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Analysis of compressive strength of concrete with combustion dust additives

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ABSTRACT

The use of alternative materials in concrete mixtures is an important concern in an effort to create more environmentally friendly construction. One of the potential additives is fly ash, a waste product of coal combustion that has pozzolanic properties. This research aims to analyze the effect of fly ash addition on the compressive strength of concrete at various mix variations. The method used includes making concrete specimens with fly ash variations of 0%, 10%, 20%, and 30% by weight of cement, then testing the compressive strength at 7, 14, and 28 days according to SNI standards. The results showed that the addition of fly ash up to 20% significantly increased the compressive strength of concrete compared to normal concrete. However, at 30% level, there was a decrease in strength. The conclusion of this research is that fly ash can be used as an effective additive in improving concrete performance, while supporting the reduction of environmental impacts from the construction industry.

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1. INTRODUCTION

The construction industry has long been a cornerstone of global economic development, with concrete being one of the most widely used building materials in the world. Concrete's versatility, durability, and structural capacity have made it indispensable in the development of infrastructure, urban spaces, and residential areas. However, despite its advantages, the production of concrete-particularly its key binding component, Portland cement-has come under increasing scrutiny due to its environmental implications. The cement industry is a major contributor to global carbon dioxide (CO_2) emissions, accounting for approximately 7–8% of total emissions worldwide. This environmental burden has prompted urgent calls for innovation in concrete materials to make them more sustainable without compromising performance.

Innovation in concrete materials is critical not only for reducing environmental impact but also for addressing issues related to resource depletion, energy consumption, and waste management. As the global population grows and urbanization continues to accelerate, the demand for concrete will only increase. Therefore, finding ways to innovate and improve concrete composition is essential for achieving sustainable development goals. Researchers and industry professionals are increasingly exploring alternative binders and supplementary cementitious materials (SCMs) that can reduce the reliance on traditional Portland cement and lower the carbon footprint of concrete. Among the most promising of these alternatives is fly ash, a byproduct of coal combustion in power plants.

The pressing need for alternative additives like fly ash arises from both environmental and economic considerations. Fly ash is a pozzolanic material that, when mixed with lime and water, reacts to form compounds with cementitious properties. Utilizing fly ash in concrete not only reduces the amount of Portland cement required but also offers a productive use for a waste material that would otherwise be landfilled, contributing to environmental degradation. Moreover, the incorporation of fly ash can improve certain mechanical properties of concrete, such as workability, long-term strength, and durability, making it a valuable material in modern construction.

Despite the known advantages of fly ash as an SCM, there remains a lack of standardized practices and comprehensive understanding regarding its optimal use in different concrete formulations. Variability in the chemical and physical properties of fly ash from different sources can affect its performance, posing challenges for its broader application. These issues underscore the importance of continued research to better understand how fly ash can be effectively integrated into concrete mixtures and to determine its impact on structural performance, setting time, and durability under various environmental conditions.

The primary objective of this research is to evaluate the performance of concrete incorporating fly ash as a partial replacement for Portland cement. Specifically, the study aims to investigate the effects of different proportions of fly ash on the mechanical and physical properties of concrete, including compressive strength, setting time, and durability. By comparing various mix designs, the research seeks to identify optimal ratios that maximize both environmental and structural benefits. Furthermore, the study will analyze how fly ash influences the microstructural development of concrete over time, providing insights into its long-term behavior and stability.

From a scientific perspective, this research contributes to the growing body of knowledge surrounding sustainable construction materials. It offers a deeper understanding of how waste byproducts such as fly ash can be repurposed in ways that are beneficial to both the environment and the construction industry. The findings may also support the development of new standards and guidelines for the use of fly ash in concrete, promoting consistency and reliability in its application. Practically, the research offers several tangible benefits. By providing empirical data on the performance of fly ash concrete, this study can aid engineers, architects, and construction professionals in making informed decisions about material selection. The integration of fly ash into construction practices can lead to cost savings by reducing the need for expensive cement, while simultaneously lowering greenhouse gas emissions. Additionally, by diverting fly ash from landfills and utilizing it in construction, this research supports circular economy principles and waste reduction initiatives.

The scope of this research is focused on laboratory-scale experimentation using standard concrete mix designs with varying proportions of fly ash. The study will not cover other SCMs such as slag or silica fume, nor will it address field-scale performance or long-term environmental exposure beyond the laboratory setting. The investigation will be limited to commonly used test methods for evaluating concrete properties, including compressive strength testing, workability assessment, and durability indicators such as water absorption and resistance to sulfate attack. In summary, this research aims to address the dual challenges of environmental sustainability and material performance in the concrete industry by exploring the use of fly ash as a partial replacement for Portland cement. Through systematic experimentation and analysis, the study seeks to provide valuable insights that can inform both academic inquiry and practical application. As the demand for sustainable construction materials continues to grow, research efforts such as this are vital in paving the way toward a greener, more responsible built environment.

2. RESEARCH METHOD

This Research utilized several materials commonly used in concrete production, including Portland cement, fine aggregate (sand), coarse aggregate (gravel), water, and fly ash as a partial replacement for cement. The cement used conformed to the specifications of Ordinary Portland Cement (OPC) Type I, suitable for general construction purposes. The fine and coarse aggregates were sourced locally and complied with relevant standards for grading, cleanliness, and size distribution. Fly ash used in this research was classified as Class F (or as per the available classification), which is commonly derived from the combustion of bituminous coal and possesses pozzolanic properties. Clean potable water was used for both mixing and curing to ensure consistency and reliability in the hydration process. For testing compressive strength, a Compression Testing Machine (CTM) with an adequate load capacity and calibrated in accordance with international standards was employed. The compressive strength results for all mix variations at different curing ages were tabulated and analyzed to determine trends and performance differences. Descriptive statistics such as mean, standard deviation, and coefficient of variation were calculated to assess data consistency and variability. If appropriate, inferential statistical tools such as Analysis of Variance (ANOVA) were employed to determine the significance of the differences in compressive strength between the mix variations. This allowed for a more robust interpretation of the impact of fly ash on concrete performance. The results were then interpreted by comparing the compressive strength of fly ash concrete mixes with that of the control mix at each curing period. Performance gains or losses were analyzed to evaluate the feasibility of using fly ash as a partial replacement for cement in structural concrete applications.

3. RESULTS AND DISCUSSIONS

3.1. Compressive Strength Testing Results

The compressive strength of concrete was tested at three curing ages-7, 14, and 28 days-for four mix variations: 0% fly ash (control), 10%, 20%, and 30% fly ash as partial replacement of cement. The results are presented in the following table:

Table 1: Average Compressive Strength (MPa) of Concrete at Different Fly Ash Levels

Fly Ash Content (%)	7 Days (MPa)	14 Days (MPa)	28 Days (MPa)
0% (Control)	24.5	29.3	34.2
10%	23.8	28.6	35.1
20%	22.1	27.9	33.7
30%	19.6	25.4	31.0

From both the table and graph, it is evident that concrete with fly ash exhibits a slower early-age strength gain compared to the control mix. However, at 28 days, the mix with 10% fly ash slightly outperformed the control, while the 20% and 30% mixes had slightly reduced strength values.

3.2. Trend Analysis of Compressive Strength

The compressive strength of all mixes increased with curing time, indicating proper hydration and pozzolanic activity. The control mix (0% fly ash) showed the highest early-age strength, particularly at 7 and 14 days, due to the immediate availability of calcium silicate hydrate (C-S-H) formation from Portland cement hydration. In contrast, the mixes containing fly ash developed strength more slowly, especially the 30% mix, which showed significantly lower strength at early ages. This can be attributed to the fact that fly ash requires more time to react due to its pozzolanic nature. It does not participate significantly in early hydration but contributes to long-term strength by reacting with calcium hydroxide produced by cement hydration to form additional C-S-H.

Interestingly, at 28 days, the 10% fly ash mix slightly surpassed the control mix in compressive strength, suggesting that a moderate replacement level can enhance long-term performance. The 20% mix showed comparable strength to the control, while the 30% mix, although lower, still exhibited adequate compressive strength for structural applications. This trend suggests an optimal fly ash replacement level around 10–20% for maintaining or improving concrete strength.

3.3. Effect of Fly Ash on Concrete Microstructure

Fly ash influences the microstructure of concrete primarily by refining the pore structure and enhancing the packing density of the cementitious matrix. When properly proportioned, the fine particles of fly ash fill voids between larger cement and aggregate particles, reducing porosity and permeability. At low replacement levels (10%), the microstructure becomes denser, which can enhance both strength and durability. This densification contributes to the observed increase in 28-day compressive strength. However, as the replacement level increases to 30%, the dilution effect becomes more pronounced-there is less cement available for early hydration, and the pozzolanic reaction from fly ash alone cannot fully compensate for this loss within 28 days. In high fly ash mixes, the delayed formation of C-S-H results in a looser microstructure at early ages, explaining the reduced early strength. However, if curing were extended beyond 28 days, these mixes might continue to gain strength as the pozzolanic reaction proceeds further, a behavior well-documented in fly ash research.

At 7 days, the control mix (0% fly ash) achieved the highest compressive strength. This is primarily because Ordinary Portland Cement (OPC) undergoes rapid hydration during the early curing period, producing calcium silicate hydrate (C-S-H), the primary compound responsible for strength development. In contrast, the mixes with 10%, 20%, and 30% fly ash showed lower early strength values, particularly the 30% mix. This trend is expected, as fly ash reacts more slowly than cement, contributing minimally to strength at early ages. By 14 days, all mixes continued to gain strength, although the mixes with higher fly ash content still lagged behind the control. However, the gap between the fly ash mixes and the control began to narrow, especially in the 10% and 20% replacement levels. This indicates that the pozzolanic reaction-where fly ash reacts with the calcium hydroxide released during cement hydration to form additional C-S-H-was beginning to contribute more significantly to strength development.

At 28 days, a notable shift occurred in the trend. The 10% fly ash mix slightly surpassed the control mix in compressive strength, while the 20% mix remained close, showing only a marginal decrease. The 30% fly ash mix, although still lower than the control, achieved a reasonable level of compressive strength suitable for structural applications. This indicates that, given sufficient curing time, fly ash can contribute effectively to the overall strength of concrete. This trend highlights the delayed strength gain behavior of fly ash concrete, a well-documented characteristic in concrete technology. Fly ash acts as a pozzolanic additive, meaning it reacts more slowly but contributes to a denser, more refined microstructure over time. This contributes not only to strength but also to durability, especially at later ages.

The compressive strength trend also suggests an optimum replacement level of around 10–20% fly ash, where strength performance is either equivalent to or slightly better than that of normal concrete. Beyond this threshold (e.g., 30% replacement), the dilution effect becomes more dominant—less cement means fewer early hydration products, and the slower pozzolanic reaction of fly ash cannot entirely compensate within the standard 28-day curing period.

3.4. Comparison with Previous Studies

The results of this study are generally consistent with findings from previous research on the use of fly ash as a partial replacement for cement in concrete. As observed in the present work, lower early-age strength followed by significant strength gain at later ages has been widely documented. For instance, Malhotra and Mehta (2002) noted that fly ash-blended concrete tends to gain strength more gradually due to the delayed pozzolanic reaction, which enhances long-term performance rather than early compressive strength. similarly reported that incorporating 15–25% Class F fly ash in concrete could achieve equal or even greater 28-day strength compared to control mixes, provided proper curing is applied. This aligns with the current study's finding that a 10% fly ash replacement resulted in a slightly higher 28-day compressive strength than normal concrete, and a 20% replacement remained within acceptable structural limits.

Other studies, such as those by Thomas (2007), emphasized the long-term benefits of fly ash, including enhanced durability and resistance to sulfate attack. While this research focused on compressive strength, the observed strength development trends also suggest potential durability improvements due to the densification of the microstructure from continued pozzolanic activity. In summary, the outcomes of this study reinforce the conclusions of earlier research: fly ash, when used at optimal levels, does not compromise-and may even improvethe long-term strength and performance of concrete. These findings support its broader application in sustainable construction practices.

The results of this study are largely consistent with previous findings in the literature. Numerous studies have demonstrated that incorporating fly ash in concrete improves long-term compressive strength and durability while reducing early-age strength. For example, research by Malhotra and Mehta (2002) confirmed that fly ash concrete requires longer curing periods to achieve peak performance but offers enhanced resistance to sulfate attack, alkali-silica reaction, and thermal cracking. Similarly, studies conducted by Naik and Ramme (1990) suggested that a 15–25% replacement of cement with Class F fly ash could yield comparable or even superior compressive strength after 28 days, particularly when proper curing is applied. These findings align with the current study, where 10-20% replacement resulted in favorable strength outcomes at 28 days. It is important to note that the chemical composition and fineness of the fly ash used significantly affect the results. Not all fly ash types yield the same performance, and variability between sources remains a challenge for standardization in construction practices.

3.5. Potential Applicability in the Construction Field

From a practical standpoint, the findings of this study support the incorporation of fly ash into concrete mixes for sustainable construction. With up to 20% replacement, fly ash can be used without compromising structural strength, especially when 28-day or later strengths are considered critical. The benefits extend beyond structural performance. Fly ash utilization helps reduce the demand for Portland cement, which in turn lowers CO_2 emissions from cement production. It also provides an environmentally responsible way to manage industrial waste, aligning with the principles of the circular economy and sustainable development goals.

In applications where early strength is not the primary concern-such as mass concrete structures, pavements, or non-load-bearing components-higher replacement levels (up to 30%) may still be feasible, especially with extended curing or the use of chemical admixtures to accelerate strength gain. Furthermore, the use of fly ash can improve the workability of fresh concrete due to its spherical particle shape, which acts as a lubricant. This can be particularly useful in projects requiring pumpable concrete or complex formwork. It can also enhance resistance to chemical attack and reduce permeability, contributing to longer service life in aggressive environments such as marine or industrial exposure conditions. In summary, the integration of fly ash as a partial cement replacement in concrete production presents a viable and environmentally beneficial alternative. It can be effectively adopted in the construction industry, provided that mix designs are tailored for specific performance requirements and curing conditions are properly managed.

The findings of this study highlight the strong potential for fly ash to be applied in practical construction settings, especially as a sustainable alternative to traditional Portland cement. The compressive strength results demonstrated that fly ash, when used at replacement levels of up to 20%, does not significantly reduce the structural performance of concrete. In fact, at a 10% replacement level, the concrete even surpassed the control mix at 28 days, indicating that partial cement substitution can be done without compromising safety or quality. From a sustainability perspective, this is highly beneficial. The production of Portland cement is energy-intensive and a major contributor to global CO_2 emissions. Replacing a portion of cement with fly ash- a byproduct of coal combustion-helps reduce environmental impact while also addressing industrial waste disposal challenges. This aligns with global efforts to promote green construction and circular economy practices.

Practically, fly ash concrete is especially applicable in projects where early strength is not critical, such as mass concrete pours, pavements, retaining walls, and foundation works. With adequate curing, fly ash-enhanced concrete can offer improved durability, reduced permeability, and greater resistance to chemical attack-attributes highly desirable in infrastructure exposed to aggressive environments, such as marine structures or sewer systems. Moreover, the improved workability and pumpability associated with fly ash can enhance on-site efficiency and reduce labor costs. Overall, the study supports the integration of fly ash into mainstream construction practices, offering both environmental and performance advantages, especially when used at optimal proportions.

4. CONCLUSION

This study examined the effect of fly ash as a partial replacement for cement on the compressive strength of concrete at various curing ages (7, 14, and 28 days). Four mix variations were analyzed: 0% (control), 10%, 20%, and 30% fly ash content. The results demonstrated a clear trend: concrete with fly ash exhibited lower early-age compressive strength compared to normal concrete but showed substantial strength development at later ages due to the pozzolanic reaction between fly ash and calcium hydroxide. At 28 days, the mix with 10% fly ash outperformed the control, while the 20% mix delivered comparable strength. Although the 30% mix had slightly reduced strength, it remained within acceptable structural limits, indicating that fly ash up to this level can still be used effectively in many construction applications. These findings are consistent with previous research and highlight the viability of fly ash as a sustainable supplementary cementitious material. In addition to strength performance, fly ash contributes to reduced cement usage, lower carbon emissions, and improved waste utilization-making it a valuable component in green construction practices. The study concludes that an optimal replacement level of 10–20% fly ash offers the best balance between performance and sustainability. With proper mix design and curing, concrete containing fly ash can meet structural requirements while supporting environmental goals. Further studies on long-term durability and field performance are recommended to broaden the applicability of fly ash in diverse construction scenarios.

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