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The Effect of Silica Fume Pozzolan Percentage as a Partial Cement Substitution on Concrete Compressive Strength

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ABSTRACT: This research aims to investigate the effect of varying percentages of pozzolanic silica fume on the compressive strength of normal concrete at the age of 28 days. Cube specimens with dimensions of 15 cm × 15 cm × 15 cm were tested using a compression testing machine with a capacity of 2000 kN. The variations of silica fume addition used were 0.05%, 0.10%, and 0.15% by cement weight, and the results were compared to control concrete without any silica fume. The findings indicate that the addition of silica fume significantly affects the compressive strength of concrete. Concrete with 0.05% silica fume achieved an average compressive strength of 56.319 MPa, higher than that of the control concrete. The optimum result was obtained at 0.10% addition, reaching 56.744 MPa, which marked the highest strength in this study. However, the addition of 0.15% silica fume resulted in a lower compressive strength of 55.559 MPa, likely due to poor homogeneity in the mixture and the formation of clumps of silica fume. It can be concluded that the use of silica fume as an additive improves the quality of concrete when applied in the proper proportion, with 0.10% being the most effective dosage. This study highlights the importance of mix proportioning and homogeneity in maximizing the benefits of silica fume to enhance concrete compressive strength.

KEYWORDS: Concrete, Silica Fume, Compressive Strength, Pozzolanic, Additive.

INTRODUCTION

Natural disasters such as volcanic eruptions, earthquakes, floods, and the Lapindo Brantas mudflow tragedy in Sidoarjo have caused significant material and non-material losses. However, these catastrophic events also present opportunities for the reutilization of residual construction materials with pozzolanic properties, such as crushed bricks, tiles, and other materials containing reactive silica. The recycling of such materials offers an innovative solution that supports the development of sustainable construction material technologies.

In the context of national development, Indonesia heavily relies on cement as a primary construction material. The demand for cement has surged in tandem with economic growth and the extensive infrastructure development, including ports, reservoirs, toll roads, and maritime highway projects. This situation necessitates an abundant supply of construction materials that not only meet quantitative demands but also exhibit superior quality to ensure the success of government-led infrastructure initiatives.

Although commercially available cement fulfills basic construction requirements, the demand for higher-quality concrete is increasing. Consequently, research into alternative supplementary materials or partial cement substitutes is essential to produce concrete with enhanced performance. One promising material is silica fume, a pozzolanic material recognized for its effectiveness in improving concrete quality.

Silica fume does not possess identical properties to cement. However, when combined with lime and water in specific proportions, it forms a mass with cement-like characteristics. This phenomenon occurs due to the reactive silica and alumina content in silica fume, which interact with calcium hydroxide produced during cement hydration to form calcium silicate hydrate (C-S-H). This compound significantly strengthens the concrete structure.

The benefits of incorporating silica fume into concrete mixtures are well-documented. It enhances compressive strength, reduces permeability, and improves resistance to sulfate attack. According to Bagus et al., the durability of concrete is a critical factor in construction, as concrete must withstand aggressive environmental conditions to ensure long-term performance.

The influence of silica fume on concrete occurs through two primary mechanisms: physical and chemical. Physically, the ultrafine particles of silica fume fill microvoids within the concrete matrix, thereby increasing its density. Chemically, its pozzolanic properties enable a secondary reaction with calcium hydroxide, improving the bonding between different phases in the concrete.

A significant advantage of silica fume is its ability to strengthen the transition zone, the thin layer between hydrated cement paste and aggregate. This zone is typically the weakest and most permeable part of concrete. The addition of silica fume enhances the quality of the transition zone, substantially reducing permeability.

Concrete permeability is a crucial determinant of its resistance to the penetration of liquids and aggressive ions. Low-permeability concrete is more resistant to environmental degradation and has a longer service life. Thus, silica fume not only enhances the compressive strength of concrete but also significantly contributes to the long-term durability of structures.

Based on the above discussion, this study focuses on evaluating the effects of varying percentages of silica fume as a partial cement substitute on the compressive strength of concrete. The findings are expected to contribute to the development of high-quality concrete technologies that support national infrastructure needs while addressing challenges related to cement usage efficiency in the construction industry.

RESEARCH METHODOLOGY

This study adopts a quantitative approach underpinned by a deductive-inductive theoretical framework. The initial phase of the research involves a comprehensive review of existing theories developed by experts concerning the use of silica fume as a partial cement substitute. These theories serve as the foundation for formulating hypotheses, which are subsequently tested through the collection of empirical data to achieve more objective validation.

The quantitative methodology employed in this study is grounded in the philosophy of positivism, with the analysis focusing on measurable and statistically testable data. This approach enables the researcher to evaluate the relationship between the independent variable, namely the percentage of silica fume substitution, and the dependent variable, which is the compressive strength of concrete.

Data were collected through laboratory experiments involving the preparation of concrete test specimens with varying percentages of silica fume as a partial cement replacement. These specimens were then subjected to compressive strength testing at specified ages in accordance with established concrete testing standards. The resulting measurements were analyzed using inferential statistical methods to test the hypotheses proposed earlier.

Thus, the research methodology not only serves to describe the observed phenomena but also facilitates the systematic testing of hypotheses. Through rigorous data analysis, this study aims to derive valid conclusions regarding the impact of varying silica fume substitution percentages on the compressive strength of concrete.

Research Location

This research was conducted on PT.Sucofindo Palembang's Laboratory

RESULTS AND DISCUSSION

Mix Design

The initial phase of testing involved analyzing the characteristics of aggregates to establish a foundation for designing the concrete mix. These tests encompassed sieve analysis, determination of specific gravity, water absorption capacity, moisture content, unit weight, and aggregate abrasion testing to ensure the materials met the required quality standards. The production of high-quality concrete depends not only on the blending of primary materials but also on meticulous attention to various technical parameters that influence the final outcome. In designing the concrete mix proportions, this study adhered to the guidelines outlined in SNI 03-2834-2002, which specifies the procedures for producing normal concrete.

Following the acquisition of baseline data, the subsequent phase involved designing a concrete mix targeting a compressive strength of 26.8 MPa. The mix design was developed using a graphical relationship between the compressive strength of concrete and the water-cement ratio, based on cylindrical test specimens, to determine the average compressive strength aligned with the planned design. Through this process, the mix proportions were established to serve as a reference for the concrete production process.

Based on the developed design, the final composition of the concrete mix per cubic meter of volume is detailed as follows:

Table 1. Concrete Mix Composition

Cement :	Sand :	Coarse Agregate :	Water
447,377 :	599,842 :	1224,933 :	165,767
1 :	1,325 :	2,767 :	0,352
Cement :	Sand :	Coarse Agregate :	Water
447,377 :	599,842 :	1224,934 :	165,773
1,621 :	2,174 :	4,432 :	0,563

Source: 2023 Testing

Concrete Compressive Test

The compressive strength testing of concrete was conducted at 28 days, the standard age widely used to assess the maximum strength of concrete. The tests were performed using a compression testing machine with a capacity of 2000 kN, capable of applying gradual loading until the test specimen failed. The specimens used were cubic, measuring

15 cm × 15 cm × 15 cm, in compliance with the standards for normal concrete testing.

Prior to testing, each specimen was meticulously prepared by cleaning its surface to remove any contaminants or residual curing materials that could affect the test results. The loading process was applied slowly and uniformly until the specimen reached its maximum load-bearing capacity. The maximum load was recorded and used to calculate the compressive strength of the concrete based on the cross-sectional area of the specimen.

Through this procedure, empirical data were obtained regarding the concrete's ability to withstand compressive forces. The results from the 28-day tests provided the basis for evaluating the impact of varying percentages of silica fume as a partial cement substitute on the compressive strength of concrete.

Tabel 2. Results of compressive strength test of normal cube concrete at 28 days.

Cube 150x150x150 (mm)		Maximum Load	Compressive Strength (MPa)	Average (MPa)
Concrete	Test Object	(kg)		
Normal	1	126000	55,567	52,313
	2	112000	50,246	
	3	115000	51,125	

After a standard 28-day curing period, the control concrete exhibited an average compressive strength of 52.313 MPa. This value exceeded the target compressive strength of 43 MPa, indicating that the produced concrete not only met but surpassed the design standards. This achievement underscores the high quality and consistency of the base mix used in the study, as well as the effectiveness of the concrete preparation and curing processes.

Testing was also conducted on concrete incorporating 0.05% silica fume (by weight of cement) at the same 28-day age to evaluate the extent to which this additive enhanced concrete performance. These results provided a comparative analysis between standard concrete and concrete modified with silica fume, enabling an assessment of whether the addition of silica fume significantly influenced the achieved compressive strength.

Detailed results of the compressive strength tests for concrete with 0.05% silica fume are presented in Table 3, which includes the compressive strength values for each test specimen and the calculated average. These data facilitate further analysis of the compliance of the compressive strength with established standards and the effectiveness of silica fume as a partial cement substitute.

Tabel 3. Compressive strength test results for 28-day pozzolanic mixed cube concrete with 0.05% Silica Fume.

Cube 150x150x150 (mm)		Maximum Load	Compressive Strength (MPa)	Average (MPa)
Concrete	Test Object	(kg)		
Silica Fume 0,05 %	1	126000	56,042	
	2	128000	56,891	56,319
	3	126000	56,023	

Following the standard 28-day curing period, concrete with an additional 0.05% silica fume exhibited an average compressive strength of 56.319 MPa. This value was notably higher than that of the control concrete, which achieved an average compressive strength of 52.313 MPa at the same age. This improvement suggests that even a small addition of silica fume significantly enhances concrete performance, particularly in terms of compressive strength.

These findings reinforce the view that silica fume, as a pozzolanic material, is highly effective in improving the mechanical properties of concrete. Chemically, the ultrafine silica fume particles react with calcium hydroxide produced during cement hydration to form additional calcium silicate hydrate (C-S-H), which strengthens the concrete's microstructure. Physically, the nanoscale particles fill microvoids within the cement paste, resulting in a denser and more homogeneous concrete matrix. The combined physical and chemical effects explain the significant increase in compressive strength observed with the 0.05% silica fume addition.

These results provide empirical evidence that partial cement substitution with specific percentages of silica fume not only enhances material efficiency but also improves overall concrete quality. Thus, incorporating silica fume at low proportions holds potential for widespread application in the construction industry, particularly in producing stronger, more durable, and efficient concrete.

Detailed results of compressive strength testing for concrete with a 0.10% silica fume addition are presented in Table 4, which provides comparative data to evaluate the impact of increasing the percentage of this additive on concrete quality.

Tabel 4. Compressive strength test results for 28-day pozzolanic mixed cube concrete with 0.10% Silica Fume.

Cube 150x150x150 (mm)		Maximum Load	Compressive Strength (MPa)	Average (MPa)
Concrete	Test Object	(kg)		
Silica Fume 0,10 %	1	127000	56,447	56,744
	2	128000	56,892	
	3	128000	56,892	

The results indicate that at 28 days, concrete with 0.10% silica fume achieved an average compressive strength of 56.744 MPa, slightly higher than the 56.319 MPa recorded for the 0.05% silica fume mix. Although the difference is relatively small, it suggests a trend of increasing compressive strength with higher silica fume substitution.

This phenomenon can be attributed to the increasingly optimal pozzolanic reaction of silica fume as the quantity of fine particles in the mix increases. These particles not only fill micropores in the cement paste, resulting in a denser concrete structure, but also chemically react with calcium hydroxide ($Ca(OH)_2$) to form additional C-S-H, the primary component contributing to concrete’s compressive strength. Consequently, within certain limits, higher silica fume content enhances the potential for strength improvement.

However, it is noteworthy that the increase in compressive strength with 0.10% silica fume was not substantially greater than that with 0.05%. This indicates a limit to the effectiveness of silica fume, where excessive additions may reduce the workability of the concrete mix, affect the hydration process, and fail to yield linear strength improvements.

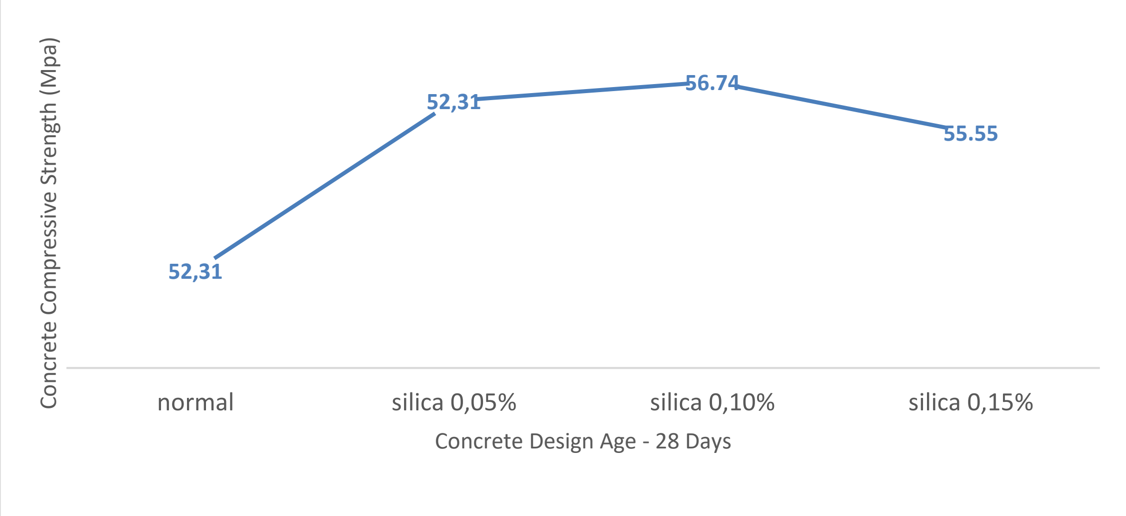
Table 5. Compressive strength test results for 28-day pozzolanic mixed cube concrete with 0.15% Silica Fume.

Cube 150x150x150 (mm)		Maximum Load	Compressive Strength (MPa)	Average (MPa)
Concrete	Test Object	(kg)		
Silica Fume 0,15 %	1	127000	54,224	55,559
	2	128000	55,562	
	3	128000	56,892	

The study further revealed that at 28 days, concrete with 0.15% silica fume achieved an average compressive strength of 55.559 MPa, lower than the 56.744 MPa recorded for the 0.05% silica fume mix. This finding suggests that increasing the silica fume percentage does not always correlate with improved compressive strength and may, at certain thresholds, lead to a decline in mechanical performance.

The reduction in strength with 0.15% silica fume can be explained by several factors. First, higher silica fume content increases the water demand of the mix due to the fine particle size and large surface area, potentially compromising workability if the water-cement ratio is not appropriately adjusted. Second, uneven distribution of silica fume particles in the mix may lead to agglomeration, reducing the density of the concrete microstructure. Consequently, the transition zone between aggregates and cement paste weakens, diminishing the concrete’s ability to withstand compressive forces.

These results, when visualized in a chart, would appear as follows:



These findings underscore that the effectiveness of silica fume depends heavily on the proportion used and the mixing techniques applied. Insufficient quantities may yield negligible effects, while excessive amounts can introduce technical challenges related to mix homogeneity. Therefore, determining the optimal silica fume proportion is critical to maximizing concrete strength without adversely affecting workability or microstructure.

CONCLUSION

Based on the results of compressive strength testing conducted on concrete specimens at 28 days with varying percentages of silica fume pozzolan (by weight of cement), it was found that the incorporation of silica fume can either enhance or diminish the compressive strength of concrete, depending on the dosage applied. The addition of 0.05% silica fume resulted in an average compressive strength of 56.319 MPa, which was higher than that of the control concrete without additives. Subsequently, at a 0.10% silica fume substitution, the compressive strength increased to 56.744 MPa, representing the highest value achieved in this study. This demonstrates that the appropriate inclusion of silica fume effectively serves as a filler material while improving the concrete microstructure, thereby enhancing inter-particle bonding and resulting in a denser and stronger matrix.

However, at a 0.15% silica fume substitution, a decline in the average compressive strength to 55.559 MPa was observed. This reduction indicates that excessive silica fume incorporation may lead to mix heterogeneity and the potential formation of agglomerates, consequently compromising concrete quality. Therefore, it can be concluded that the optimal silica fume dosage in this study is 0.10% by weight of cement, at which the concrete exhibited the best mechanical performance.

Overall, this study confirms that the addition of silica fume at specific proportions significantly enhances concrete quality. However, uncontrolled dosages can adversely affect compressive strength. Consequently, precise control over mix proportions and material homogenization processes is essential to maximize the benefits of silica fume incorporation.

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