# Effect of Fly Ash, Bottom Ash, and Silica Fume as Cement Substitutes on Mortar Compressive Strength

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## ABSTRACT

This research aims to study the effect of fly ash, bottom ash, and silica fume on the compressive strength of mortar. The experimental tests were performed for mortar with six variations in the percentage of cement partial replacement material to investigate its impact on the compressive strength. The cement partial replacement material used in this research mainly came from industrial waste materials. Fly ash (FA), ground bottom ash (GBA), and silica fume (SF) were the waste materials used in this research. Tests were carried out for twenty-eight days for each variation to observe the effect on compressive strength every seven days. The research results show that as concrete ages, its compressive strength increases, with values varying across treatments. At 28 days, compressive strength increased by 11% and 5% in the treatments with 30% FA and 5% SF, respectively. Meanwhile, the BA addition variation did not show a significant increase. The 30% fly ash addition was the variation that showed the largest percentage increase in compressive strength.

***Keywords:*** *cement substitution; compressive strength; fly ash; ground bottom ash; silica fume*

## ABSTRAK

Penelitian ini bertujuan untuk menganalisis pengaruh penggunaan material pengganti semen berupa fly ash (FA), bottom ash (BA), dan silica fume (SF) terhadap kuat tekan mortar. Material pengganti semen yang digunakan sebagian besar berasal dari limbah industri, sehingga penelitian ini juga mendukung upaya pemanfaatan material ramah lingkungan. Pengujian dilakukan secara eksperimental dengan enam variasi persentase penggantian parsial semen menggunakan FA, BA, dan SF. Setiap variasi diuji selama 28 hari dengan pengamatan kuat tekan dilakukan setiap interval tujuh hari. Hasil penelitian menunjukkan bahwa kuat tekan mortar meningkat seiring bertambahnya umur beton, meskipun nilai peningkatan bervariasi pada setiap perlakuan. Pada umur 28 hari, variasi dengan penambahan 30% FA menunjukkan peningkatan kuat tekan terbesar, yaitu sebesar 11%, sedangkan penambahan 5% SF menghasilkan peningkatan sebesar 5%. Sementara itu, variasi dengan penambahan BA tidak menunjukkan peningkatan signifikan terhadap kuat tekan mortar. Hasil ini menegaskan bahwa fly ash memiliki potensi paling besar sebagai material pengganti semen dalam meningkatkan performa mekanik mortar, sedangkan silica fume memberikan kontribusi moderat, dan bottom ash relatif kurang efektif.

***Kata Kunci:*** *material pengganti semen; kuat tekan; fly ash; ground bottom ash; silica fume*

## 1. INTRODUCTION

The increasing demand for sustainable construction materials has encouraged researchers to explore alternatives to ordinary Portland cement (OPC), which is widely used in mortar and concrete production. Cement manufacturing is known to contribute significantly to carbon dioxide emissions, energy consumption, and environmental degradation (Farkhodovna, 2022). The cement production process with a view to identifying the principal air pollutants, sources, and associated environmental issues, and also reviewed the pollution control measures currently in use and called for a concerted effort from researchers, industry operators, and regulators to work to reduce emissions to uphold environmental sustainability (Elehinafe et al., 2022). Therefore, the partial substitution of cement with industrial by-products has become an important strategy to reduce environmental impacts (Shah et al., 2022) while maintaining or improving the mechanical properties of mortar.

Several studies have investigated the use of supplementary cementitious materials such as fly ash, bottom ash, and silica fume (Singh, 2018). Fly ash, a by-product of coal combustion, has been widely recognized for its pozzolanic properties and ability to enhance long-term strength (M K, 2024). Ground Bottom ash, another residue from coal-fired power plants, has been studied as a potential aggregate or binder replacement, although its performance varies depending on particle fineness. Moderate substitution levels, particularly around 30% GBA, can enhance long-term strength performance, while excessive replacement reduces effectiveness due to limited pozzolanic activity (Wulandari et al., 2023). Silica fume, a by-product of silicon and ferrosilicon alloy production, is known for its high reactivity and ability to improve strength and durability. Previous research has generally focused on the individual effects of these materials, but limited studies have examined their combined influence on mortar compressive strength. The synergistic effect of silica fume and fly ash when used together demonstrates that optimized proportions of industrial by-products can improve concrete durability and strength while reducing reliance on Portland cement. This contributes to sustainable construction practices by lowering environmental impact and enhancing structural performance (Chaitanya et al., 2022).

This study emphasizes the necessity for a methodical experimental study that assesses mortar performance when fly ash, bottom ash, and silica fume are used in different ratios to partially replace cement. This study's comparative methodology, which examines the combined and individual effects of three industrial waste materials on mortar compressive strength during varying curing ages, is what makes it new.

This study aims to evaluate the impact of fly ash, bottom ash, and silica fume as partial cement replacement materials on the compressive strength of mortar based on the identified research gap. This study is interesting since it evaluates three industrial byproducts simultaneously in a single experimental setup. By offering insights into sustainable material consumption, assisting with infrastructure planning, and influencing construction policies that favor eco-friendly substitutes for conventional cement, the findings are anticipated to advance civil engineering knowledge and practice.

Based on the identified research gap, this study aims to investigate the effect of fly ash, bottom ash, and silica fume as partial cement replacement materials on the compressive strength of mortar. The novelty of this study lies in the simultaneous evaluation of three industrial by-products within one experimental framework. The results are expected to contribute to civil engineering knowledge and practice by providing insights into sustainable material utilization, supporting infrastructure planning, and informing construction policies that promote environmentally friendly alternatives to conventional cement.

## 2. METHODS

The methodology of this study was designed to ensure that the experimental process could be clearly understood, evaluated, and replicated. A systematic approach was adopted, beginning with the selection and preparation of materials, followed by the design of mortar mixtures with varying proportions of cement substitution using fly ash (FA), bottom ash (BA), and silica fume (SF). Standardized procedures and instruments were employed to guarantee accuracy and consistency, while internationally recognized testing standards guided the experimental process. Data collection was carried out through compressive strength testing at different curing ages, and the results were analyzed using statistical and comparative techniques. This methodological framework provides transparency and reliability, allowing other researchers to reproduce the study and validate its findings within the broader context of sustainable civil engineering practices.

### 2.1 Research Design

This study employed an experimental laboratory design to evaluate the effect of partial cement substitution using fly ash (FA), ground bottom ash (GBA), and silica fume (SF) on the compressive strength of mortar. These experimental compressive strength tests were conducted on mortar cubes with seven variations, specifically by varying the type and percentage of cementitious additives: 15% and 30% for fly ash and bottom ash, and 5% and 10% for silica fume. Details of these test sample variations are shown in Table 1.

*Table 1. Variation of testing samples*

| Sample Code | Sample Type | Sample Size (cm) |
|---|---|---|
| OPC | Mortar | 5 x 5 x 5 |
| FA15 | Mortar | 5 x 5 x 5 |
| FA30 | Mortar | 5 x 5 x 5 |
| GBA15 | Mortar | 5 x 5 x 5 |
| GBA30 | Mortar | 5 x 5 x 5 |
| SF5 | Mortar | 5 x 5 x 5 |
| SF10 | Mortar | 5 x 5 x 5 |

Each specimen was tested for compressive strength at curing ages of 7, 14, and 28 days.

### 2.2 Materials

The materials employed in this study are generally similar to those commonly used in conventional concrete production. Ordinary Portland Cement from Gresik was utilized as the primary binder, while fly ash (FA), bottom ash (BA), and silica fume (SF) served as partial cement replacement materials. FA and BA were obtained from coal combustion residues at PLN Paiton, with their chemical compositions determined through X-ray Fluorescence (XRF) analysis, as presented in Table 2.

*Table 2. Chemical composition of fly ash and ground bottom ash*

| SCMs Type | Components | SiO2 | Al2O3 | Fe2O3 | CaO | MgO | Na2O |
|---|---|---|---|---|---|---|---|
| Fly ash | (%) | 37,75 | 19,11 | 12,49 | 13,46 | 6,25 | 5,40 |
| Ground Bottom ash | (%) | 50,63 | 14,04 | 13,79 | 7,46 | 3,48 | 3,28 |
| SCMs Type | Components | K2O | TiO2 | MnO2 | P2O5 | Cr2O3 | SO3 |
| Fly ash | (%) | 1,92 | 0,86 | 0,27 | 0,38 | 0,01 | 0,98 |
| Ground Bottom ash | (%) | 1,62 | 0,79 | 0,77 | 0,21 | 0,01 | 0,43 |

In order to achieve the same level of fineness as cement, bottom ash must be ground into smaller particles. To achieve the grain fineness, the material is ground for ± 4 hours using a ball mill tool that smooths the material with a rotating ball (tube) system. MasterLife SF, a silicon metal alloy type with a SiO2 concentration between 87 and 98%, was utilized for silica fume. Table 3 displays specifics of the chemical makeup of the silica fume X-ray fluorescence (XRF) test findings.

*Table 3. Chemical composition of silica fume XRF results*

| Components | Al2O3 | SiO2 | P2O5 | SO3 | K2O | CaO |
|---|---|---|---|---|---|---|
| (%) | 0,5 | 93,8 | 0,96 | 0,82 | 1,2 | 2,14 |
| Components | Fe2O3 | CuO | ZnO | As2O3 | Re2O7 | PbO |
| (%) | 0,28 | 0,096 | 0,028 | 0,009 | 0,04 | 0,11 |

### 2.3 Mixing Standards

Cement, sand, and water make up the mortar, and the FA, BA and SF materials is utilized to partially replace the cement. The ASTM C-311 standard mix procedures and quantities are used in the mortar manufacturing process. The standard specifies the proper ratio of sand to cement and the amount of water needed to achieve the desired consistency (American Society of Testing and Materials, 2013). Table 4 displays the proportions of the mortar mix for each modification.

*Table 4. Proportion of mortar mix*

| SCMs Type | Sample Code | Cement (Kg/m3) | Fine Aggregate (Kg/m3) | w/c | Variation of SCMs (% of cement) |
|---|---|---|---|---|---|
| - | OPC | 666,67 | 1833,33 | 0,484 | 0% |
| Fly Ash | FA15 | 666,67 | 1833,33 | 0,484 | 15% |
| Fly Ash | FA30 | 666,67 | 1833,33 | 0,484 | 30% |
| Bottom Ash | GBA15 | 666,67 | 1833,33 | 0,484 | 15% |
| Bottom Ash | GBA30 | 666,67 | 1833,33 | 0,484 | 30% |
| Silica Fume | SF5 | 666,67 | 1833,33 | 0,484 | 5% |
| Silica Fume | SF10 | 666,67 | 1833,33 | 0,484 | 10% |

*Note: The above proportion is for 1 mortar mix of 6 samples.*

### 2.4 Instruments and Procedures

The experimental work was carried out using a set of standardized instruments and procedures to ensure accuracy and reproducibility. Mortar specimens were prepared with the aid of a mechanical mixer to achieve uniform blending of cement, sand, water, and replacement materials. The mixtures were then cast into 50 mm cube molds, which served as the specimens for compressive strength testing. A Universal Testing Machine (UTM) with calibrated load capacity was employed to measure compressive strength at different curing ages.

The experimental procedure involved drying, sieving, and grinding fly ash (FA), bottom ash (BA), and silica fume (SF) to the required fineness, followed by mixing according to designed proportions. Specimens were cured under controlled conditions and tested at 7, 14, and 28 days to evaluate strength development. All results were systematically recorded and compared across variations to assess the impact of each substitution material on mortar performance.

## 3. RESULTS

The results of compressive strength testing for OPC and FA mixtures are presented in Table 5 and Figure 1. The findings indicate that the incorporation of fly ash enhances strength development up to 30% replacement, with the highest value observed in FA30 at 28 days, while FA15 shows comparable performance to OPC.

*Table 5. Compressive Strength Test Results for Different OPC and Fly Ash Variations*

| Waktu (hari) | Nilai Kuat Tekan (f'c) | Nilai Kuat Tekan (f'c) | Nilai Kuat Tekan (f'c) |
|---|---|---|---|
| Waktu (hari) | OPC | FA15 | FA30 |
| 1 | 12,54 | 8,55 | 10,25 |
| 3 | 27,82 | 18,30 | 20,84 |
| 7 | 35,64 | 29,39 | 28,87 |
| 28 | 40,74 | 40,52 | 45,40 |

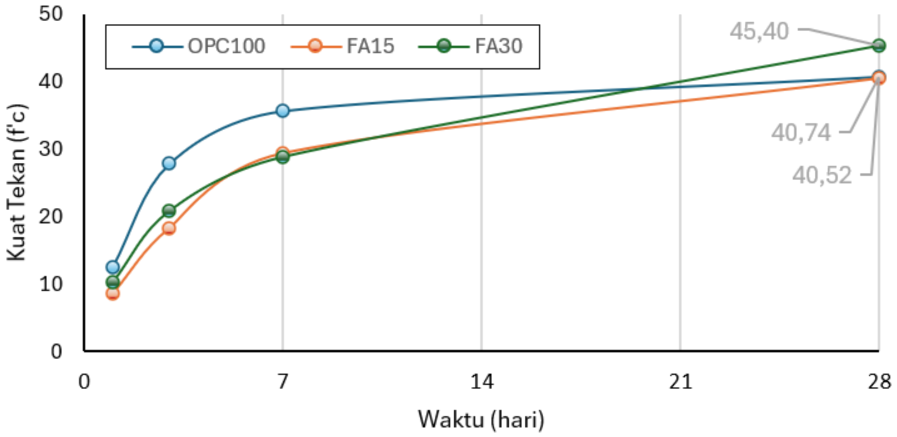


*Figure 1. Comparison Chart of Compressive Strength Values for Different Varieties of OPC and FA*

Meanwhile, Table 6 and Figure 2 present the findings of the compressive strength tests for OPC and Ground Bottom Ash (GBA) combinations. While GBA30 demonstrated a notable increase in strength at later ages, the results indicated that substitution with basalt ash typically results in poorer strength compared with OPC. On day seven, GBA50 had the lowest value, indicating minimal pozzolanic action at high replacement levels.

*Table 6. Compressive Strength Test Results for Different OPC and Ground Bottom Ash Variations*

| Waktu (hari) | Nilai Kuat Tekan (f'c) | Nilai Kuat Tekan (f'c) | Nilai Kuat Tekan (f'c) |
|---|---|---|---|
| Waktu (hari) | OPC | GBA15 | GBA30 |
| 1 | 12,54 | 10,79 | 7,20 |
| 3 | 27,82 | 22,71 | 19,64 |
| 7 | 35,64 | 28,28 | 27,13 |
| 28 | 40,74 | 29,11 | 37,38 |

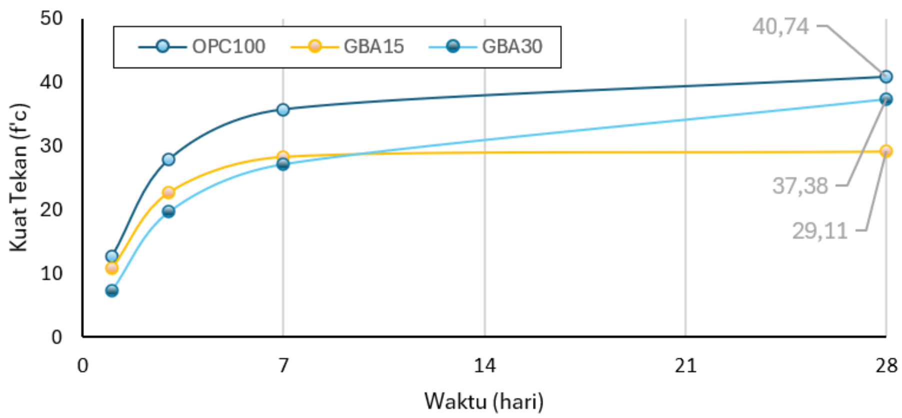


*Figure 2. Comparison Chart of Compressive Strength Values for Different Varieties of OPC and GBA*

The results of compressive strength testing for OPC and SF mixtures are summarized in Table 7 and Figure 3. The findings suggest that silica fume substitution improves compressive strength moderately, with SF5 and SF10 achieving values close to OPC at 28 days. The highest strength was observed in SF5 at 28 days, indicating that small proportions of silica fume are effective in enhancing mortar performance.

*Table 7. Compressive Strength Test Results for Different OPC and Silica Fume Variations*

| Waktu (hari) | Nilai Kuat Tekan (f'c) | Nilai Kuat Tekan (f'c) | Nilai Kuat Tekan (f'c) |
|---|---|---|---|
| Waktu (hari) | OPC | SF5 | SF10 |
| 1 | 12,54 | 15,48 | 13,22 |
| 3 | 27,82 | 23,94 | 19,64 |

| | | | |
|---|---|---|---|
| 7 | 35,64 | 32,87 | 27,13 |
| 28 | 40,74 | 42,84 | 40,47 |

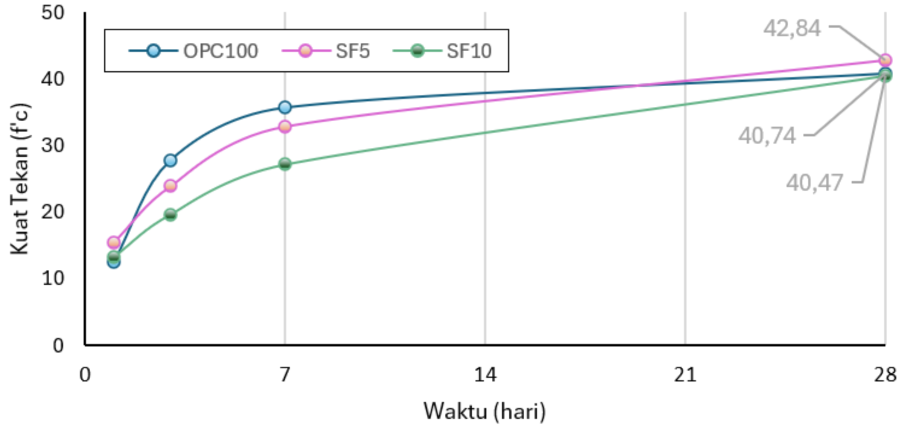


*Figure 3. Comparison Chart of Compressive Strength Values for Different Varieties of OPC and SF*

## 4. DISCUSSION

The results for fly ash (FA) show that mixtures with moderate FA content exhibit slower early strength development, yet superior or equivalent compressive strength at 28 days compared to the OPC control, with the highest value at 28 days observed at a 30% replacement rate in this study. Meanwhile, ground bottom ash (GBA) mixtures exhibited behavior that was very different from the OPC, FA, and SF mixtures: replacement with GBA resulted in lower early-age compressive strength, and only a few mixtures (particularly those with a 30% replacement rate) showed a significant increase in strength at day 28; however, in general, they still lagged behind the OPC control at early ages.

Silica fume (SF) produces a consistent increase in strength even at low dosages, where the addition of small amounts (approximately 5–10%) increases matrix density and results in compressive strength that is close to or slightly higher than that of the OPC control sample on day 28. The notable effects of SF stem from its extremely fine particle size and high amorphous silica content, which accelerate pozzolanic reactions at the microstructural level and fill microvoids in the interface transition zone, thereby refining the pore structure and improving durability-related properties such as permeability and chloride resistance. In practice, SF is particularly valuable when early microstructural consolidation and long-term durability are priorities; however, its high surface area increases water demand and may reduce workability unless compensated for with a superplasticizer; cost and supply considerations also influence its practical application. Overall, these findings suggest a complementary strategy—moderate replacement of FA to reduce cement content and small additions of SF to improve early microstructure and durability—while emphasizing the need for mix optimization, quality control of admixtures, and further testing under field-drying conditions and over longer aging periods to ensure long-term performance.

The results above show that partially replacing Portland cement with industrial by-products has varying effects on the compressive strength of mortar, depending on the type of material and the replacement rate. Fly ash (FA) enhances long-term strength development, with the highest compressive strength on day 28 observed at a 30% replacement rate in this study; silica fume (SF) produces a moderate yet consistent increase in strength at low replacement ratios (5–10%), whereas ground bottom ash (GBA/BA) exhibits limited early performance, and only a few mixtures (e.g., 30% GBA after extended curing) approach the strength of the control. These patterns suggest that pozzolanic reactivity and particle packing determine strength development: FA and SF provide additional pozzolanic reactions as well as a micro-filler effect that densifies the matrix over time, whereas the effectiveness of GBA is limited by lower reactivity and coarser particle characteristics unless it is further processed.

The trends observed are generally consistent with previous experimental studies reporting increased long-term strength with the use of fly ash and silica fume, as well as slower early-stage strength development for high-volume admixtures. Several studies have shown that the latent hydraulic reactions and pozzolanic reactions of FA accelerate strength gain after the first week (Duan et al., 2023), and that the extremely fine SF particles and high silica content improve the properties of the interface transition zone even at low dosages (Xu et al., 2016). On the other hand, GBA mixtures exhibit poor performance at high replacement rates, which aligns with the claim that ground basalt ash requires further grinding or processing to achieve performance comparable to fly ash. The precise ideal replacement percentage and the magnitude of the strength increase are what distinguish this study from some of the literature; these differences are most likely due to variables in the chemistry of the raw materials, fineness, mix design (water-cement ratio, sand gradation), and the curing method used in this study (Babajide Olabimtan & Mosaberpanah, 2023).

From a practical standpoint, the results of this study provide actionable guidance for sustainable concrete practices. Moderate replacement of FA (up to the identified optimal level) can reduce cement consumption and associated $CO_2$ emissions while maintaining or improving 28-day compressive strength, making it suitable for structural applications where long-term performance is critical. Adding small amounts of SF (approximately 5%) can be used to improve early microstructure and durability without high costs or compromising workability (Sadr Momtazi et al., 2016). Bottom ash may be suitable for partial replacement only after undergoing mechanical or chemical activation (e.g., finer grinding, thermal treatment) or when used in combination with more reactive pozzolans; conversely, high-volume replacement of bottom ash risks compromising early strength and may limit its use in structural applications. These results also indicate that ground bottom ash (GBA) is less suitable for high replacement ratios in structural applications where early strength is critical. To make GBA a viable cementitious additive, it is recommended to perform pretreatment (e.g., finer grinding, classification, or thermal/chemical activation) or to blend it with more reactive pozzolans (such as FA or SF) to enhance its reactivity and improve particle packing.

## 5. CONCLUSION

This study concludes that partial replacement of Portland cement with industrial by-products can maintain or improve mortar compressive strength when applied at appropriate proportions. Specifically, fly ash and silica fume produced the most consistent benefits: moderate fly ash replacement (up to the optimal level identified in this work) enhanced 28-day strength, and small additions of silica fume (around 5–10%) improved matrix densification and strength development. Ground bottom ash showed limited early-age performance and only certain moderate replacement levels (e.g., ~30%) approached control strengths; very high replacement ratios (e.g., 50%) consistently reduced compressive performance.

These results imply that targeted use of fly ash and silica fume offers a practical route to reduce cement consumption and associated environmental impacts without compromising structural performance, while bottom ash requires pre-treatment or combination with more reactive pozzolans before wide structural application. Future research should extend curing and durability testing (56–90+ days and indicators such as chloride penetration, sulfate resistance, and shrinkage), evaluate activation or beneficiation methods for bottom ash, and perform life-cycle and techno-economic assessments to support field implementation and standardization.

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## AUTHOR CONTRIBUTIONS

Adveni Hesty Altisari Lada was solely responsible for conceptualization, methodology, material preparation, experimental investigation, data collection, data analysis and interpretation, validation of the results, manuscript preparation, review, editing, and final approval of the version for publication.

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## CONFLICT OF INTEREST STATEMENT

The author declares that there is no conflict of interest regarding the publication of this article.

## DATA AVAILABILITY STATEMENT

The experimental data supporting the findings of this study are available from the corresponding author upon reasonable request.

## ETHICAL STATEMENT

This study was conducted in accordance with academic research ethics. It involved laboratory testing of mortar materials and did not involve human participants, personal data, animals, or experimental interventions involving living subjects. All external sources have been appropriately acknowledged.

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