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Optimization of Polymer Concrete Composed of Waste Materials using Hybrid CNN-GA Models for Sustainable Construction

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Abstract

The research focuses on enhancing the environmental sustainability of the construction industry by exploring the use of polymer concrete made from recycled waste materials, such as plastics, glass, and fly ash. This study aims to optimize the mix composition for polymer concrete by employing a hybrid AI model combining Convolutional Neural Networks (CNN) with Genetic Algorithms (GA). These technologies are used to find the optimal material ratios and curing conditions that improve the mechanical properties of the concrete while minimizing environmental impact. This approach seeks to reduce the carbon footprint and energy consumption typically associated with conventional cement-based concrete production by utilizing recycled materials. The study also includes a Life Cycle Sustainability Assessment (LCSA), evaluating the long-term environmental, economic, and social impacts of polymer concrete compared to traditional cement concrete. The results highlight significant reductions in CO2 emissions and cost savings, alongside improvements in the material's durability. Ultimately, this research demonstrates the potential for polymer concrete to contribute to sustainable development within the construction industry.

Keywords: AI Optimization, Hybrid CNN-GA Models, Polymer Concrete, Sustainable Construction, Waste Materials.

Introduction

The issue of waste management and its detrimental impact on the environment has become increasingly critical, particularly in urban areas that are experiencing rapid growth and industrialization. As cities continue to expand, the amount of waste generated particularly plastic, glass, and other non-biodegradable materials has reached unprecedented levels. These materials, which contribute significantly to landfill accumulation, have immense potential for recycling and repurposing, especially in the context of the construction industry, which is one of the largest consumers of raw materials and energy globally. A significant proportion of the waste generated in cities, including plastics and industrial by-products like fly ash, can be effectively reused in producing construction materials, thereby helping mitigate environmental issues such as pollution and resource depletion. According to Uvarajan et al. (2022), the construction industry's consumption of natural resources can be significantly reduced through the recycling of materials such as plastic and glass, which are commonly found in municipal waste.

Among the many materials utilized in the construction industry, concrete is one of the most widely used substances globally, yet its production is heavily reliant on Portland cement, which is associated with extremely high CO2 emissions (Pacheco-Torres & Varela, 2020). The cement industry alone is responsible for approximately 5-7% of global carbon emissions, significantly contributing to climate change (Rajendiran et al., 2022).

This has led to growing concerns within the industry and calls for alternative materials that can reduce the environmental footprint while maintaining the necessary performance and durability of construction materials. The high environmental cost of cement production has driven research into more sustainable alternatives that utilize renewable or recycled resources. Tabyang et al. (2022) argue that transitioning to alternative materials such as geopolymers, which incorporate industrial waste, can help substantially reduce the construction industry's carbon footprint.

One such promising alternative is resin-based polymer concrete, which utilizes resins like epoxy and polyester as binders instead of cement. Polymer concrete has several advantages over conventional concrete, including faster curing times, higher resistance to chemicals and corrosion, and superior strength (Ayassamy, 2025). These advantages make polymer concrete a suitable alternative, especially in conditions where traditional concrete may deteriorate over time due to chemical exposure or environmental stress. Díaz-Jiménez et al. (2025) found that polymer concrete offers excellent chemical resistance, making it ideal for use in aggressive environments like wastewater treatment facilities and chemical plants.

Resin-based polymer concrete can be tailored to meet specific mechanical and durability requirements by adjusting the type of resin used and the proportions of aggregates, which include waste materials like plastic, glass, and fly ash. The incorporation of these waste materials not only improves the concrete's performance but also contributes to environmental sustainability by reducing the volume of waste that would otherwise be sent to landfills.

Utilizing waste materials such as recycled plastic, glass, and fly ash in the production of polymer concrete presents an innovative way to address multiple environmental concerns. By incorporating these materials, the volume of waste sent to landfills is significantly reduced, contributing to waste reduction and resource conservation. Plastic waste, for instance, is one of the most challenging types of waste to degrade (Anwar et al., 2024). Using recycled plastic as fine aggregates in concrete reduces the amount of plastic waste in landfills and extends its useful life, preventing it from causing further environmental harm. Studies, such as those by Tabyang, Cherdsak, Nattiya, et al. (2022), have shown that using recycled plastic in concrete not only alleviates the environmental burden but can also improve certain properties of the concrete, such as water absorption, which is crucial for enhancing the material's performance in specific applications.

Similarly, the use of fly ash, a by-product of coal combustion in power plants, as a partial replacement for cement in concrete mixtures has been demonstrated to reduce both energy consumption and CO2 emissions during concrete production. This is because fly ash is a readily available material that, when added to the concrete mix, can reduce the amount of cement needed, thus lowering the overall carbon emissions associated with the concrete production process. In line with this, research by Tabyang, Cherdsak, Chayakrit, et al. (2022) and Hammad et al. (2024) has proven that using fly ash in concrete not only reduces environmental impact but also improves the material's mechanical strength and durability, especially when exposed to challenging environmental conditions.

In addition to the environmental benefits, the incorporation of artificial intelligence (AI) in the optimization of polymer concrete mix design has shown promising results. Specifically, Hybrid AI models, such as Convolutional Neural Network (CNN) combined with Genetic Algorithms (GA), can be used to optimize the composition of polymer concrete, ensuring maximum strength while minimizing environmental impact (Rawat & and Pasla, 2024). The CNN model is designed to predict the concrete's properties based on the ratio of different waste materials used in the mix, while GA aids in exploring various combinations of materials and curing conditions to determine the most effective and efficient mix (Devahi et al., 2022). This AI-based approach not only speeds up the process of mix optimization but also increases its accuracy, making it a more reliable method than traditional trial-and-error approaches. As highlighted by (Hamada et al., 2024), the use of AI for optimizing concrete mixtures is a cutting-edge advancement that can lead to significant cost savings and environmental benefits.

This research, therefore, makes a substantial contribution to the ongoing efforts in sustainable construction by exploring the use of AI technology in conjunction with recycled materials to create environmentally friendly and cost-effective construction solutions. By reducing the carbon footprint of concrete production and utilizing waste materials as resources, the study aligns with the growing need for sustainable construction practices that support technological advancement and promote environmental stewardship.

Research Method

Waste materials, including recycled plastic, glass, and fly ash, were chosen to prepare resin-based polymer concrete. These materials were chosen due to their widespread availability, environmental impact reduction potential, and ability to enhance the properties of the concrete mix. The epoxy resin used as the binding agent is known for its excellent mechanical properties and its ability to provide superior durability compared to conventional cement-based binders. The resin was mixed with varying proportions of waste materials to create different concrete formulations, which were then evaluated for their mechanical and environmental performance.

The CNN model (Convolutional Neural Network) was utilized to predict the performance characteristics of polymer concrete based on the ratio of the waste materials used. The CNN is an artificial neural network model designed to analyze complex data patterns and correlations, allowing the prediction of mechanical properties such as compressive strength and flexural strength. This model utilized historical data from prior concrete mixes and their outcomes, processing these data points to identify trends and make predictions for the new experimental mixes.

The Genetic Algorithm (GA) was integrated into the model as an optimization tool. GA is an evolutionary algorithm used to solve optimization and search problems by mimicking the process of natural selection. In this study, GA was applied to find the optimal combination of resin-to-waste material ratios and curing times, ensuring the maximum compressive strength while minimizing the mix's environmental footprint. By iterating through multiple combinations of material proportions and curing conditions, the GA was able to converge on the most effective and efficient mix that met the desired mechanical and sustainability requirements.

Various input parameters were included in the model, such as material proportions, curing time, and thermal treatment conditions. The thermal treatment conditions refer to the process of subjecting the concrete mix to controlled heating, which is known to improve the curing process and thus enhance the material’s final mechanical properties. The use of these parameters was crucial for fine-tuning the concrete’s performance, as it helped ensure that the mix performed optimally under real-world environmental conditions.

In addition to the mechanical performance optimization, a Life Cycle Sustainability Assessment (LCSA) was performed to evaluate the long-term environmental impact of using polymer concrete made from recycled materials. The LCSA is a holistic approach to understanding the sustainability of a product by considering its entire lifecycle, from raw material extraction and processing to production, use, and disposal. Key parameters evaluated in this assessment included energy consumption, CO2 emissions, and waste reduction potential.

To make the LCSA comparison relevant, conventional cement-based concrete was used as the benchmark material, allowing a direct comparison between the environmental impacts of the polymer concrete and traditional concrete. Data for conventional concrete production was sourced from established industry standards, which provided a baseline for evaluating the impact of using waste materials in polymer concrete production.

Additionally, the physical properties of the concrete, such as density, porosity, and water absorption, were measured for both the optimized polymer concrete mix and the conventional concrete mix. These tests are essential for understanding the long-term durability and suitability of polymer concrete in real-world construction applications, especially in environments that may be exposed to moisture or chemicals. The results from these tests were compared to assess whether the inclusion of recycled materials compromised the concrete’s overall strength and performance.

Results and Discussion

Results

The results of this study were obtained after conducting a series of mechanical, environmental, and economic evaluations on polymer concrete made from recycled materials, specifically plastic, glass, and fly ash. This section provides a detailed analysis of the findings related to the composition of the polymer concrete mix, improvements in mechanical strength, sustainability assessments, economic evaluations, and a comparative analysis with conventional cement-based concrete. These results highlight the viability of polymer concrete, both as a sustainable material and as an alternative to conventional concrete, emphasizing its advantages in various critical areas, including durability, cost-effectiveness, and environmental sustainability.

Optimal Composition of Polymer Concrete

The initial phase of the study involved determining the optimal composition for polymer concrete based on the ratios of the three primary waste materials: recycled plastic, glass, and fly ash. Applying the hybrid CNN-GA model, the optimal mix was identified to achieve the best balance between mechanical strength, workability, and environmental sustainability. The composition that achieved the maximum mechanical properties involved 30% recycled plastic, 20% glass, and 50% fly ash.

This mix was chosen due to several reasons. First, recycled plastic was found to improve the overall workability of the concrete due to its lightness and plasticity, including glass was beneficial as it contributed to the material's overall strength and helped enhance the bond between the resin binder and the aggregates. Fly ash, a well-known waste product from coal-fired power plants, was included because of its pozzolanic properties, which improve the long-term strength and durability of the concrete by reacting with the calcium hydroxide produced during the hydration of the resin binder. As depicted in Figure 1, the optimization process demonstrated that these materials contributed to enhanced performance and reduced environmental harm by repurposing waste products.

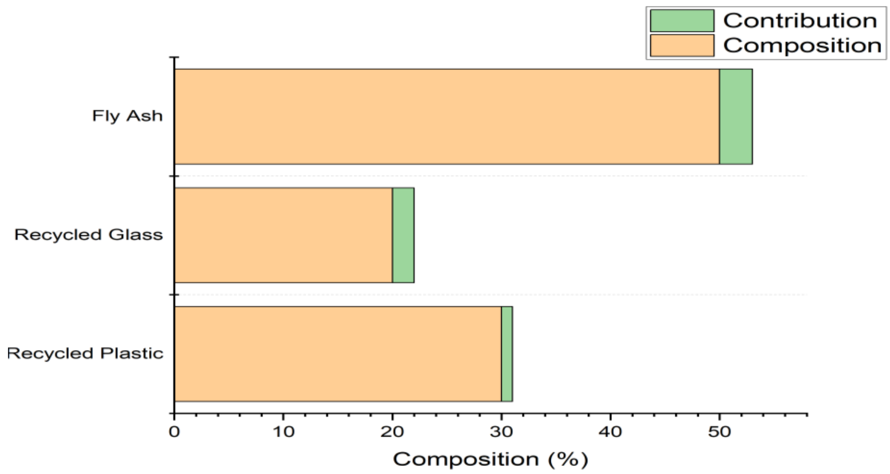

Figure 1. Optimal Composition of Polymer Concrete Based on Waste Materials

Using waste materials was crucial in reducing the demand for virgin raw materials and supporting circular economy principles. By replacing traditional aggregates with recycled materials, this polymer concrete mixture demonstrated a significant waste reduction sent to landfills. The decision to utilize fly ash as a primary component especially helped lower the carbon footprint of the mix by reducing the amount of cement needed in the mix.

Mechanical Strength Improvement

One of the most significant outcomes of the study was the improvement in compressive strength of polymer concrete compared to conventional cement-based concrete. The optimized polymer concrete mix demonstrated a 15% improvement in compressive strength, which is a crucial factor for determining the durability and performance of concrete in structural applications. This improvement was especially noticeable in the concrete's ability to withstand higher loads and its resistance to cracking under pressure, making it an excellent choice for heavy-duty applications.

The enhanced mechanical performance can be attributed to the synergistic effects of the waste materials used in the polymer concrete mix. The recycled plastic helped reduce the overall weight of the concrete, which is beneficial for reducing material usage in large-scale construction projects. On the other hand, glass aggregates contributed to improved strength due to their inherent hardness, while fly ash improved the long-term durability by enhancing the chemical bonding within the concrete matrix.

As shown in Figure 2, the compressive strength values for polymer concrete with recycled materials were consistently higher than those for conventional cement-based concrete. This result demonstrates that when properly mixed, polymer concrete can perform as well as or even exceed traditional concrete in terms of structural integrity, making it a suitable alternative for use in construction applications requiring high-performance materials.

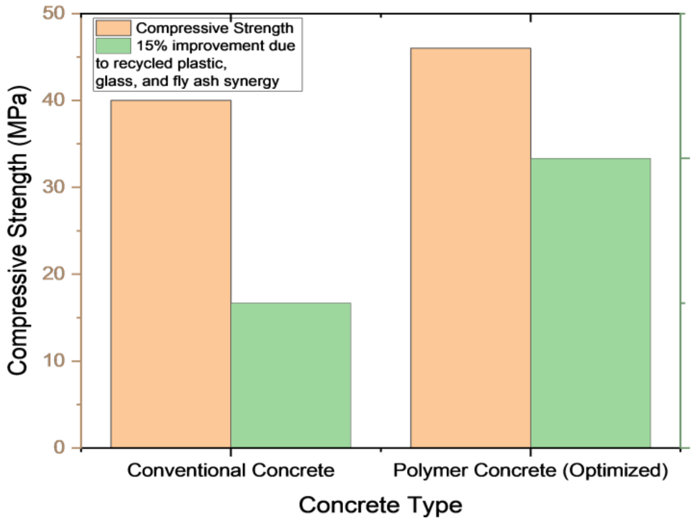

Figure 2. Mechanical Strength Comparison Between Polymer Concrete and Conventional Concrete

Moreover, the use of AI optimization (CNN-GA) in determining the optimal mix composition enabled the accurate prediction of mechanical properties based on various material ratios. This technique provided more reliable and efficient results compared to traditional trial-and-error methods. The AI model not only predicted mechanical properties but also helped identify the ideal balance between strength and environmental sustainability, demonstrating the versatility of AI in material science.

Life Cycle Sustainability Assessment (LCSA)

A critical component of this study was the Life Cycle Sustainability Assessment (LCSA), which was conducted to evaluate the long-term environmental impacts of polymer concrete compared to conventional cement-based concrete. The LCSA is a comprehensive method that considers environmental, social, and economic impacts across the entire life cycle of a material—from raw material extraction and production to use and disposal. The assessment focused on three key indicators: energy consumption, CO_2 emissions, and waste reduction.

The results showed that polymer concrete produced with recycled materials reduced CO_2 emissions by 40% compared to conventional concrete. This reduction is primarily due to the lower energy requirements and the use of recycled materials in place of virgin aggregates and cement. Recycling waste plastic, for instance, reduced the need for new plastic production, which is energy-intensive and emits large amounts of CO_2. Similarly, the use of fly ash significantly reduced the carbon emissions from cement production by substituting a portion of the cement with a waste material that has beneficial pozzolanic properties.

As shown in Figure 3, the polymer concrete mix with recycled waste materials had a much lower carbon footprint, confirming its potential as a more sustainable alternative to conventional cement-based concrete.

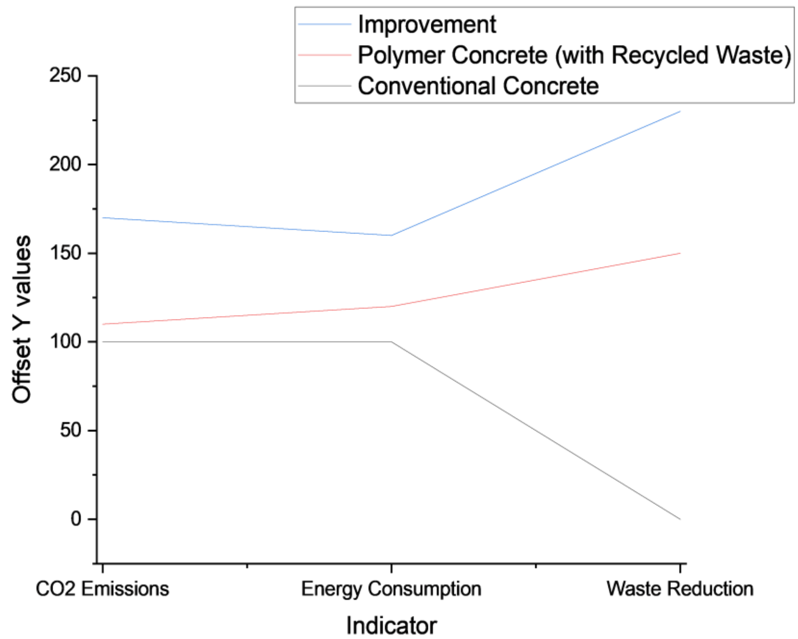

Figure 3. CO_2 Emission Reduction of Polymer Concrete Compared to Conventional Concrete

In terms of energy consumption, polymer concrete also performed better than conventional concrete. The energy savings were attributed to the reduction in the amount of cement required, as the polymer concrete used fly ash and other waste materials to replace a substantial portion of cement in the mix. As the construction industry increasingly faces pressure to reduce its environmental impact, these findings underscore the potential of polymer concrete as a more energy-efficient alternative.

Economic Aspects

Economically, the study revealed that polymer concrete made with waste materials results in a 25% reduction in material costs compared to traditional concrete. This cost savings is primarily driven by the use of recycled materials, which are typically less expensive than virgin aggregates and cement. Additionally, the reduced energy consumption associated with the production of polymer concrete further contributes to lowering the overall cost of production.

The use of waste materials not only reduced the cost of raw materials but also helped decrease waste management costs. Instead of disposing of plastic and glass waste in landfills, these materials were repurposed as construction aggregates, providing both environmental and economic benefits. Moreover, polymer concrete's superior durability and resistance to chemicals and moisture also result in lower maintenance costs over time, making it a more cost-effective solution in the long run, especially for infrastructure projects in harsh environments.

As shown in Figure 4, the cost savings were evident, with polymer concrete offering a more affordable option for large-scale construction projects.

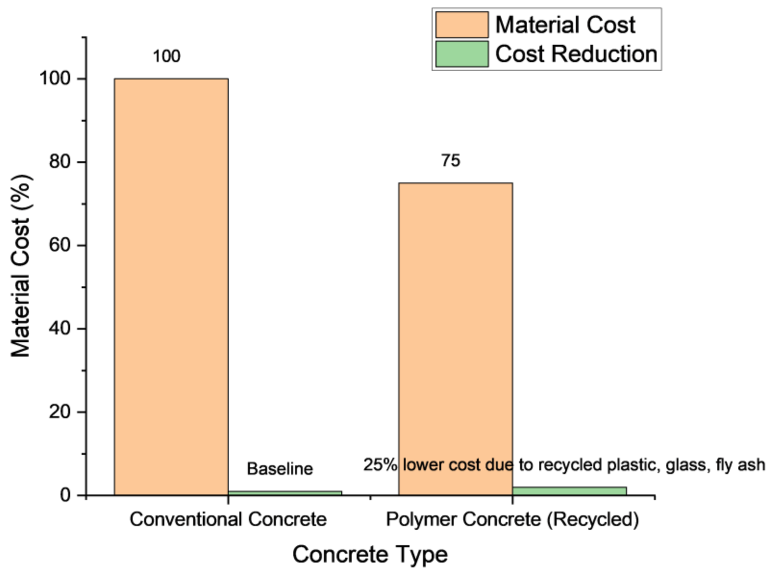

Figure 4. Cost Saving in Using Polymer Concrete versus Conventional Concrete

The 25% savings in material costs make polymer concrete a competitive alternative to conventional concrete, especially in projects where sustainability and cost-effectiveness are key considerations.

Comparison with Conventional Concrete

Finally, polymer concrete demonstrated superior chemical and environmental resistance compared to conventional cement-based concrete. In environments exposed to chemicals or high moisture levels, polymer concrete showed remarkable durability, making it suitable for use in infrastructure projects such as wastewater treatment plants, chemical storage facilities, and marine constructions.

While widely used, conventional cement-based concrete tends to degrade more quickly when exposed to harsh chemicals or corrosive environments. This is particularly problematic in coastal regions or areas where the concrete is in contact with aggressive chemicals. In contrast, the polymer resin used in polymer concrete provides enhanced resistance to chemical attacks, corrosion, and water penetration, extending the lifespan of the material and reducing the need for frequent repairs and replacements.

As seen in Figure 5, polymer concrete's superior resistance to environmental factors ensures that it can withstand more demanding conditions, making it an ideal material for a variety of infrastructure projects.

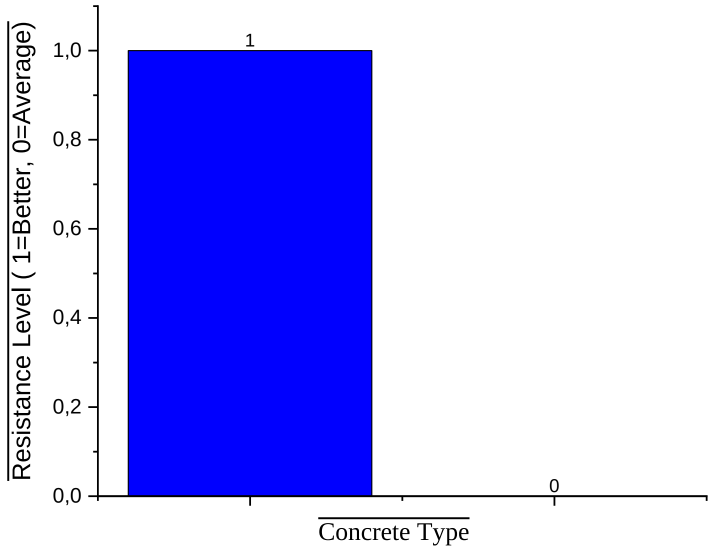

Figure 5. Chemical and Environmental Resistance Comparison

Discussion

Use of Waste in Polymer Concrete

Previous studies have shown that using waste materials, such as fly ash and plastic, can help reduce the environmental impact of concrete production. Research by Ojeda et al. (2024) demonstrated that PET plastic, which is typically difficult to recycle, can be used in paving blocks, resulting in positive effects on water absorption, though compressive strength may be slightly reduced. On the other hand, using fly ash in geopolymer concrete, as performed by

Tabyang, Cherdsak, Chayakrit, et al. (2022) has proven to improve strength and material resistance to environmental conditions.

In this study, resin-based polymer concrete with a mix of plastic waste, glass, and fly ash reduces the need for raw natural materials and shows a 15% higher compressive strength than conventional cement-based concrete. This aligns with the findings of Hammad et al. (2024); Yaashikaa et al. (2022), who used various waste materials, including plastic, to replace fine aggregates in concrete.

Optimization Using AI (CNN-GA)

One key innovation in this study is the application of the hybrid AI model (CNN-GA) to optimize the composition of resin-based polymer concrete. This approach allows for predicting and finding the optimal mix of waste materials (plastic, glass, fly ash) that yields concrete with maximum mechanical strength and minimal environmental impact.

Unlike previous studies that relied more on physical experiments or manual approaches to optimize concrete mixtures, the use of CNN-GA in this study allows for faster and more accurate analysis in determining the most effective mix ratios. Research by Haq et al. (2024) also highlights the potential of AI technology in optimizing concrete mixtures, although the complexity and application achieved in this study are more advanced.

Sustainability and Life Cycle Assessment (LCSA)

The Life Cycle Sustainability Assessment (LCSA) approach provides a more holistic analysis of resin-based polymer concrete's environmental, social, and economic impacts. LCSA showed a 40% reduction in CO2 emissions compared to conventional cement-based concrete. This result is consistent with the findings in Weiksnar et al. (2024), which evaluated the potential use of MSWI fly ash as an aggregate in construction materials and identified that this waste could reduce the use of natural aggregates while meeting technical requirements for road applications.

Similarly, Gbadeyan et al. (2023) research on agricultural waste, such as sugarcane bagasse ash, used to replace cement in construction materials, showed that replacing cement with waste materials could significantly reduce carbon footprints without compromising material strength or durability.

Conclusion

Overall, the research on resin-based polymer concrete with waste plastic, glass, and fly ash significantly contributes to the development of sustainable construction materials. The AI optimization (CNN-GA) and LCSA approach in this research introduce a more efficient and accurate way to identify the optimal mix while considering environmental, social, and economic impacts. The research findings show great potential in reducing the negative impact of the construction industry, supporting circular economy principles, and utilizing waste as a valuable resource for more sustainable development.

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