role in increasing the ease of processing fresh concrete (Alterary et al., 2021). These round-shaped fly ash particles act as fillers in concrete mixtures, reducing friction between aggregate particles and cement. According to research conducted by Room, S. et al., (2023), type C fly ash with its fine particle shape can reduce friction between particles in concrete mixtures, thereby increasing the softness of concrete. As a filler, this fly ash also helps to improve the distribution of materials in the mixture, provides a better mixing effect, and ensures that the concrete is more homogeneous and easily cast into the mold.

In addition, the use of type C fly ash can also help reduce the need for other additional materials, such as superplasticizer additives, which are commonly used to improve the workability of concrete. This additive is often used in concrete mixtures that have a thicker composition to achieve higher slump values. By replacing part of the cement with type C fly ash, the concrete can have optimal softness without the need for additional chemicals. Research by Akbulut et al., (2024) shows that partial replacement of cement with type C fly ash can produce concrete that has better workability, reduces dependence on chemical additives, and reduces the environmental impact of excessive use of chemicals.

Type C fly ash itself is known to have higher reactive properties compared to type F fly ash, thanks to its higher calcium oxide content (Win et al., 2022). This type C fly ash has the ability to react with water in the hydration process, contributing to the formation of better hydration products and improving the overall quality of concrete. This is in line with the findings of a study conducted by Da Silva et al., (2022), which states that type C fly ash is more effective in improving the mechanical properties of concrete, especially in terms of the workability and durability of concrete to external factors.

With the increase in the percentage of type C fly ash in the concrete mixture, the slump value increases due to the positive influence of fine particles acting as fillers and improving the distribution of materials in the concrete mixture. Type C fly ash used as a partial replacement material for cement functions as a pozolan material that can improve the quality of fresh concrete mixtures. This increase in slump value also shows that fresh concrete with type C fly ash is easier to mix and cast, which can speed up the construction process in the field (Rao et al., 2023).

In addition, the increased softness obtained through the substitution of type C fly ash in concrete mixtures provides advantages in terms of efficiency. An easier casting process can reduce the likelihood of problems occurring during application, such as uncontrolled shrinkage or uneven compaction, which can affect the strength and durability of concrete. Therefore, the use of type C fly ash is not only beneficial for increasing softness, but also makes a positive contribution to the overall quality of concrete. The test results can be seen in Figure 2.

From Figure 2, it can be concluded that type C fly ash, with its unique physical properties, can improve the softness of concrete mixtures, reduce the need for additives, and contribute to improving the quality of fresh concrete. The substitution of type C fly ash in concrete is not only technically advantageous, but also more environmentally friendly because it reduces the use of cement, which has a significant impact on carbon emissions in the construction industry. The increase in slump values that occur in concrete with the substitution of type C fly ash reflects that concrete is becoming easier to process, more homogeneous and more efficient for use in a wide range of construction applications.

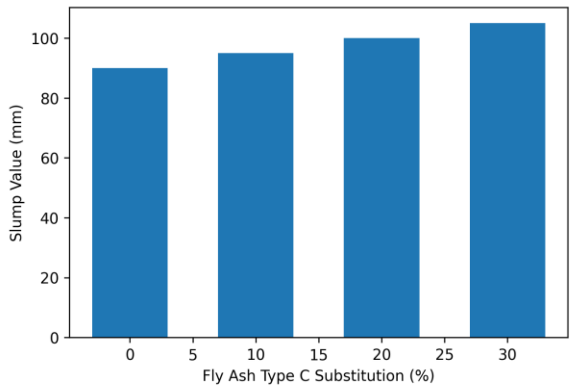

Figure 2. Slump Test Results on Concrete Mixtures with Various Percentages of Type C Fly Ash

4.2. Flexural Strength Test Results

The flexural strength test on concrete is used to measure the ability of concrete to withstand bending or bending when subjected to load. The results of the flexural strength test provide very important information regarding the durability and performance of concrete under various conditions. Based on the table provided, the analysis can be carried out to assess the effect of type C fly ash substitution on the bending strength of concrete at the test age of 7 days, 14 days, and 28 days. The results of the bending strength test can be seen in Table 3.

Table 3. Concrete Bending Strength Test Results with Type C Fly Ash Substitution

Persentase Substitusi Fly Ash Tipe C (%)	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)
0%	3,8	4,5	5,0
10%	4,0	4,7	5,2
20%	4,1	4,9	5,3
30%	3,9	4,6	5,2

Source : Analysis Results

Based on the results seen in Table 3, it can be concluded that the substitution of type C fly ash for the bending strength of concrete tends to show an increase at the age of 7 days and 14 days. However, there was a slight decrease at 28 days of age, especially in the replacement of type C fly ash by 30%. The results of

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the bending strength test can be seen more clearly in Figure 3.

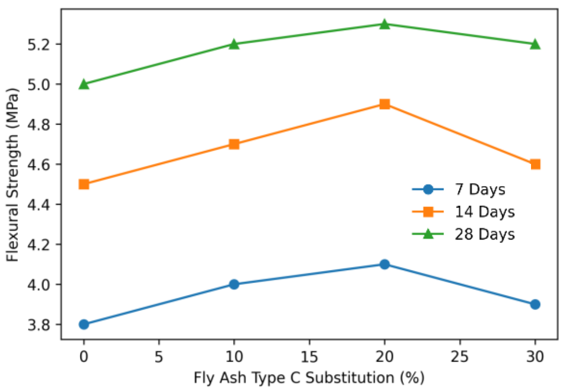

Figure 3. Results of Flexural Strength Test on Concrete Mixtures with Various Percentages of Type C Fly Ash

In the control mixture (without fly ash), the flexural strength at 7 days of age was 3.8 MPa, increased to 4.5 MPa at 14 days of age, and reached 5.0 MPa at 28 days of age. This shows that concrete that does not use fly ash has a stable strength development during the test period. In general, concrete that does not contain fly ash has a higher resistance to bending because there are no additives that reduce the performance of concrete.

At the substitution of type C fly ash by 10%, the flexural strength at 7 days of age is slightly increased to 4.0 MPa. At 14 days of age, the flexural strength increased again to 4.7 MPa, and at 28 days of age, the flexural strength reached 5.2 MPa. This improvement suggests that a 10% substitution of type C fly ash can increase the bending strength of concrete in the initial stages (7 days and 14 days), possibly due to a chemical reaction between type C fly ash and cement components resulting in stronger hydration products. Type C fly ash, which has a high calcium content, is more reactive compared to F-type fly ash, which allows for faster improvement in concrete quality and strength (Gaikwad et al., 2025).

The 20% substitution of type C fly ash showed a further improvement in flexural strength. At 7 days of age, the flexural strength increased to 4.1 MPa, at 14 days of age to 4.9 MPa, and at 28 days of age it reached 5.3 MPa. This increase is higher compared to 10% control and substitution. This shows that at the 20% level, type C fly ash makes a positive contribution to the bending strength of concrete, improving the ability of concrete to withstand bending loads.

At 30% substitution, the flexural strength at 7 days of age decreased slightly to 3.9 MPa, at 14 days of age to 4.6 MPa, and at 28 days of age it remained at 5.2 MPa. Although there was a decrease at 7 days of age, the flexural strength at 28 days of age was not much different compared to the controls. This decrease can be explained by the fact that at higher type C fly ash substitutions, concrete tends to experience more hydration retardation in the early stages, which leads to a decrease in bending strength in the early days. However, at a longer lifespan (28 days), concrete with a 30% substitution of fly ash still showed strength almost equivalent to the control.

Type C fly ash has pozzolan and hydraulic properties that make it possible to react with lime ($Ca(OH)_2$) in concrete mixtures, resulting in stronger calcium silicate hydrate (C-S-H), which increases the strength of concrete over time. Therefore, the higher the substitution of type C fly ash, the greater the amount of hydration products formed, which can improve the strength of concrete in the long run.

However, at higher substitution rates (such as 30%), there is a possibility of a power reduction effect in the early stages due to a slower hydration process, especially at 7 days of age. This slower hydration process leads to a decrease in the initial strength of the concrete. However, at 28 days of age, the positive effects of type C fly ash on the quality of concrete microstructures began to be seen, leading to an increase in bending strength even though it did not reach the control level.

The results of the bending strength test carried out on concrete with the substitution of type C fly ash have significant implications in the application of concrete to structural elements, especially in parts that receive bending loads, such as beams and slabs. This test provides an important picture of the strength of concrete against loads acting in the bending direction, which is one of the key factors in the design of reinforced concrete structures. Although the substitution of type C fly ash in concrete can increase the bending strength at most stages of concrete life,

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there are several factors to consider in optimizing the use of fly ash as a partial cement replacement material in concrete mixtures.

The use of type C fly ash as a partial substitute for cement not only has a positive impact on the strength of concrete, but also contributes to the reduction of the carbon footprint in the construction industry. Fly ash substitution reduces reliance on the use of cement, which is known to be one of the main contributors to CO_2 emissions in concrete production processes. By partially replacing cement with type C fly ash, the amount of CO_2 emitted during the concrete production process can be significantly reduced (Akbulut et al, 2024). This shows that the application of fly ash in concrete mixtures is not only technically advantageous, but also supports sustainability efforts in the construction sector. Therefore, the use of type C fly ash can be seen as a very relevant step to meet the demands of environmentally friendly development, reduce negative impacts on the climate, and create more sustainable concrete.

In general, the results of the bending strength test show that the use of type C fly ash in concrete mixtures can improve the strength of concrete, especially at 14 days and 28 days. At the replacement of type C fly ash by 20%, it is seen that concrete shows the best improvement in bending strength.

This is due to the ability of type C fly ash to act as a filler that can improve the distribution of particles in concrete mixtures, as well as support the formation of better hydration products during the hardening process. At 28 days of age, concrete using type C fly ash with 20% replacement showed higher bending strength compared to control concrete (without fly ash), suggesting that fly ash plays a positive role in improving the quality of concrete microstructures.

Nevertheless, although the use of type C fly ash provides benefits in improving flexural strength at long-term stages, very high substitution, such as at 30%, can cause some challenges. At higher substitution rates, such as 30%, although the bending strength at 28 days of age remains acceptable, in the early stages, particularly at 7 days of age, a decrease in bending strength is seen. This decrease is likely due to the slower hydration process in type C fly ash. The hydration process in higher fly ash tends to be slower compared to cement, which can affect the strength of concrete in the early stages of hardening.

In concrete mixtures that use high amounts of type C fly ash, concrete tends to have a longer hardening time, which has the potential to decrease strength at the initial age (such as at 7 days of age). While this does not reduce the potential strength of concrete in the long run, it is important to consider the balance between short-term and long-term strength when determining the amount of fly ash used in concrete mixtures. Therefore, the use of type C fly ash must consider the material properties and characteristics of the hydration process in order to optimize the strength of concrete both in early life and in old age.

In practical applications, it is important to balance between the short-term strength required for the needs of the concrete structure in the initial construction stage and the long-term strength that supports the durability of the concrete structure after construction is completed. Concrete that relies too heavily on type C fly ash with high substitution may not achieve the desired strength in the early stages, but may perform better in the long run after the hydration process is complete.

Therefore, decisions regarding the percentage of substitution of type C fly ash should be based on a careful analysis of the initial strength requirements and long-term strength for the structure to be built.

Overall, the results of the flexural strength test show that the substitution of type C fly ash in concrete has the potential to increase the strength of concrete, especially at 14 days and 28 days. The 20% substitution of type C fly ash provides the best improvement in flexural strength, while at 30% substitution, despite a slight decrease in the initial stages, the concrete still retains good strength at 28 days of age. The use of type C fly ash not only improves the quality of concrete but also contributes to sustainability efforts in construction. However, it is important to consider the balance between short-term and long-term strengths when using type C fly ash, in

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order to achieve optimal concrete performance according to the needs of the project.

4.3. Compressive Strength Test

Compressive strength tests are one of the important tests in the evaluation of concrete quality. This test is carried out to determine the ability of concrete to withstand the compressive force acting on it without suffering damage or destruction. In this test, hardened concrete is tested by putting a load on the concrete sample until it reaches the point of destruction. The results of compressive strength tests are typically used to assess the bearing capacity of concrete to be used in structural elements that receive compressive loads, such as columns and slabs.

In Table 4, it can be seen that compressive strength testing was performed on various percentages of type C fly ash substitution, namely 0%, 10%, 20%, and 30%. Tests were carried out at 7 days, 14 days, and 28 days to monitor the development of concrete strength over time.

Table 4. Concrete Compressive Strength Test Results with Type C Fly Ash Substitution

Persentase Substitusi Fly Ash Tipe C (%)	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)
0%	15,0	20,0	25,0
10%	14,5	20,5	26,0
20%	14,0	20,8	26,5
30%	13,5	20,0	25,5

Source : Analysis Results

Based on Table 4, above, we can see that although type C fly ash substitution causes a slight decrease in compressive strength at 7 days of age, overall, fly ash substitution provides an increase in compressive strength at 14 days and 28 days of age. Let's discuss further the compressive strength test results on each type C fly ash substitution percentage.

In the control mixture (without fly ash), the compressive strength at 7 days of age was 15.0 MPa. This figure shows that in the early stages of hardening, concrete without fly ash has a fairly good compressive strength. At the age of 14 days, the compressive strength increases to 20.0 MPa, and at the age of 28 days, the concrete reaches the compressive strength of 25.0 MPa. This steady increase indicates that without fly ash substitution, concrete achieves optimal compressive strength at 28 days' lifespan, in line with what is expected for normal-quality concrete.

At 10% replacement of type C fly ash, there was a slight decrease in compressive strength at 7 days of age, to 14.5 MPa, compared to control of 15.0 MPa. However, at 14 days of age, the compressive strength increased to 20.5 MPa and at 28 days of age it reached 26.0 MPa. This suggests that the use of type C fly ash at 10% level can increase the compressive strength of concrete at a later stage (14 and 28 days), although slightly decreasing compressive strength at the initial stage (7 days). Type C fly ash helps improve the performance of concrete in the long run as it contributes to the formation of better hydration bonds at a later stage.

At 20% substitution, the compressive strength of the concrete at 7 days of age decreases slightly to 14.0 MPa. However, at 14 days of age, the compressive strength increased to 20.8 MPa and at 28 days of age it reached 26.5 MPa. This shows that replacing cement with type C fly ash at a rate of 20% gives positive results in increasing the strength of concrete at longer stages. The compressive strength recorded at 28 days of age was higher compared to the controls, suggesting that type C fly ash plays a role in improving the structural strength of concrete in the long term.

At 30% replacement of type C fly ash, the compressive strength at 7 days of age was slightly lower (13.5 MPa) compared to 10% and 20% substitution. However, at 14 days of age, the compressive strength was still recorded at 20.0 MPa, and at 28 days of age, the compressive strength was 25.5 MPa. The compressive strength at 28 days was almost equivalent to that of control, although there was a decrease at 7 days of age. The decrease in compressive strength at this early stage may be due to the slower hydration process in the type C fly ash, leading to a decrease in the initial strength of the concrete. However, at a later stage of life, type C fly ash shows a positive contribution to the increase in concrete strength.

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Fly ash type C is a pozzolan material that has a high calcium content, which can react with lime ($Ca(OH)_2$) in concrete to form calcium silicate hydrate (C-S-H), a hydration product that increases the strength of concrete. In Figure 5. Results of Flexural Strength Test on Concrete Mixtures with Various Percentages of Type C Fly Ash.

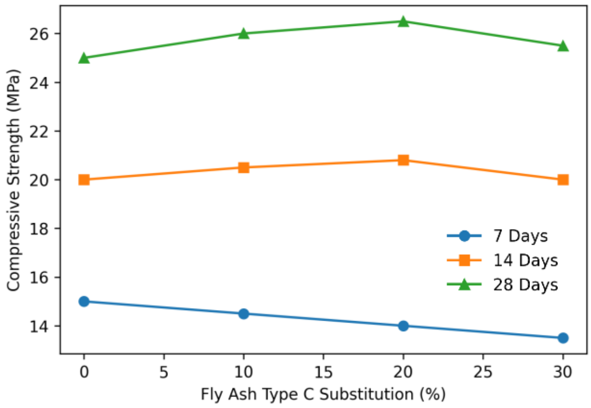

Figure 4. Compressive Strength Test Results on Concrete Mixtures with Various Percentages of Type C Fly Ash

However, although type C fly ash can increase the strength of concrete in the long run, the use of type C fly ash can slow down the hydration process in the early stages due to lower reactivity in the first days (Akmalaiuly et al., 2022; Ge et al., 2022). This is due to the fact that type C fly ash, despite being high in calcium, has a slower reactivity compared to regular cement. At higher substitutions, such as 30%, concrete tends to experience a decrease in compressive strength in the initial stage (7 days). This may be an important consideration in concrete applications that require high initial strength, especially in constructions that require rapid drying or hardening. However, although compressive strength in the initial stages is slightly reduced, the use of type C fly ash provides significant long-term benefits. Concrete containing type C fly ash shows increased strength at 28 days of age, with the ability to achieve higher structural resistance.

The substitution of type C fly ash also contributes to the improvement of concrete durability, i.e. its resistance to external factors that can affect its quality and durability, such as chemical attack, freeze-thaw cycles, and moisture fluctuations. C-type fly ash, with its fine particles, has the ability to fill the empty space between cement particles and aggregates. This increases the density of concrete, reduces porosity, and in turn increases resistance to water penetration and harmful chemicals. By increasing the density of concrete microstructures, type C fly ash helps slow down the degradation process of concrete due to harsh environments, making concrete more resistant to structural damage in the long term. This makes it an excellent choice for concrete applications exposed to extreme environmental conditions.

4.4. Water Absorption and Porosity Test

Water absorption and porosity tests are one of the important tests in the evaluation of concrete quality. This test is carried out to determine the ability of concrete to absorb water and its porosity level, which can affect the durability and performance of concrete. In this test, a hardened concrete sample is tested by measuring the amount of water that can be absorbed by the concrete in a certain period of time. The results of water absorption and porosity tests are typically used to assess the resistance of concrete to moisture and other external factors, as well as to determine the suitability of concrete in structural elements exposed to humid or wet environmental conditions.

Table 5. Effect of Type C Fly Ash Substitution on Water Absorption and Porosity

Substitusi Fly Ash (%)	Water Absorption (%)	Porosity (%)
0%	6.0	13.5
10%	5.7	12.8
20%	5.3	12.0
30%	5.0	11.5

Table 1 presents the results of a study on the effect of Class C fly ash substitution on the water absorption and porosity of concrete. This research was conducted to evaluate the extent to which fly ash replacement in concrete influences durability-related properties, particularly water absorption and porosity, which are critical indicators of concrete resistance to water ingress, permeability, and deterioration caused by wet–dry cycles as well as other aggressive

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environmental conditions. Class C fly ash was used as a partial replacement of cement at varying proportions of 0%, 10%, 20%, and 30% by mass. The results illustrate a clear relationship between the level of fly ash substitution and changes in the physical characteristics of the concrete (Alterary et al., 2021). In general, moderate fly ash contents tend to refine the pore structure through filler and pozzolanic reactions, thereby reducing porosity and water absorption. However, at higher replacement levels, an increase in porosity may occur due to dilution effects and slower hydration. These findings highlight the importance of optimizing fly ash content to enhance concrete durability without compromising overall performance. Figure 5 shows.

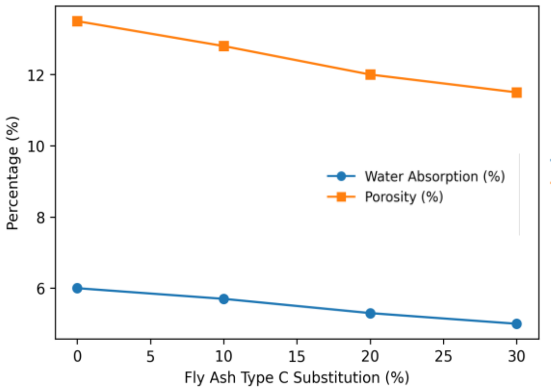

Figure 5. Results of Water Absorption and Porosity Test in Concrete Mixture with Various Percentages of Type C Fly Ash

In Figure 5, it can be seen that 0% fly ash substitution (control) results in a water absorption value of 6.0%. This figure reflects the rate of water absorption of concrete using pure Portland cement. Portland cement has a tendency to produce concrete structures with greater porosity, making it easier to absorb water. However, when type C fly ash is used as a substitution, concrete water absorption decreases at each substitution level (Huang et al., 2021).

With the substitution of 10% fly ash, water absorption drops slightly to 5.7%. This decrease is due to the fact that fly ash has the ability to fill pores in concrete, reducing the empty space that can absorb water. By increasing the amount of fly ash to 20%, water absorption is further reduced to 5.3%. This further decline suggests that fly ash further improves the concrete microstructure, reduces porosity, and thus reduces concrete's ability to absorb water.

At 30% fly ash substitution, water absorption drops to 5.0%. Although this decrease is less compared to the 20% substitution, it still shows that fly ash has a positive effect in decreasing water absorption. This decrease in water absorption is important because concrete that is denser and less water-absorbing has better resistance to damage due to environmental factors such as freezing, drying, and wet-dry cycles. Concrete with low water absorption tends to be more resistant to strength degradation over time (Chen et al., 2021).

The porosity of concrete is directly related to the level of strength and durability of the concrete. Concrete with high porosity has more empty space within its matrix, which can affect the strength of the concrete and its resistance to damage. Reduced porosity indicates increased concrete density and potential increased resistance to water and chemical damage (Sánchez et al., 2024)

Based on Table 1, the porosity of the control concrete is 13.5%. This shows that concrete with 100% Portland cement has a lot of pore spaces, which makes concrete more susceptible to damage due to water and chemical penetration from the environment. However, with type C fly ash substitution, there is a decrease in porosity at each level of fly ash substitution (Juanir et al., 2024).

At 10% fly ash substitution, the porosity drops to 12.8%. Although this decrease is not very large, it does indicate that fly ash is starting to fill the pore spaces in the concrete, which increases the density of the concrete and reduces the space for water penetration. With the substitution of 20% fly ash, the porosity is further reduced to 12.0%. This decrease shows that the more fly ash is used, the more pore space is filled, increasing the density of concrete and reducing the dependence of concrete on Portland's cement microstructure (Park et al., 2021).

At 30% fly ash substitution, the porosity drops to 11.5%. Although there was a slight decrease compared to the 20% fly ash, this value was still lower than the control, which suggests that fly ash plays an important role in repairing concrete microstructures. This reduction in porosity also indicates that concrete with fly ash substitution is denser and more resistant to damage due to water absorption and other environmental factors.

V. CONCLUSIONS AND SUGGESTIONS

5.1 Conclusion

Based on the results of the tests carried out, the use of type C fly ash as a substitute for some cement in

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concrete mixtures has a positive impact on various mechanical properties and durability of concrete. Increased fly ash content in concrete mixtures consistently improves the workability or softness of concrete, which simplifies the mixing and casting process. The use of type C fly ash also contributes to a decrease in water absorption and porosity of concrete, which directly increases the resistance of concrete to damage due to moisture and extreme environmental factors. In the compressive strength test, although there was a slight decrease in the initial stage (7 days) in all variations of fly ash substitution, a significant increase in compressive strength was recorded at 14 days and 28 days of age. The 10% and 20% substitution of type C fly ash showed an increase in compressive strength at 28 days of age, which exceeded that of control concrete (without fly ash), with the achievement of compressive strength of 26.0 MPa and 26.5 MPa respectively at 28 days of age. On the other hand, the 30% substitution showed a compressive strength similar to the control at 28 days of age, although there was a decrease at 7 days of age. The results of the flexural strength test also showed an improvement at 14 days and 28 days of age, although a slight decrease at 7 days of age especially at 30% substitution. The use of type C fly ash makes a positive contribution to the bending strength of concrete, which is essential for applications in structural elements that are subject to bending. The 20% substitution of type C fly ash provides the best results with the highest flexural strength at 28 days of age. In addition, water absorption and porosity testing showed that type C fly ash can improve the microstructure of concrete, reduce water absorption, and lower porosity. This has implications for increasing the resistance of concrete to damage due to chemical attack and freeze-thaw cycles, which increases the overall durability of concrete. Overall, the use of type C fly ash in concrete mixtures can improve long-term strength and resistance to external factors, as well as contribute to the reduction of carbon footprint, making it a good choice for environmentally friendly concrete in the construction sector.

5.2 Suggestions

Dose Optimization of Type C Fly Ash: This study shows that a substitution of type C fly ash of 20% provides the best results in compressive strength and bending. Therefore, it is recommended to optimize the dose of type C fly ash in the range of 10–20% to achieve a balance between strength, durability, and cost efficiency in environmentally friendly concrete applications.

Hydration Process Control: Given that type C fly ash can slow down hydration in the early stages, it is recommended to pay attention to strict control of the water-to-cement ratio (w/c) as well as the use of superplasticizer additives in concrete mixtures with high fly ash doses to ensure optimal mechanical performance in the early stages of hardening.

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