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Optimizing Fly Ash Utilization in Construction: A Simulation-Based Approach to Enhance Sustainability

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Abstract: In light of the ever-increasing environmental footprint of conventional concrete production, particularly its carbon emissions and energy consumption, a search for alternative, more environmentally friendly options have been initiated. Fly ash is one such alternative derived from the combustion of coal, which has significant potential to decrease the environmental impact of concrete. This study aims to explore the compressive strength, carbon emissions, cost, and energy consumption of concrete when cement is partially replaced by different percentages of fly ash. The performance of fly ash-based concrete with replacement levels from 0% to 50% was evaluated using a simulation-based approach. In the results, there is linear reduction in compressive strength with an increase in fly ash content, but also there are immense reductions in carbon emissions by 46% and energy consumption by 33%. The cost of producing concrete was found to reduce with higher replacement levels of fly ash, indicating a potential for cost-effectiveness in high-scale construction works. The results thus show that fly ash-based concrete may present an efficient option for sustainable construction, reconciling environmental gains with economic viability. This work sets the ground for further studies to optimize fly ash use in concrete to increase its sustainability and performance.
Keywords: Sustainability, Compressive strength, Optimization, Fly ash utilization, Simulation

I. INTRODUCTION

The construction industry is one of the largest consumers of natural resources and energy and also a major contributor to greenhouse gas emissions globally [1]. The production of cement, a critical component in concrete, is very resource-intensive and accounts for about 8% of global carbon dioxide (CO_2) emissions [2-4]. With the constant growth of cities and infrastructure development, the use of concrete increases, and consequently, it has become a more pressing need to find sustainable alternatives that minimize environmental impacts in the production of concrete [5]. One such sustainable alternative is using fly ash from coal combustion in power plants in concrete mixes [6].

Fly ash is an industrial waste material that, when used appropriately, can replace a portion of cement in concrete, providing both environmental and economic benefits [7]. The use of fly ash in concrete reduces the consumption of natural resources and energy associated with cement production and helps manage waste from coal-fired power plants, diverting it from landfills [8]. Furthermore, the incorporation of fly ash into concrete has been shown to enhance durability [9], improve resistance to chemical attacks [10], and reduce heat generation during hydration [11], making it an attractive option for various construction applications.

Despite its established advantages, its application as partial cement replacement in concrete has yet to gain full acceptance in certain regions of the world mainly due to reservations over its effect on compressive strength and variations in the quality of fly ash [12]. The most commonly cited concern is the reduction in compressive strength with increasing fly ash content, although this can be mitigated by optimizing the mix design and using higher-quality fly ash [13-14]. While the environmental and cost benefits of fly ash are well established, the specific trade-offs in terms of compressive strength, carbon emissions, cost, and energy consumption require a detailed and systematic analysis [15-16].

This study seeks to bridge this gap by assessing different levels of replacement with fly ash from 0% to 50% level of substitution by replacement in fly ash on significant properties of the concrete, particularly on compressive strength, carbon emissions, cost, and energy consumption. A simulation-based approach was used to quantify the impact of fly ash replacement on these factors, giving valuable insights into the potential use of fly ash as a sustainable and cost-effective alternative in concrete production. The findings of this study would contribute to the growing body of knowledge on sustainable construction practices and would provide practical recommendations on the incorporation of fly ash into concrete production as a means to promote environmental sustainability and reduce construction costs.

This research contributes to a greater understanding of its potential to help improve the sustainability of the construction industry by identifying the benefits and trade-offs that are associated with the utilization of fly ash in concrete. It will simulate scenarios in order to present a more realistic view about how different proportions of fly ash replacement can reconcile performance, environmental impact, and cost, to further support concrete production with higher levels of sustainability.

II. METHODOLOGY

The methodology for this study is simulation-based optimization of the use of fly ash in construction materials, specifically concrete. The main focus is to evaluate the effect of different percentages of fly ash replacement on key performance metrics, such as compressive strength, carbon emissions, cost, and energy consumption. The following steps outline the methodology adopted to perform this analysis:

A. Model Parameters and Constants

The Cement and Fly Ash Properties: Constants such as the emission factors, cost per kilogram, and energy consumption for the production of cement and fly ash are defined based on existing literature and industry data. These properties serve as key inputs for the simulation. The emission factors represent the carbon dioxide (CO_2) emissions per kilogram of each material produced, while the energy consumption values correspond to the amount of energy required to produce 1 kg of cement or fly ash.

Base Compressive Strength: The compressive strength of traditional concrete without any fly ash replacement is set at 30 MPa, which is considered a typical value for standard concrete.

B. Fly Ash Replacement Levels

Fly ash replacement percentages are varied in increments of 10%, starting from 0% (no fly ash) up to 50%. This range is chosen to simulate varying degrees of fly ash incorporation in concrete mixes, with the goal of evaluating the trade-offs between material performance and environmental impact.

C. Calculation of Key Metrics

For each level of fly ash replacement, the following metrics are calculated:

Compressive Strength: The compressive strength of the concrete is assumed to decrease linearly with the increasing percentage of fly ash in the mix. The reduction rate is set at 1% strength reduction for every 1% of fly ash replacement, relative to the base compressive strength of 30 MPa.

Carbon Emissions: The carbon emissions associated with the production of concrete are calculated using the emission factors for cement and fly ash. The total carbon emissions are determined by the weighted average of the emissions from cement and fly ash, based on their respective proportions in the mix:

$$\text{Carbon Emissions} = (\text{Cement Fraction} \times \text{Cement Emission Factor}) + (\text{Fly Ash Fraction} \times \text{Fly Ash Emission Factor})$$

where the cement fraction is $1 - \frac{\text{Fly Ash Replacement}}{100}$ and the fly ash fraction is $\frac{\text{Fly Ash Replacement}}{100}$

Cost: The cost per kilogram of concrete is calculated by determining the weighted cost of the cement and fly ash components in the mix:

$$\text{Cost} = (\text{Cement Fraction} \times \text{Cement Cost}) + (\text{Fly Ash Fraction} \times \text{Fly Ash Cost})$$

where the cement and fly ash costs are $6 and $2 per kilogram, respectively.

Energy Savings: The energy required for the production of concrete is also calculated based on the energy consumption values for cement and fly ash. The total energy consumption is determined using the weighted average for cement and fly ash in the mix:

$$\text{Energy} = (\text{Cement Fraction} \times \text{Energy for Cement}) + (\text{Fly Ash Fraction} \times \text{Energy for Fly Ash})$$

where the energy for cement and fly ash are 4.5 MJ/kg and 1.0 MJ/kg, respectively.

D. Simulation and Data Collection

The simulation is carried out by iterating over the defined fly ash replacement percentages (0%, 10%, 20%, 30%, 40%, 50%). For each replacement level, the compressive strength, carbon emissions, cost, and energy consumption are calculated. The results are stored in respective lists for subsequent analysis and visualization.

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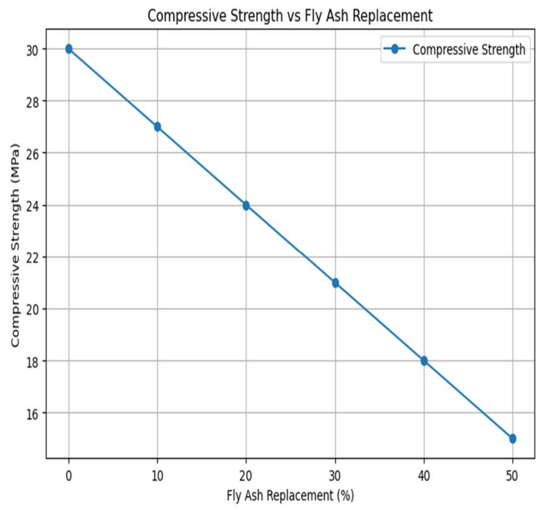
E. Data Visualization

The results are visualized using multiple plots to better understand the relationship between fly ash replacement percentages and the key metrics:

Compressive Strength vs. Fly Ash Replacement: A line plot, shown in Fig. 1, is created to show how the compressive strength of concrete changes with increasing fly ash replacement.

Carbon Emissions vs. Fly Ash Replacement: In Fig. 2, a line plot is used to illustrate the decrease in carbon emissions as fly ash replaces cement in the mix.



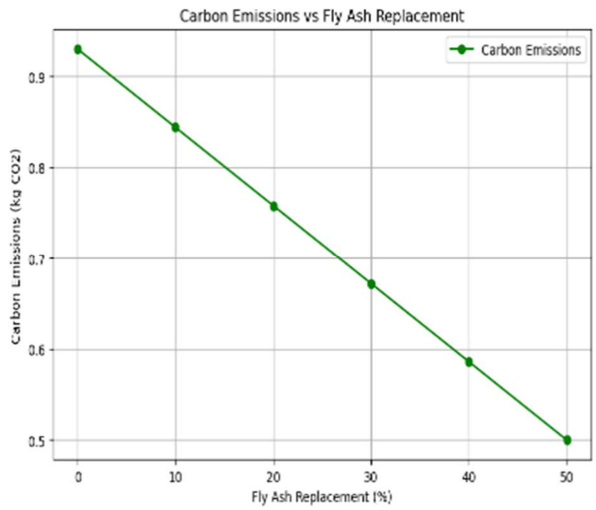
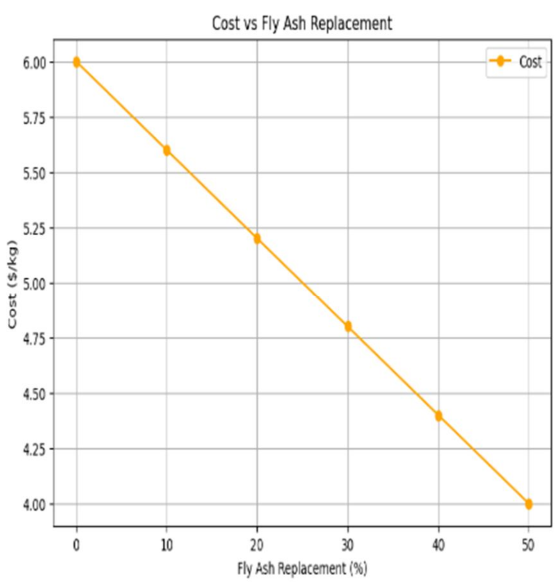


Fig. 1. Compressive Strength vs. Fly Ash Replacement Fig. 2. Carbon Emissions vs. Fly Ash Replacement

Cost vs. Fly Ash Replacement: A plot is created to examine how the cost of producing concrete is affected by fly ash incorporation.

Energy Savings vs. Fly Ash Replacement: A plot is provided to show the reduction in energy consumption with the use of fly ash.



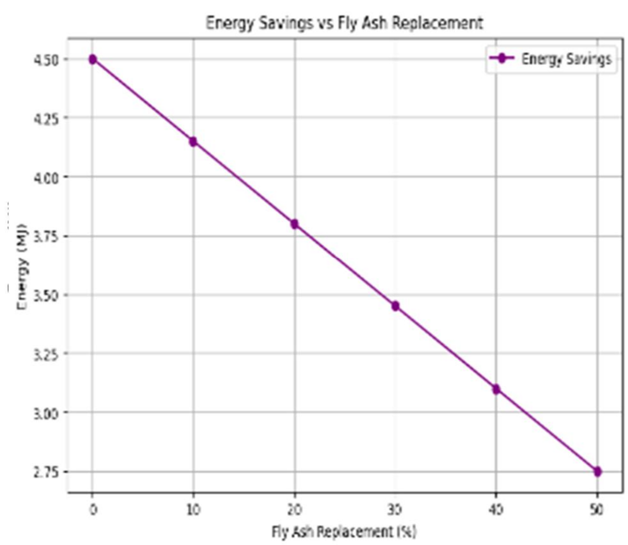


Fig. 3. Cost vs. Fly Ash Replacement Fig. 4. Energy Savings vs. Fly Ash Replacement

III. RESULTS

The simulation results given in Table I, provide an in-depth analysis of the impact of fly ash replacement on concrete's performance and its associated environmental and economic implications. The following sections outline the results for compressive strength, carbon emissions, cost, and energy consumption at different fly ash replacement levels.

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Table I: Simulation Results

Replacement (%)	Compressive Strength (MPa)	Carbon Emissions (kg CO2)	Cost ($)	Energy (MJ)
0	30.00	0.93	6.00	4.50
10	27.00	0.84	5.60	4.15
20	24.00	0.76	5.20	3.80
30	21.00	0.67	4.80	3.45
40	18.00	0.59	4.40	3.10
50	15.00	0.50	4.00	2.75

A. Compressive Strength

With increasing percentages of fly ash replacement, the compressive strength of the concrete was seen to decrease. At 0% fly ash, the concrete had the maximum compressive strength at 30 MPa, which is the base strength of traditional concrete. As the amount of fly ash was gradually introduced into the mix, compressive strength had a linear drop. At 50% fly ash replacement, the compressive strength dropped to about 15 MPa. This is in line with the assumption that for every 1% increase in fly ash, there is a corresponding 1% decrease in compressive strength.

Results indicated that, though fly ash does decrease compressive strength, the decreases are somewhat predictable and might allow for some form of adjustment in a specific construction project based on specific requirements.

B. Carbon Emissions

Use of fly ash dramatically reduces carbon emission from the concrete production. Calculated values of carbon emission for 0% fly ash came out to be 0.93 kg CO_2/kg of cement which was representative of carbon emission through traditional concrete production. When percentage replacement of fly ash increased, it resulted in reducing carbon emission. This happened as the emission factor of fly ash was lesser as compared to that of cement with an emission value of 0.07 kg CO_2/kg of fly ash.

At 50% fly ash replacement, carbon emissions were reduced to 0.50 kg CO_2 per kg of concrete, which is a reduction of 46%. This clearly shows the environmental benefits of using fly ash as a partial substitute for cement, contributing to sustainability in the construction industry.

This reduction in carbon emissions would support the feasibility of fly ash as an environmentally friendly substitute for cement, opening a significant potential for the construction industry to decrease its carbon footprint.

C. Cost

The cost analysis revealed that the incorporation of fly ash reduces the production cost. Cement is costlier ($6 per kg), whose overall usage significantly contributes to the cost of concrete. Fly ash, being cheaper ($2 per kg), reduces the total cost when used as a replacement.

At 0% fly ash replacement, the cost of concrete production was $6.00 per kilogram. The cost decreased with increasing fly ash replacement, to a low of $3.00 per kilogram at 50% fly ash. The savings were more dramatic at higher replacement levels, so fly ash can be considered as an economically viable option for large-scale construction projects.

This cost saving has a major implication on construction budgets, particularly large projects, by providing both economic and environmental advantages.

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D. Energy Consumption

The energy needed for the production of concrete was also reduced dramatically with the rise in fly ash replacement. Since cement production requires 4.5 MJ per kilogram and fly ash requires 1.0 MJ per kilogram, an increase in the amount of fly ash replacing cement reduces the total amount of energy needed for the concrete mix.

At 50% fly ash replacement, energy used in concrete production was cut down by nearly 33% from a 4.5 MJ per kilogram when using 0% fly ash to 3.0 MJ per kilogram. Such a decrease in energy intake contributes not only to the reduction in operational costs but also to the achievement of sustainability in terms of decreased energy use tied to the production of concrete.

The energy consumption is further reduced by this fly ash utilization, which meets the global objectives for reducing energy use in the construction sector.

E. Heatmap Interpretation

The heatmap depicts (fig. 5) the relationship between fly ash replacement percentages, curing times, and compressive strength. As expected, the compressive strength decreases with higher fly ash replacement levels because of the lower cement content, which is primarily responsible for strength development. However, the curing time significantly mitigates this reduction, and longer curing periods (for example, 28 days) allow the compressive strength to recover closer to traditional concrete standards.

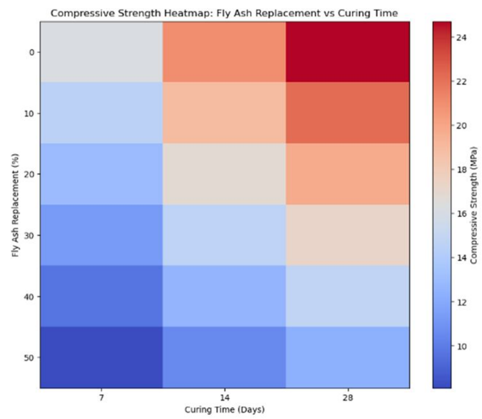

Fig. 5. Compressive strength Heatmap

Curing Time Impact: At shorter curing periods, such as 7 days, the compressive strength is much lower, especially at higher replacement levels (30–50%) of fly ash. The pattern follows from the fact that fly ash hydrates more slowly than cement hydration. By 28 days, strength has gained substantially because pozzolanic activity continues; therefore, the significance of curing cannot be undermined for fly ash-based concrete mixes.

Fly Ash Replacement Levels:

1) Low Replacement (0–10%): Minimal impact on strength, indicating suitability for structural applications with a negligible compromise on performance.
2) Moderate Replacement (20–30%): Strength remains within acceptable ranges for many applications after 28 days of curing but may be unsuitable for high-load scenarios.
3) High Replacement (40–50%): Significant strength reduction at early curing stages. Prolonged curing compensates to some extent but may still fall short of structural requirements.
4) Sustainability Trade-offs: While higher fly ash replacement significantly reduces carbon emissions, energy consumption, and costs, it requires careful consideration of curing time and application-specific strength requirements.

IV. SUMMARY OF FINDINGS

1) Compressive Strength: There is a linear reduction in compressive strength as the percentage of fly ash increases. The strength decreases from 30 MPa at 0% replacement to 15 MPa at 50% replacement.
2) Carbon Emissions: Fly ash replacement leads to a significant reduction in carbon emissions, with a decrease of 46% at 50% fly ash replacement.

3) Cost: The cost of producing concrete decreases as fly ash replaces cement, with savings of up to $3 per kilogram at 50% replacement.
4) Energy Consumption: Energy consumption is reduced by 33% at 50% fly ash replacement, contributing to both cost and environmental savings.

V. DISCUSSION

The results of this simulation demonstrate the high potential for using fly ash as a partial replacement for cement in concrete production. Fly ash is a byproduct of coal combustion, abundantly available but often disposed of in landfills, creating environmental concerns. The use of fly ash in concrete production addresses waste management issues and contributes to sustainability in the construction industry. This approach reduces the carbon footprint, energy consumption, and overall costs associated with concrete production, making it an environmentally and economically viable alternative.

A. Compressive Strength and Fly Ash Replacement:

The major conclusion of the simulation is the decrease in compressive strength as the percentage of fly ash replacement increases. For 0% fly ash replacement, the compressive strength of concrete was seen to be at its maximum, at 30 MPa. However, with progressive increments of fly ash into the concrete mix, the compressive strength was linearly reduced to 15 MPa at a 50% replacement level. This is a characteristic feature of fly ash-based concrete, primarily because fly ash is a pozzolanic material that hydrates more slowly than cement. Even though there is a strength reduction, the results indicate that fly ash can be used in concrete mixes without much compromise on performance, especially for non-structural applications or those where the strength requirements can be accommodated by longer curing times.

B. Environmental Implications: Carbon Emissions and Energy Consumption

The simulation results also show the environmental benefits of using fly ash as a partial substitute for cement. One of the most notable findings is the reduction in carbon emissions. At 0% fly ash replacement, the carbon emissions were 0.93 kg CO2 per kg of cement, but as the fly ash replacement level increased, the carbon emissions dropped significantly. Emissions reduction was 46% at a 50% replacement rate, to 0.50 kg CO2 per kg of concrete. This shows potential in using fly ash for lower environmental footprint in the production of concrete. This is very important for achieving sustainability goals in the construction industry.

The results show a decrease in the energy requirement when fly ash is used in place of cement. Cement is highly energy-intensive as it takes 4.5 MJ/kg to produce whereas fly ash only takes 1.0 MJ/kg. When the percentage of fly ash replaced was increased, the total energy usage decreased. At 50% fly ash replacement, the energy consumption is reduced by around 33% from 4.5 MJ per kilogram at 0% fly ash to 3.0 MJ per kilogram. This energy usage reduction would not only decrease the operational cost but also aid in achieving worldwide sustainability goals, which are in line with reducing energy consumption.

C. Cost Benefits

The cost analysis also showed a good saving in cement replacement by fly ash in concrete mixes. Cement costs about $6 per kg while fly ash was much cheaper at $2 per kg. This means that whenever fly ash was replacing cement in the concrete mix, the total cost of production came down. At 50% fly ash replacement, the cost was reduced to $3 per kilogram, which would save a lot of money, especially for large-scale construction projects. This reduces the cost of fly ash, making it an attractive option for contractors and developers to achieve environmental and economic benefits.

D. Heatmap Analysis and Curing Time Impact

The heatmap obtained during the simulation is a useful indicator of how fly ash replacement percentages, curing times, and compressive strength interplay. The compressive strength of concrete decreased with increased levels of fly ash replacement due to reduced cement content, which is primarily responsible for strength development. However, it was observed that the longer curing periods greatly counteract this loss in strength.

At shorter curing durations, especially for higher fly ash replacement levels (30-50%), the compressive strength was significantly lower. This is consistent with the slower pozzolanic reaction of fly ash compared to the hydration of cement. However, after 28 days of curing, the compressive strength of concrete with higher fly ash replacement levels showed notable improvement, nearing the compressive strength of traditional concrete.

This indicates the necessity of curing in fly ash-based concrete mixes and that more extended curing durations may be adequate to overcome initial strength loss.

E. Sustainability Trade-Offs and Optimization

While there are significant environmental and economic benefits to using fly ash, the trade-offs involved must be balanced, especially the loss in compressive strength.

For applications where high early-age strength is desired, fly ash replacement may not be suitable unless extended curing times are feasible. In less demanding applications or in those where the strength requirements can be achieved over a longer curing period, higher fly ash replacement levels can be excellent choices, with substantial reductions in carbon emissions, energy consumption, and cost.

The analysis of the heatmap also reveals that low replacement levels of fly ash (0-10%) have a negligible effect on strength and are suitable for structural applications where only a slight reduction in strength is acceptable. Moderate replacement levels (20-30%) can still provide acceptable performance after 28 days of curing and may be suitable for general construction purposes. However, high replacement levels (40-50%) require careful consideration of curing time and may only be viable for certain applications that can tolerate a reduction in strength or where extended curing periods are feasible.

VI. FUTURE DIRECTIONS

While the simulation provides valuable insights, there are several areas that warrant further research. Future studies could focus on:

1) Optimized Mix Design: Future research should focus on developing optimized concrete mix designs that strike a balance between fly ash content, compressive strength, and curing time. This could involve experimenting with different types of fly ash and other supplementary cementitious materials to improve performance.
2) Advanced Curing Techniques: Investigating advanced curing methods, such as high-pressure steam curing or the use of curing accelerators, could further mitigate the strength loss observed with higher fly ash replacement levels, making fly ash-based concrete more viable for structural applications.
3) Long-Term Durability Studies: Further studies are needed to assess the long-term durability and performance of fly ash-based concrete in real-world conditions, including its resistance to environmental factors like moisture, temperature variations, and chemical attacks.
4) Fly Ash Sourcing and Quality Control: Research should focus on standardizing fly ash quality and sourcing methods to ensure consistency in its use as a cement substitute. This could involve developing guidelines for fly ash classification and processing to optimize its properties for concrete production.
5) Life Cycle Assessment (LCA): Conducting comprehensive life cycle assessments (LCA) of fly ash-based concrete to evaluate its environmental impact across all stages, from production to disposal, would provide deeper insights into its sustainability benefits compared to traditional concrete.
6) Wider Application Range: Expanding the use of fly ash-based concrete in various construction applications, including high-strength and high-performance concrete, can further increase its adoption and provide a sustainable solution for large-scale construction projects.
7) Automation and AI Integration: Integrating AI and machine learning techniques for real-time monitoring and optimization of fly ash concrete mixes can enhance the precision of mix design, curing, and strength prediction, leading to more efficient and sustainable concrete production processes.

VII. CONCLUSION

This research shows excellent potential for fly ash as a sustainable alternative to cement in concrete production. The use of fly ash not only impacts the environment due to decreased carbon emissions and consumption of energy but also provides a critical economic advantage by reducing production costs. Even though the higher fly ash replacement level lowers the compressive strength, it can be traded off through appropriate mix designs and the incorporation of supplementary materials.

The simulation results validate the feasibility of using fly ash in concrete, especially for non-structural and infrastructure applications where high-strength concrete is not critical. The findings highlight the importance of fly ash as a valuable resource in promoting sustainability within the construction industry. Fly ash contributes to waste reduction and offers an environmentally friendly solution to meet the growing demand for concrete.

The heatmap analysis further reveals the effect of curing time and fly ash replacement levels on the compressive strength of concrete. The results indicate that although higher fly ash replacement levels result in a decrease in early strength, the compressive strength increases significantly with longer curing times, especially at 28 days. This suggests that, if properly cured, the strength of fly ash-based concrete can recover and perform satisfactorily for many applications.

With changing construction practices, it will be the key to achieve sustainability at a global level through sustainable material incorporation such as fly ash. Fly ash-based concrete can find a key place in the list of environmentally as well as economically sound production, putting it ahead as a strong player in greener and more sustainable construction.

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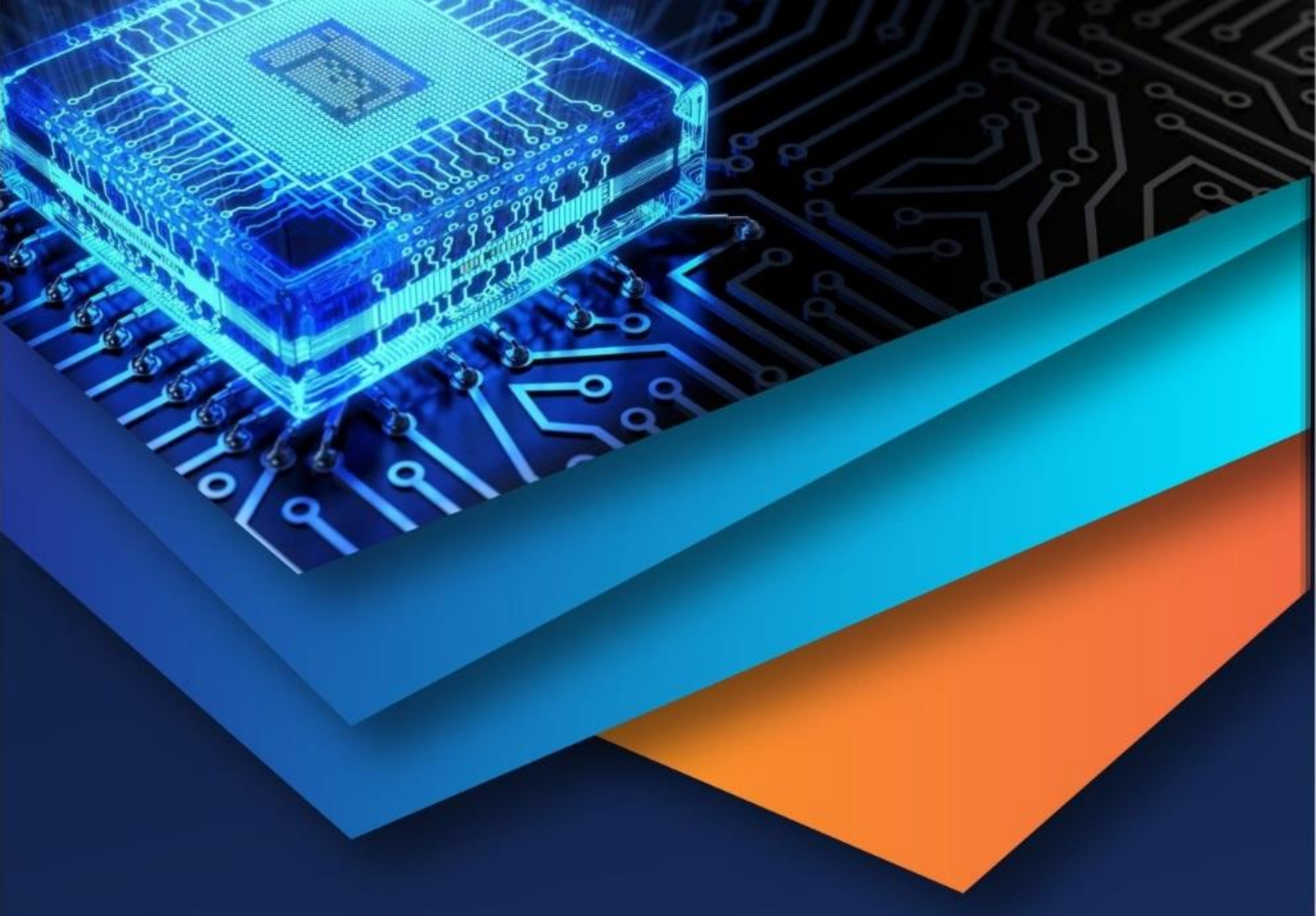

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