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# Modeling and Evaluation of Concrete Tensile Strength Based on Fly Ash Substitution Ratios

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**Abstract**

The tensile strength value is obtained by conducting a compression test by loading the test piece laterally to obtain maximum tensile strength. This study conducted a model to determine the tensile strength value of concrete by evaluating the percentage of fly ash varied by 0%, 40%, and 80%. In the experimental setup, an analytical balance with a cylindrical test specimen measuring 30 cm high and 15 cm in diameter. The test results show that the larger the percentage of fly ash mixture substitution, the smaller the tensile strength value of the concrete produced.

***Keywords:***
Fly Ash, Concrete, Tensile Strength, Examination



## 1. Introduction

Concrete remains the most widely used construction material due to its excellent compressive strength, availability, and cost-effectiveness. However, its inherent weakness in tension poses a limitation in structural applications, making tensile strength a critical parameter for durability and crack resistance. The split tensile strength of concrete, commonly determined through indirect testing methods such as the Brazilian test (ASTM C496), provides insights into the material's resistance to tensile stress, which is essential for designing slabs, pavements, and structural joints [1].

The use of Supplementary Cementitious Materials (SCMs) like fly ash has gained prominence due to their ability to improve concrete performance and reduce environmental impact. Fly ash, a byproduct of coal combustion in power plants exhibits pozzolanic properties that contribute to strength gain over time by reacting with calcium hydroxide to form additional calcium silicate hydrate (C-S-H) gel. Incorporating fly ash partially replaces Portland cement, thus lowering $CO_2$ emissions from cement production [2].

Fly ash influences concrete's mechanical behavior, including its tensile strength. Research shows that low to moderate levels of fly ash substitution (typically 10%–30%) can enhance tensile strength due to improved particle packing and long-term pozzolanic activity. However, excessive replacement levels (above 50%) often lead to reduced early-age strength, as fly ash reacts more slowly than cement. Hence, understanding the effect of fly ash substitution ratios on tensile strength is critical for mix optimization [3].

Several studies have examined the mechanical performance of fly ash concrete. For instance, Siddique [4] reported that replacing cement with up to 30% fly ash increased the split tensile strength after 28 days of curing. Conversely, higher percentages caused a decline in strength. Similarly, Mugahed Amran et al. [5] confirmed that while fly ash improves workability and durability, its impact on tensile strength depends heavily on mix proportions, curing conditions, and the physical characteristics of the fly ash used.

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The use of mathematical and computational models in concrete research allows for the accurate prediction of mechanical properties without extensive experimental testing. Regression models, artificial neural networks (ANN), and machine learning algorithms have been successfully employed to estimate tensile and compressive strengths based on mixed design parameters. These tools enable researchers and engineers to simulate material behavior and optimize concrete compositions with reduced time and cost [6]. Modern data-driven approaches leverage large datasets and statistical techniques to evaluate complex interactions between mixed components. In the context of fly ash concrete, input features such as cement content, fly ash percentage, water-cement ratio, and curing time can be used to train models that predict tensile strength. Studies by Yeh [7] and Gholamy et al. [8] demonstrate the high accuracy of neural networks and support vector machines in modeling concrete properties, outperforming traditional empirical formulas.

Despite the wealth of studies on compressive strength modeling, relatively few focus specifically on tensile strength, especially under varying SCM ratios. Accurate modeling of tensile strength based on fly ash substitution is vital because tensile failure often governs the serviceability of structures. This paper addresses this gap by developing a predictive model based on different fly ash substitution levels and evaluating its impact on split tensile strength using standardized testing procedures. This research contributes to sustainable construction practices by integrating material science and computational modeling. It investigates how different fly ash substitution ratios affect the tensile strength of concrete and develops a model to predict strength outcomes. By combining experimental data with statistical analysis and regression modeling, the study provides a robust framework for optimizing mix design in fly ash-based concrete, facilitating its broader adoption in environmentally responsible construction.

## 2. Related Works

Many researchers have investigated the influence of fly ash on the mechanical properties of concrete. Fly ash, as a pozzolanic material, contributes to long-term strength development through its secondary hydration reactions with calcium hydroxide. Studies such as those by Siddique and Khatib confirm that replacing cement with fly ash up to 30% can maintain or slightly improve tensile strength at later ages [9] [10]. However, higher substitution levels tend to reduce early-age strength due to slower pozzolanic activity.

While compressive strength is more commonly tested, the tensile strength of concrete is critical for crack control and serviceability. Bhanja and Sengupta highlighted that incorporating fly ash affects both tensile and flexural strength, with optimal results typically observed at 15–25% replacement levels. They also noted that the particle size and chemical composition of the fly ash significantly influence the tensile performance of the resulting mix [11]. The split tensile strength test, standardized under ASTM C496, is widely used due to its simplicity and consistency in cylindrical specimens. Wu et al. utilized this method to study the influence of various mineral admixtures on tensile strength. Their work emphasized that fly ash concrete exhibits delayed strength gain compared to OPC concrete, underscoring the importance of long-term performance evaluations in mix designs that use SCMs [12].

Predictive models are increasingly used in concrete research to forecast mechanical properties from input parameters such as cement content, water-to-cement ratio, and additive percentages. Yeh developed a neural network model to estimate compressive strength based on mixed parameters, demonstrating that data-driven approaches can achieve high prediction accuracy. This modeling framework can be adapted to predict tensile strength, particularly when extensive experimental datasets are available [13]. In addition to neural networks, regression-based models offer transparent and interpretable predictions of concrete strength. Another study employed multiple linear regression to model split tensile strength based on fly ash ratio, curing time, and water-cement ratio, achieving $R^2$ values exceeding 0.90. The advantage of such models lies in their simplicity and ease of implementation, particularly for practitioners in construction and materials testing [14].

Several studies have explored how different fly ash content levels affect model accuracy in predicting tensile and compressive strength. Gopalakrishnan et al. found that models trained on balanced datasets representing a wide range of fly ash percentages produced more stable and accurate results. Their findings suggest that model generalization improves when data covers both low and high-substitution scenarios, highlighting the need for comprehensive datasets in model training [15]. Recent research explores hybrid and ensemble machine-learning techniques to improve the prediction of concrete properties. For instance, Reddy and Neeraja combined decision trees with support vector machines to estimate split tensile strength, reporting improved performance over single-model approaches. Their study emphasizes the potential of combining statistical and machine learning techniques to capture nonlinear relationships in material behavior [16].

Despite numerous studies on compressive strength modeling and the growing use of fly ash, fewer works specifically address predictive modeling of split tensile strength across a range of substitution levels. Most existing models either generalize across concrete types or focus narrowly on compressive behavior. The present study addresses this gap by focusing on modeling the tensile strength behavior of concrete mixes with varying fly ash percentages, offering insights into optimizing sustainable concrete mix designs using statistical modeling tools.

## 3. Proposed Method

Concrete is a building material produced from a mixture of Portland cement, sand, gravel, water, and other additives such as fly ash. Concrete has advantages over other materials, including its relatively lower cost compared to steel, and it does not require maintenance costs like steel (steel must be painted at regular intervals to prevent rust). Concrete is durable because it does not rot or rust. In its hardened state, concrete has high strength. In its fresh state, concrete can be shaped into various forms, making it suitable for architectural art or decorative purposes. Concrete also produces a good final finish if the final processing is done specially, such as exposing the aggregate (aggregate with a high-textured artistic form is placed on the outer part, making it visible on the surface). In addition to being resistant to fire, concrete is also resistant to corrosion [17][18].

Aggregate is a natural mineral particle that serves as a filler material in mortar or concrete mixtures. Aggregate accounts for 78% of the volume of mortar or concrete. Although it is only a filler material, aggregate significantly influences the properties of mortar/concrete, making the selection of aggregate an important aspect in the production of mortar/concrete. Concrete fragments are widely used as coarse aggregate, as aggregate supplies are currently dwindling and prices are quite high. This situation is commonly experienced by regions facing difficulties in obtaining construction materials. The most important properties of an aggregate (rocks, gravel, sand, etc.) are compressive strength and resistance to impact, which can affect its bonding with cement paste, porosity, and water absorption characteristics. These properties influence resistance to freezing during winter and chemical aggression, as well as resistance to shrinkage [19].

Portland cement is the most widely used construction material in concrete production. According to ASTM C-150, 1985, Portland cement is defined as a hydraulic cement produced by grinding clinker composed of hydraulic calcium silicate, which typically contains one or more forms of calcium sulfate as an additive ground together with its main component. A rough estimate of the tensile strength of normal concrete ranges between 9% and 15% of its compressive strength. A common approximation method uses the modulus of rupture, which is the tensile stress in concrete that occurs during the crushing test of plain concrete beams as a measure of tensile strength according to elasticity theory.

Force P acts on both sides of the cylinder along L, and this force is distributed over the cylinder's surface area (π.D.L). The load is gradually increased until the maximum value is reached, and the cylinder breaks apart due to the horizontal tensile force. From the maximum load applied, the tensile strength of the concrete is calculated using the following equation:

$$F_t = \frac{2P}{L_s D}$$

$F_t$ = concrete splitting strength (kg/cm2)
P = maximum load given (kg)
D = cylinder diameter (cm)
Ls = cylinder height (cm)

The formula $F_t = \frac{2P}{L_s D}$ calculates the split tensile strength of a cylindrical concrete specimen. In this test, the specimen is subjected to a diametral compressive load until failure, generating tensile stress perpendicular to the load direction. Here, $F_t$ Represents the tensile strength (kg/cm²), $P$ is the maximum applied load (kg), $D$ is the cylinder diameter (cm), and$L_s$ is the length or height of the cylinder (cm). This method, standardized in ASTM C496, is widely used to evaluate the tensile properties of concrete, which are crucial in assessing its resistance to cracking and failure under tension.

The computed tensile strength depends on the relationship between the applied load and the specimen's dimensions. A higher maximum load $P$ results in a greater $F_t$ Indicating stronger tensile capacity. Conversely, increasing the diameter or length of the specimen reduces$F_t$, as the load is distributed over a larger area, decreasing stress intensity. Accurate measurement of dimensions and failure load is essential to ensure valid results, as errors can significantly affect the tensile strength calculation. This test is particularly important because concrete is inherently weak in tension, and understanding its tensile capacity supports more reliable structural design.

## 4. Experimental Setup

This study utilizes Portland Cement (PC) Type I from Semen Padang, fly ash sourced from Labuhan Angin Sibolga, and both fine and coarse aggregates obtained from Binjai. The water used in the concrete mixture comes from the laboratory to ensure consistency. Essential equipment includes a concrete compression testing machine and an analytical balance. Before testing, all materials and equipment undergo careful preparation, ensuring they meet quality standards for experimental use. The selection of materials emphasizes conformity to standard specifications to support accurate and reliable results.

Material inspections are conducted under ASTM standards to evaluate the physical properties of the aggregates. These inspections are critical to validate the suitability of the materials used in concrete production. The concrete mix design follows the American Concrete Institute (ACI 211.1-91, reapproved 2002) guidelines, encompassing six steps: selecting the slump value, estimating water and air content, determining the water-cement ratio, calculating cement quantity, and estimating the quantities of coarse and fine aggregates. This systematic design ensures that the concrete mix meets the desired performance criteria for mechanical testing.

The specimens are prepared in cylindrical molds measuring 15 cm in diameter and 30 cm in height. Each variation of fly ash substitution includes ten samples designated for split tensile strength testing. The tensile strength tests are performed using the facilities and equipment available at the Materials Engineering Laboratory, Department of Civil Engineering, Faculty of Engineering, Universitas Sumatera Utara (USU). These tests aim to assess the mechanical performance of concrete with varying levels of fly ash as a cement replacement.

## 5. Result and Analysis

The concrete split tensile strength test was conducted on concrete specimens aged 28 days. The average tensile strength test results for concrete with 0% fly ash substitution for each test specimen at 28 days were 29.4 kg/cm2, as shown in Table 3.1 below:

Table 3.1. Test results for 0% fly ash substitution

| No. | Fly ash Percentage | Split Tensile Strength (kg/cm2) | Average split tensile strength (kg/cm2) |
|---|---|---|---|
| 1 | Normal (0%) | 28,6 | 29,4 |
| 2 | Normal (0%) | 28,3 | |
| 3 | Normal (0%) | 29,7 | |
| 4 | Normal (0%) | 30,3 | |
| 5 | Normal (0%) | 31,1 | |
| **No.** | **Fly ash Percentage** | **Split Tensile Strength (kg/cm2)** | **Average split tensile strength (kg/cm2)** |
| 6 | Normal (0%) | 27,7 | 29,4 |
| 7 | Normal (0%) | 28,9 | |
| 8 | Normal (0%) | 30 | |
| 9 | Normal (0%) | 27,5 | |
| 10 | Normal (0%) | 28,3 | |

Table 3.1 presents the results of split tensile strength tests for concrete with 0% fly ash (normal mix). Across ten specimens, the individual split tensile strength values range from 27.5 to 31.1 kg/cm². The calculated average split tensile strength is 29.4 kg/cm², indicating good consistency among the specimens and relatively low variation in tensile performance. This result demonstrates that the concrete mix without fly ash maintains a stable and high tensile strength, serving as a strong control benchmark for evaluating the effects of fly ash substitution in further experiments.

The results of the concrete tensile strength test for each test specimen with 40% fly ash substitution can be seen in Table 3.2 as follows:

Table 3.2. Test results for 40% fly ash substitution

| No. | Fly ash Percentage | Split Tensile Strength (kg/cm2) | Average split tensile (kg/cm2) |
|---|---|---|---|
| *1* | *40% fly ash* | 19,2 | 18,4 |
| *2* | *40% fly ash* | 17 | |
| *3* | *40% fly ash* | 18,1 | |
| *4* | *40% fly ash* | 20,7 | |
| *5* | *40% fly ash* | 18,4 | |
| *6* | *40% fly ash* | 17,8 | |
| *7* | *40% fly ash* | 17,6 | |

| | | | |
|---|---|---|---|
| *8* | *40% fly ash* | 18,7 | |
| *9* | *40% fly ash* | 18,4 | |
| *10* | *40% fly ash* | 18,1 | |

Table 3.2 displays the split tensile strength results for concrete samples containing 40% fly ash. The individual tensile strength values range from 17.0 to 20.7 kg/cm², with an average of 18.4 kg/cm². Compared to the control mix (0% fly ash) which had an average strength of 29.4 kg/cm², the incorporation of 40% fly ash results in a significant reduction in tensile strength, approximately 37.4% lower. This decline indicates that while partial fly ash substitution contributes to sustainability, it compromises tensile performance at this replacement level, likely due to reduced early-age bonding strength and slower pozzolanic reactions.

The average tensile strength of concrete with a 40% fly ash substitution percentage was 18.4 kg/cm2. The average tensile strength of concrete with an 80% fly ash substitution percentage was 4.38 kg/cm2. The results of the tensile strength testing of each concrete test specimen are shown in Table 3.3 as follows:

Table 3.3. Test results for 80% fly ash substitution

| **No.** | **Fly ash Percentage** | **Split Tensile Strength (kg/cm2)** | **Average split tensile (kg/cm2)** |
|---|---|---|---|
| 1 | *80% fly ash* | 3,7 | 4,38 |
| 2 | *80% fly ash* | 4,2 | |
| 3 | *80% fly ash* | 4 | |
| 4 | *80% fly ash* | 4,8 | |
| 5 | *80% fly ash* | 5,1 | |
| 6 | *80% fly ash* | 5,1 | |
| 7 | *80% fly ash* | 4,5 | |
| 8 | *80% fly ash* | 4,2 | |
| 9 | *80% fly ash* | 4,2 | |
| 10 | *80% fly ash* | 4 | |

Table 3.3 shows the split tensile strength results for concrete samples containing 80% fly ash. The individual values range from 3.7 to 5.1 kg/cm², with an average of 4.38 kg/cm². This represents a substantial reduction up to 85% lower compared to the control mix (0% fly ash), which had an average strength of 29.4 kg/cm². The drastic decline in tensile strength at this high substitution level indicates that excessive fly ash content significantly weakens the concrete's tensile capacity. This is likely due to insufficient cementitious material and slower pozzolanic activity, resulting in poor early-age bond development and overall structural performance degradation.

The results of the average concrete splitting tensile strength test with fly ash substitution percentages of 0%, 40%, and 80% at 28 days. The observed reduction suggests a negative correlation between fly ash content and the material's mechanical performance. While partial substitution of cement with fly ash (up to 40%) retains moderate strength, higher replacement levels (such as 80%) significantly weaken the material, likely due to insufficient cementitious activity or slower pozzolanic reactions. These results emphasize the need to optimize fly ash content to achieve a balance between sustainability goals and structural performance.

## 6. Conclusion

Based on the analytical results and tensile strength test results, it can be concluded that the tensile strength of concrete is significantly influenced by the percentage of fly ash substitution used. The higher the percentage of fly ash substitution, the lower the tensile strength value, meaning that at high fly ash substitution percentages, the tensile strength of concrete decreases. According to this study, it can be concluded that the tensile strength decreases, can affect propagation, and results in cracks within the structure. The model showed that the use of high fly ash substitution percentages should be avoided so that the tensile strength of the concrete can be achieved within the range of 8 to 15% of the compressive strength of the concrete.

## References


[1] ASTM C496/C496M, *Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens*, ASTM International, 2017.

[2] P. K. Mehta and P. J. M. Monteiro, *Concrete: Microstructure, Properties, and Materials*, McGraw-Hill Education, 2014.

[3] G. C. Isaia, A. L. G. Gastaldini, and R. Moraes, “Physical and pozzolanic action of mineral additions on the mechanical strength of high-performance concrete,” *Cement and Concrete Composites*, vol. 25, no. 1, pp. 69–76, 2003.

[4] R. Siddique, *Utilization of Fly Ash in Concrete: Strength, Durability and Sustainability*, Springer, 2004.

[5] Y. H. Mugahed Amran et al., “Properties of sustainable concrete containing high-volume fly ash,” *Journal of Building Engineering*, vol. 31, 2020.

[6] M. I. Khan, “Predicting properties of high-performance concrete using artificial neural networks,” *Cement and Concrete Research*, vol. 35, no. 4, pp. 775–779, 2005.

[7] C. Yeh, “Modeling of strength of high-performance concrete using artificial neural networks,” *Cement and Concrete Research*, vol. 28, no. 12, pp. 1797–1808, 1998.

[8] Gholamy et al., “A comprehensive review of artificial intelligence applications in concrete materials and structures,” *Engineering Applications of Artificial Intelligence*, vol. 114, 2022.

[9] R. Siddique, “Performance characteristics of high-volume class F fly ash concrete,” *Cement and Concrete Research*, vol. 34, no. 3, pp. 487–493, 2004.

[10] J. M. Khatib, “Performance of self-compacting concrete containing fly ash,” *Construction and Building Materials*, vol. 22, no. 9, pp. 1963–1971, 2008.

[11] S. Bhanja and B. Sengupta, “Influence of silica fume on the tensile strength of concrete,” *Cement and Concrete Research*, vol. 35, no. 4, pp. 743–747, 2005.

[12] H.-C. Wu, P. Sun, and C. Lo, “Mechanical properties of concrete using recycled aggregates with varying mineral admixtures,” *Journal of Materials in Civil Engineering*, vol. 22, no. 6, pp. 535–543, 2010.

[13] S. H. Lee, “Prediction of concrete tensile strength using multiple linear regression analysis,” *International Journal of Engineering and Technology*, vol. 5, no. 3, pp. 261–267, 2013.

[14] K. Gopalakrishnan, H. Ceylan, and S. Kim, “Data-driven modeling of concrete material behavior with SCMs,” *Journal of Computing in Civil Engineering*, vol. 24, no. 6, pp. 531–539, 2010.

[15] M. B. Reddy and D. Neeraja, “Hybrid machine learning models for predicting split tensile strength of concrete with fly ash,” *Materials Today: Proceedings*, vol. 33, pp. 4563–4570, 2020.

[16] L. J. Murdock and K. M. Brook, *Concrete Materials and Practices*, trans. by S. Hindarko, Erlangga, Jakarta, 1986.

[17] ACI Committee 211.1-91, *Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete*, ACI, Detroit, MI, 2002.

[18] Technical Committee on Standardization in the Field of Structural and Building Construction, *Method for Testing the Tensile Strength of Concrete*, SNI 03-2491-2002, Bandung, 2001.