

Evaluation of Compressive Strength of Concrete Using Fly Ash, Silica Fume, and Steel Slag as Cementitious and Aggregate Replacements

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Abstract

This study comprehensively investigates the influence of supplementary cementitious materials and industrial by-products—specifically fly ash, silica fume, and steel slag—on the compressive strength of concrete. The primary objective is to evaluate the impact of both individual and combined replacements of cement and aggregate components on concrete performance. The research analyzes how varying proportions of these materials affect the strength characteristics of the concrete mixtures. Experimental results demonstrate that increasing the proportion of fly ash tends to reduce the compressive strength of concrete. For instance, a 20% replacement of cement with fly ash led to a 2.1% decrease in strength, while a 30% replacement caused a more significant reduction of 15.5%. Conversely, incorporating silica fumes up to a 10% replacement level enhanced the compressive strength substantially, achieving an improvement of 21.5% compared to the control mix. Regarding the use of steel slag as a coarse aggregate replacement, the study observed a progressive decline in strength, with a 2% replacement leading to a 5.1% reduction and an 8% replacement resulting in a 10.2% decrease. Similarly, replacing fine aggregates with steel slag also resulted in noticeable strength reductions, particularly at higher replacement levels. However, concrete mixes incorporating a triple combination of fly ash, silica fume, and steel slag demonstrated that compressive strength values remained within acceptable engineering limits. These mixes provided a balanced approach to performance, cost-efficiency, and environmental sustainability. Overall, the findings suggest that while excessive use of certain materials can adversely affect strength, optimized combinations—particularly those including silica fume—can yield durable and sustainable concrete suitable for modern construction needs. The study underscores the potential of strategic material substitutions to enhance the ecological footprint of construction practices without compromising structural integrity.

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INTRODUCTION

In recent years, the construction industry has shifted towards sustainable materials and practices to reduce its carbon footprint. The incorporation of industrial by-products into concrete has gained considerable attention as a means of minimizing waste and conserving resources. Supplementary materials, such as steel slag, silica fume, and fly ash, have been extensively studied for their potential to

enhance the strength, workability, and long-term performance of concrete. Steel slag, a by-product of steel manufacturing, is rich in oxides and can be used as a partial replacement for coarse aggregates. Silica fume, a fine, non-crystalline by-product of silicon and ferrosilicon alloys, acts as a pozzolanic material and significantly enhances the strength of concrete. Fly ash, generated from coal combustion in power plants, is widely used as a cement replacement because of its pozzolanic properties and ability to improve the workability of concrete. The integration of these materials addresses waste management concerns and reduces reliance on virgin resources [1–5].

OBJECTIVES

This study aims to investigate the effects of using various cementitious materials and aggregate replacements on the compressive strength of concrete. The primary focus was to evaluate the influence of fly ash, silica fume, steel slag, and rubber chips as supplementary materials in different proportions. Additionally, this study seeks to identify the optimal replacement levels that maintain or enhance the compressive strength of concrete. By analyzing the individual, dual, and triple combinations of these materials, this study aims to provide comprehensive insights into their mechanical performance. Furthermore, the economic and environmental benefits of utilizing industrial waste materials in concrete production are evaluated. These findings are intended to support sustainable construction practices by reducing reliance on traditional concrete components while maintaining structural integrity [6–8].

MATERIAL

Cement

Grade 53 Ordinary Portland Cement (OPC) was used as the primary binder. This conforms to the specifications of the IS 12269:2013. Cement plays a crucial role in binding aggregates and providing strength to concrete upon setting and hardening.

Fine Aggregate

Natural river sand was used as a fine aggregate in this study. The sand was sourced locally and conformed to IS 383:2016. The fine aggregate passed through a 4.75 mm sieve and was free from clay, silt, organic matter, and other impurities.

Coarse Aggregate

Crushed granite, with a maximum size of 20 mm, was used as the coarse aggregate. This complied with IS 383:2016 standards. The aggregates were clean, durable, and free of dust and other deleterious substances.

Water

Potable water, free from impurities and adhering to the specifications of IS 456:2000, was used to mix and cure the concrete specimens. The pH of the water was recorded as 9, ensuring its suitability for concrete production.

Supplementary Materials

Three types of supplementary materials were incorporated to replace conventional cement and aggregates, thereby enhancing the mechanical properties and sustainability of the concrete mixes.

Fly Ash

Class C Fly Ash, a by-product of coal combustion in thermal power plants, was used as a partial replacement for cement. The chemical and physical properties of fly ash conformed to the ASTM C618-93 standards.

Silica Fume

Silica fumes, obtained from the production of silicon and ferrosilicon alloys, were used as partial cement replacements. It consists of fine spherical particles and significantly improves the strength and durability of the concrete. The properties of silica fume were in accordance with ASTM C1240.

Steel Slag

Steel slag, a by-product of steel manufacturing, was used as a replacement for both the fine and coarse aggregates. The physical and chemical properties of steel slag were assessed to ensure its suitability for concrete production. The slag was collected from a local steel-manufacturing plant.

RESULTS

Cube Compressive Strength of Cementitious Replacements

The compressive strength results for individual replacements of fly ash and silica fume as cementitious materials indicated a reduction in strength with increasing fly ash content. A 20% fly ash replacement resulted in a 2.1% strength reduction, whereas a 25% replacement resulted in a 9.2% reduction. At 30% fly ash replacement, the compressive strength decreased by 15.5%.

Conversely, the addition of silica fume had a beneficial effect on compressive strength. A 5% silica fume replacement increased the strength by 10.5%, whereas a 10% replacement further enhanced the strength by 12.5%. However, workability challenges were observed with higher silica fume contents. Notably, at the 10% replacement level, the compressive strength increased by 21.5%. Similar observations were reported by Mahmoud and Ahmad (2015), who identified 7.5% silica fume replacement as an optimal choice for strength enhancement (Figure 1) [9–12].

Cube Compressive Strength of Coarse Aggregate Replacements

Steel slag was used as a partial replacement for coarse aggregates at concentrations of 2, 4, 6, and 8%. Compressive strength tests on 7 and 28 days revealed an optimal replacement percentage of 5% to 7% for coarse aggregates and 30% to 50% for fine aggregates.

A 2% steel slag replacement resulted in a 5.1% strength reduction, whereas a 4% replacement caused a 6.2% reduction. Further increases to 6% and 8% steel slag replacement reduced the compressive strength by 8.2% and 10.2%, respectively, as shown in Figure 2. These results align with findings by Devi and Gnanavel (2014), who concluded that exceeding 30% and 40% replacements for coarse and fine aggregates, respectively, led to significant strength losses [13, 14].

However, rubber chip replacements as coarse aggregates proved ineffective, resulting in a considerable strength reduction of over 30% at a mere 2% replacement. Further increases to 4% and 6% replacements resulted in even steeper declines in compressive strength. Because of these unfavorable results, rubber chips were excluded from the subsequent tests.

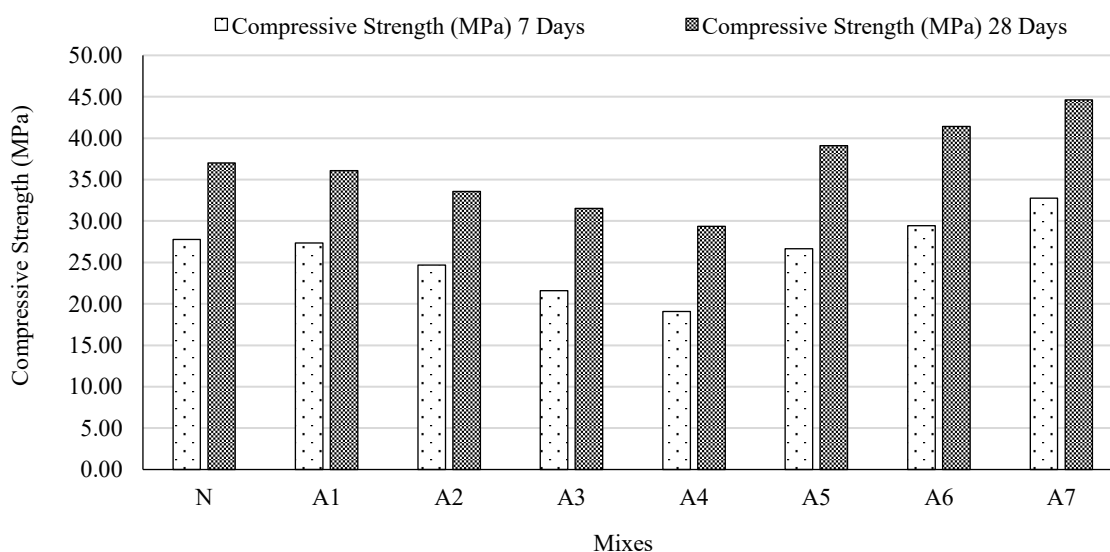


Figure 1. Cube compressive strength for cementitious material replacements.

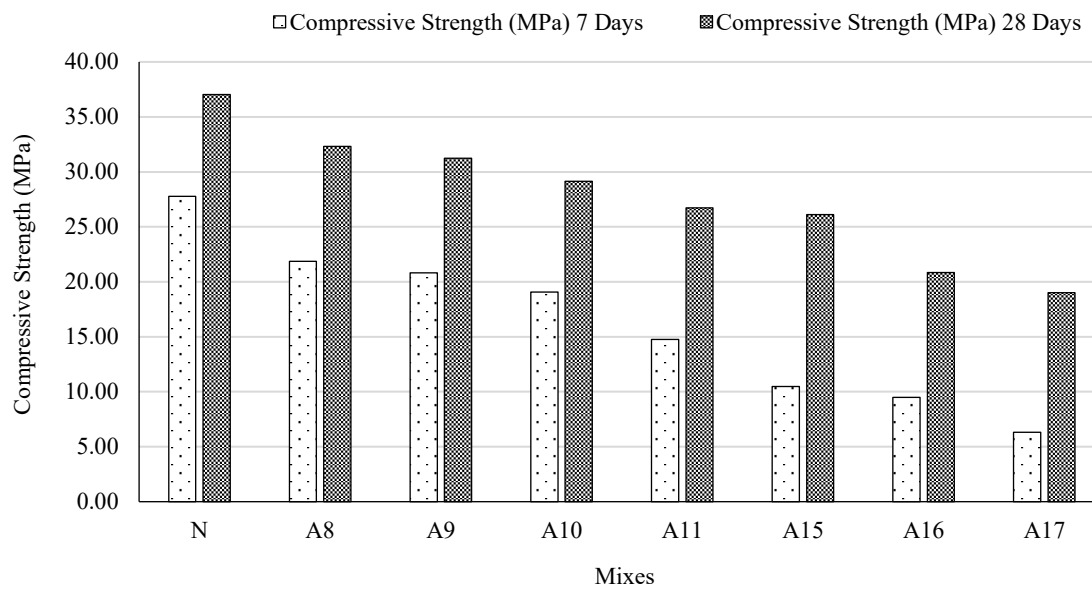


Figure 2. Cube compressive strength for coarse aggregate replacements.

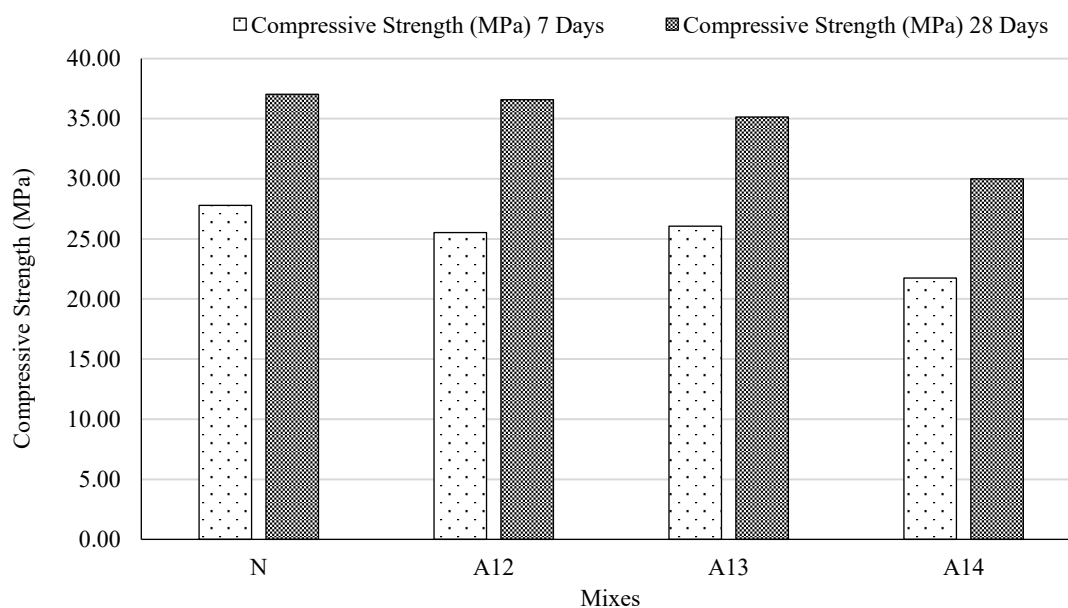


Figure 3. Comparison of cube compressive strength results for fine aggregate replacements.

Compressive Strength of Fine Aggregate Replacements

Concrete cubes were cast using various percentages of fine aggregate replacement with steel slag. Strength tests on 7 and 28 days showed a marginal reduction of 1.2% at 20% replacement. At 30% replacement, the strength decreased by approximately 5.2%. When the fine aggregate replacement reached 40.2%, a substantial 19.5% reduction in the compressive strength was observed, lowering the strength below the characteristic value. Figure 3 illustrates strength variation.

Cube Compressive Strength of Two Supplementary Material Combinations

The combination of 12% silica fume and 4% steel slag resulted in a slight reduction in strength. However, increasing the silica fume content by an additional 2% significantly enhances the compressive strength. Similarly, a combination of 15% fly ash and 4% steel slag demonstrated better strength, although higher percentages led to minor strength losses (Figures 4 and 5).

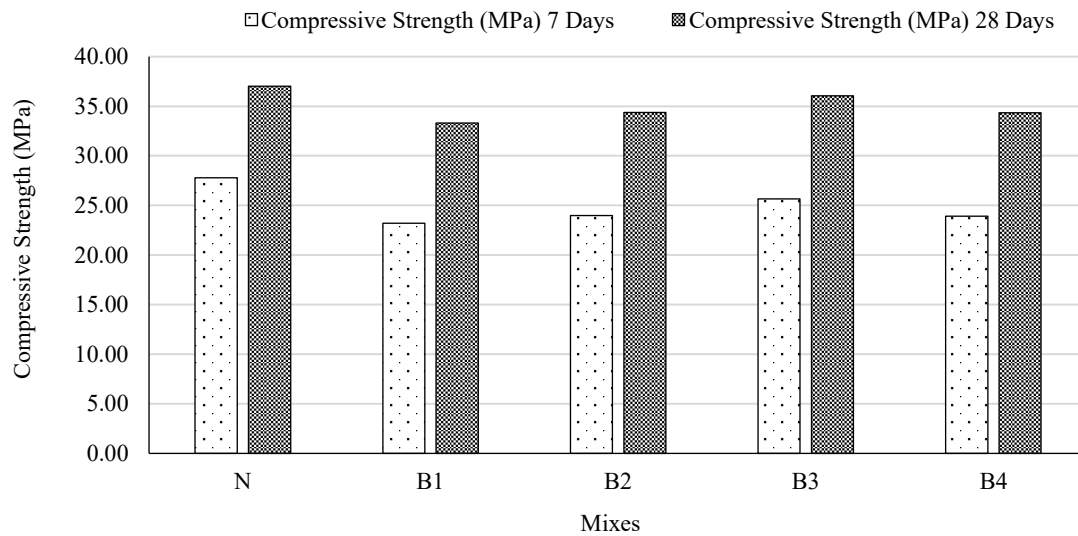


Figure 4. Comparison of cube compressive strength for two combination mixes.

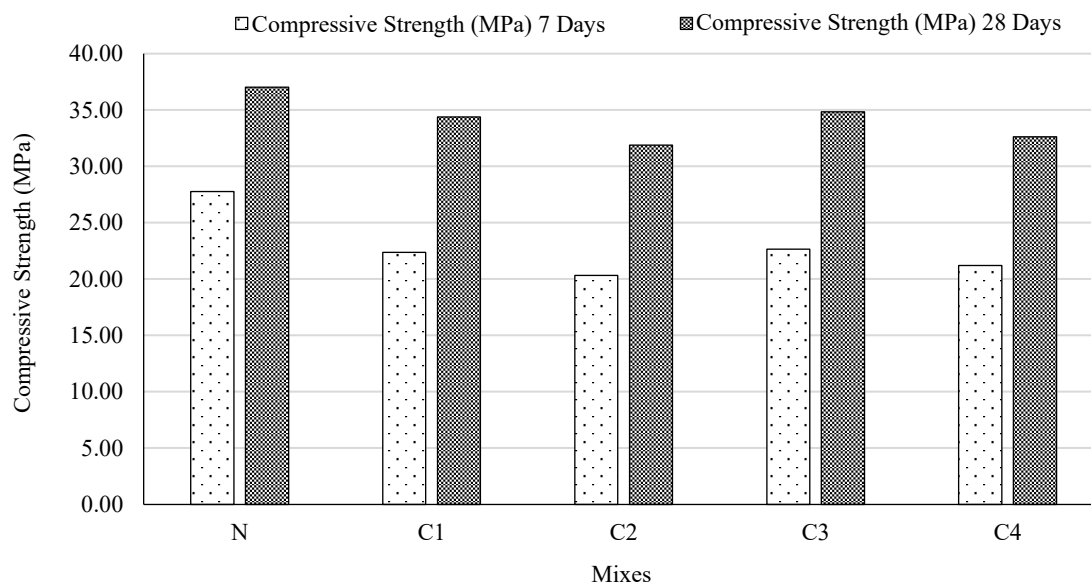


Figure 5. Comparison of cube compressive strength for three combination mixes.

Cube Compressive Strength of Three Supplementary Material Combinations

Triple-combination mixes of silica fume, fly ash, and steel slag were subjected to compressive strength testing. The results confirmed that these mixes satisfied the required strength standards. Notably, the 4% steel slag replacement exhibited superior strength compared to the 6% replacement. The addition of silica fumes positively affected the compressive strength of the triple combinations. Additionally, the use of multiple supplementary materials provides economic benefits by reducing material costs without compromising strength performance.

CONCLUSIONS

The study demonstrates that silica fumes significantly enhance the compressive strength, with optimal results observed at a 10% replacement level. In contrast, fly ash replacement results in a gradual strength reduction, particularly beyond the 20% replacement level. Steel slag, when used as a coarse or fine aggregate replacement, shows a decline in compressive strength with increasing slag content. However, its combination with silica fume or fly ash provides a balanced performance while

maintaining adequate strength. Rubber chips, owing to their detrimental impact on strength, are unsuitable for structural applications. Overall, the use of dual and triple supplementary material combinations achieved satisfactory compressive strength while promoting sustainability in concrete production. These findings offer practical guidelines for incorporating industrial by-products into concrete mixes for eco-friendly construction.

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