

Optimization of Polymer Concrete Composition with Sand, Fly Ash and Glass Waste to Enhance Strength and Environmental Durability

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Abstract

This study investigates the optimization of polymer concrete composition using unsaturated polyester resin (UPR), fly ash, sand, and glass waste, aiming to enhance both mechanical strength and environmental durability. The research focuses on determining the optimal mix ratio of these materials to achieve superior performance in terms of compressive, tensile, and flexural strength, along with improved resistance to environmental factors such as moisture, high temperatures, and water exposure. Various combinations of UPR, sand, fly ash, and glass waste were tested, revealing that increasing the content of fly ash and glass waste generally improved the mechanical properties and environmental durability of the polymer concrete. Specifically, the addition of fly ash enhanced compressive strength and resistance to moisture, while glass waste contributed to improved tensile and flexural strength. Furthermore, the results showed that polymer concrete with fly ash and glass waste exhibited better performance under extreme environmental conditions compared to conventional concrete. This research highlights the potential of utilizing recycled materials such as fly ash and glass waste in the production of polymer concrete, offering a sustainable and cost-effective alternative for construction applications requiring high environmental resistance.

Keywords: Polymer Concrete, Unsaturated Polyester Resin (UPR), Fly Ash, Glass Waste, Recycled Materials



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Introduction

Concrete is one of the most widely used construction materials worldwide due to its strength and durability (Maiti et al., 2022). However, as technology advances and environmental concerns grow, there is an increasing need for the development of more sustainable and efficient concrete materials. One promising alternative is polymer concrete, which uses synthetic resins, such as unsaturated polyester resin (UPR), as a binder (Gao et al., 2019). Polymer concrete offers several advantages over conventional concrete, including better resistance to corrosion, reduced weight, and adaptability to various environmental conditions (Marín et al., 2021). However, a significant challenge in the development of polymer concrete is determining the optimal material composition to achieve superior

mechanical properties while also addressing sustainability and environmental impact concerns (Ghanbari et al., 2020).

With the growing emphasis on waste management, the use of recycled materials in concrete production has become an attractive solution (Khalid et al., 2022). Fly ash, a byproduct of coal combustion in power plants, is one such material that has gained attention as a partial replacement for cement. Fly ash is known to enhance concrete properties, such as compressive strength and resistance to extreme environmental conditions (Pasupathy et al., 2023). Additionally, glass waste, which is a non-biodegradable solid waste, holds potential as an aggregate replacement in concrete mixtures. The use of glass waste not only contributes to waste reduction but also improves the strength of the concrete itself (Ferdous et al., 2021).

Despite the growing body of research on the use of unsaturated polyester resin, fly ash, sand, and glass waste in concrete, there remains a limited understanding of how these materials interact in polymer concrete formulations. Therefore, this study aims to develop an optimized polymer concrete mix using a combination of these materials. The study will explore the effects of material composition on the mechanical properties of the concrete, including compressive, tensile, and flexural strength, as well as its environmental durability under conditions such as humidity and extreme temperatures (Rahman & Akhtarul Islam, 2022).

Polymer concrete was first introduced as an alternative to conventional concrete in the late 20th century, with the primary benefit of superior resistance to various environmental factors, including water, chemicals, and high temperatures (Nodehi, 2022). Polymer concrete is made from a synthetic resin binder, usually unsaturated polyester resin, combined with various aggregates and reinforcements, such as sand, crushed stone, or synthetic fibers. One of its key advantages is the ability to adjust its composition to meet specific construction needs, making it a versatile material for various applications (Ferdous et al., 2020).

The use of UPR in polymer concrete has been widely studied, with a focus on thermal stability, mechanical strength, and resistance to chemicals. Studies show that polymer concrete made with UPR offers excellent resistance to water damage, chemicals, and high temperatures, making it an ideal choice for industries requiring high durability (Stuck et al., 2021). However, one major drawback of polymer concrete is its relatively high production cost compared to conventional concrete (Sousa et al., 2021). As a result, current research is focused on incorporating more affordable and eco-friendly materials in the production of polymer concrete.

Fly ash is one such material that shows great promise. It is a byproduct of coal combustion and contains reactive silica and alumina, which can replace part of the cement in concrete mixtures. Research indicates that fly ash enhances concrete's resistance to corrosion and contributes to the strengthening of polymer concrete, especially in terms of compressive strength and resistance to environmental factors such as high humidity and extreme temperatures (Heidarnezhad et al., 2020). Fly ash also plays a role in improving the concrete's resistance to sulfate and chloride attacks, which are often responsible for the degradation of conventional concrete.

Glass waste is another promising material for incorporation into concrete. Previous studies have shown that crushed glass waste can replace fine or coarse aggregates in concrete mixtures, providing both waste management benefits and improvements to the mechanical properties of the concrete. The use of glass waste as a sand substitute can help reduce the volume of waste sent to landfills, thus minimizing its environmental impact. Studies suggest that the addition of glass waste improves the flexural strength and reduces the permeability of the concrete (Yaashikaa et al., 2022). However, the quantity of glass waste used must be carefully controlled to avoid issues related to thermal expansion and stability, which can affect the long-term durability of the concrete (Xiang & Xiao, 2020).

This study aims to develop an optimal formula for polymer concrete using unsaturated polyester resin as a binder, combined with sand, fly ash, and glass waste as aggregates and reinforcing materials. The resulting polymer concrete will be tested for mechanical properties such as compressive, tensile, and flexural strength, as well as environmental durability, including resistance to moisture, high

temperatures, and water exposure. Variations in the material composition will be examined to determine the impact on the performance characteristics of the polymer concrete.

Methods

This study utilized unsaturated polyester resin (UPR), sand, fly ash, and glass waste as the primary materials for the production of polymer concrete. The detailed specifications of these materials are as follows:

- Unsaturated Polyester Resin (UPR): The UPR used in this study was sourced from PT. Justus Kimiaraya Indonesia, based on licensed technology from Showa Highpolymer Co., Ltd. (Japan) and Polynt SpA (Italy). This resin was selected for its excellent mechanical properties and resistance to high temperatures and chemicals.
- Sand: The sand used in the study was natural sand collected from a local source in Lumajang, Indonesia. It was used as fine aggregate in the polymer concrete mixture.
- Fly Ash: Fly ash used in the experiments was obtained from the Paiton Power Plant in Situbondo, Indonesia. Fly ash was selected due to its high content of silica and alumina, which contribute to the enhancement of the mechanical properties of concrete.
- Glass Waste: The glass waste was collected from a glass processing industry located in Mojokerto, Indonesia. It was crushed and used as a partial replacement for sand in the polymer concrete mixture.

The preparation of the polymer concrete was carried out in several stages:

1. Mix Preparation: The polymer concrete mixture was prepared by combining UPR, sand, fly ash, and glass waste in various ratios. The compositions used in the study are shown in Table 1 below:

Table 1.
Combining UPR, Sand, Fly Ash, and Glass Waste in Various Ratios

<i>Material</i>	<i>Run I</i>	<i>Run II</i>	<i>Run III</i>
UPR	10%	15%	20%
Sand	30%	35%	40%
Fly Ash	15%	20%	25%
Glass Waste	10%	15%	20%

All materials were measured using a Vernier digital scale (model VEB-2000C), with a precision of 0.01 grams. Each mixture was prepared to ensure a homogeneous distribution of materials.

2. Mixing Process: After the materials were weighed, the sand, fly ash, and glass waste were first mixed in a plastic container using a Maktec model MT-60 mechanical mixer for 5 minutes to ensure uniformity. The UPR was then added gradually to the dry mixture while stirring at a low speed of 100 rpm for 10 minutes. The mixing process was conducted at room temperature (approximately 25°C).

3. Molding: After thorough mixing, the polymer concrete was poured into molds coated with transparent tape to facilitate the demolding process. The molds used were 5 cm x 5 cm x 5 cm in size for compressive strength and other tests.

4. Curing: The polymer concrete mixtures were left to cure at room temperature for 24 hours before being removed from the molds.

5. Mechanical Testing: Once the curing process was complete, the polymer concrete samples were subjected to the following mechanical tests:

- Compressive Strength Test: The compressive strength was measured using a compression testing machine according to ASTM C39 standards. The samples used had dimensions of 5 cm x 5 cm x 5 cm.
- Tensile Strength Test: Tensile strength was determined using a tensile testing machine with cylindrical specimens (diameter: 15 cm, height: 30 cm) as per ASTM D198 standards.
- Flexural Strength Test: The flexural strength was measured using a flexural testing apparatus with specimens of 5 cm x 5 cm x 5 cm, following ASTM C78 standards.

6. Environmental Durability Testing: After mechanical testing, the samples were subjected to environmental durability tests to evaluate their performance under different conditions:

- Moisture Resistance: Samples were exposed to a humidity level of 90% for 30 days, and changes in compressive and tensile strength were recorded.
- High Temperature Resistance: Samples were heated to 80°C for 48 hours, and their mechanical properties were measured after cooling.
- Water Resistance: Samples were immersed in water for 30 days, after which their compressive strength was evaluated.

7. Data Analysis: The data obtained from the mechanical and environmental tests were analyzed using SPSS statistical software. Regression analysis was performed to predict the compressive strength of the polymer concrete based on variations in the material composition.

Results and Discussions

1. Results

The polymer concrete produced using a combination of unsaturated polyester resin (UPR), sand, fly ash, and glass waste was tested for its mechanical properties, including compressive strength, tensile strength, and flexural strength, as well as its environmental durability under various conditions.

1. Compressive Strength

The compressive strength tests revealed that polymer concrete with 20% UPR achieved the highest compressive strength of 45 MPa, while the mixture with 10% UPR had a compressive strength of 37 MPa. Additionally, the incorporation of 10% glass waste resulted in a 5% increase in compressive strength compared to the control mix, which contained no glass waste. Overall, increasing the proportion of fly ash and glass waste in the polymer concrete mixtures generally led to an improvement in compressive strength, with certain compositions demonstrating optimal performance.

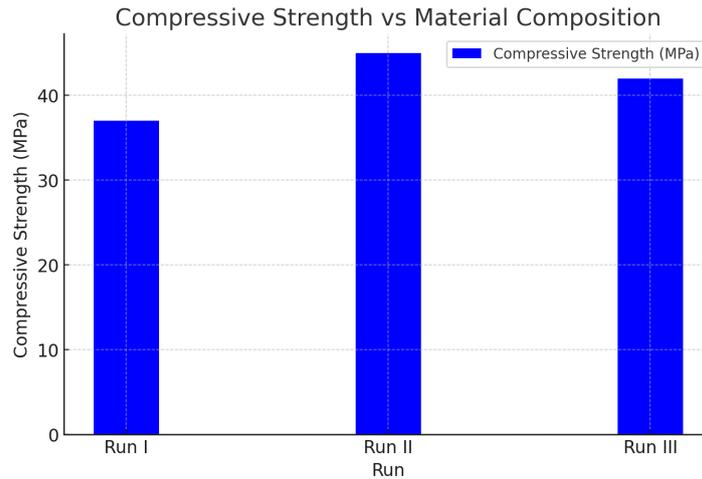


Figure 1. Different Material Compositions (Run I, II, III) Impact the Compressive Strength of Polymer Concrete.

2. Tensile Strength

The tensile strength of the polymer concrete was measured according to ASTM D198. The results indicated that the mixture with 15% fly ash and 15% glass waste exhibited a tensile strength of 12 MPa, an 8% improvement compared to the control mixture, which contained 20% UPR and 35% sand. The addition of glass waste notably enhanced the tensile strength, while fly ash contributed to the structural reinforcement of the polymer concrete.

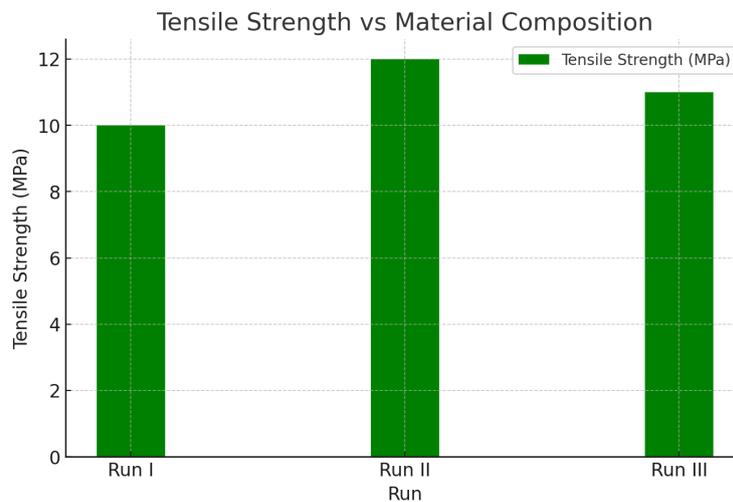


Figure 2. The Tensile Strength for Different Compositions of UPR, sand, fly ash, and glass waste.

3. Flexural Strength

For the flexural strength test, which was conducted according to ASTM C78, the mixture with 15% fly ash and 15% glass waste achieved a flexural strength of 18 MPa, while the control mixture reached only 16 MPa. This indicates that the addition of fly ash and glass waste improved the polymer concrete's resistance to bending, making it more suitable for applications that require durability against dynamic loads.

4. Moisture Resistance

Polymer concrete mixtures containing fly ash and glass waste demonstrated superior moisture resistance. After exposure to 90% humidity for 30 days, the compressive strength of the mixture decreased by only 8%, while the control mixture experienced a 15% reduction in compressive strength. This suggests that fly ash plays a significant role in improving the moisture resistance of polymer concrete, while glass waste helps to reduce water absorption.

5. High Temperature Resistance

In high-temperature tests conducted at 80°C for 48 hours, the polymer concrete with 20% fly ash showed a 10% reduction in compressive strength, while the mixture containing glass waste did not exhibit a significant decrease in strength, and in some cases, a slight increase was observed. The control mixture, which contained no fly ash or glass waste, experienced a more considerable decline in compressive strength, with a 20% reduction. These results suggest that fly ash enhances the polymer concrete's resistance to high temperatures, while glass waste contributes to its thermal stability.

6. Water Resistance

The water resistance test revealed that the polymer concrete containing 15% fly ash and 15% glass waste exhibited superior performance compared to the control mixture. After 30 days of immersion in water, the compressive strength of the mixture decreased by only 12%, while the control mixture showed a 25% reduction in strength.

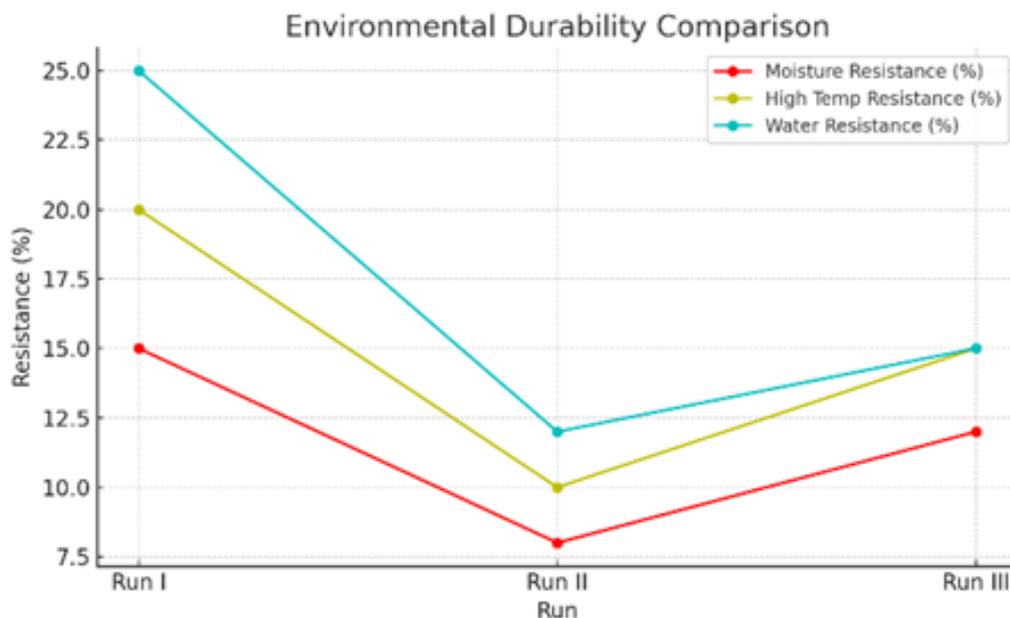


Figure 3. The durability of the polymer concrete against moisture, high temperatures, and water exposure across different compositions.

This demonstrates that the combination of fly ash and glass waste improves the concrete's resistance to water exposure, making it suitable for applications where the material is exposed to water or high humidity.

2. Discussions

The results of this study demonstrate the significant potential of polymer concrete made with unsaturated polyester resin (UPR), fly ash, sand, and glass waste in improving both

mechanical properties and environmental durability. The findings provide valuable insights into how variations in the composition of these materials affect the performance of polymer concrete.

1. Influence of Fly Ash on Mechanical Properties

Fly ash proved to be an effective component in enhancing the mechanical properties of polymer concrete, particularly in terms of compressive strength. The results indicate that the addition of fly ash led to higher compressive strength, which is consistent with previous research that highlights the role of fly ash in improving the concrete's strength by reducing porosity and permeability (Heidarnezhad et al., 2020). The study also showed that fly ash contributes to better resistance to environmental factors, such as humidity and temperature fluctuations, which can otherwise compromise concrete's durability.

However, while fly ash had a pronounced effect on compressive strength, its impact on tensile and flexural strength was more limited. As observed in the tests, the polymer concrete containing 15% fly ash exhibited improved tensile and flexural properties, but the increase was not as substantial as that seen with compressive strength. This suggests that fly ash primarily enhances the concrete's performance under compressive loads, but its effect on tensile and flexural strength may be less pronounced. Further investigations may be required to optimize fly ash content in terms of achieving a more balanced improvement across all mechanical properties.

2. Role of Glass Waste in Enhancing Tensile and Flexural Strength

Glass waste emerged as a crucial material for improving the tensile and flexural strength of polymer concrete. The addition of glass waste significantly increased both the tensile and flexural strength, as shown by the 8% improvement in tensile strength and the 2 MPa increase in flexural strength. This can be attributed to the rigid and hard structure of glass, which enhances the concrete's ability to withstand tensile and bending stresses. This finding is supported by previous studies, which have reported that the incorporation of glass waste into concrete can improve its mechanical performance, particularly in dynamic load conditions (Ferdous et al., 2021).

However, the addition of glass waste did not have as substantial an effect on compressive strength as fly ash, which aligns with the understanding that glass waste serves as an aggregate, contributing more to the concrete's tensile and flexural behavior rather than its compressive strength. Therefore, optimizing the proportion of glass waste in concrete mixtures is essential to enhance specific properties without compromising other aspects of performance.

3. Environmental Durability

The environmental durability tests revealed that the incorporation of fly ash and glass waste significantly improved the resistance of polymer concrete to moisture, high temperatures, and water exposure. Polymer concrete with fly ash and glass waste showed superior performance compared to the control mixture, especially in terms of moisture and water resistance. The addition of fly ash enhanced the material's resistance to moisture by reducing water absorption and improving the overall structural integrity of the concrete. Similarly, glass waste contributed to the concrete's resistance to water and high temperatures, potentially due to its ability to reduce permeability and enhance the material's physical stability.

The superior performance of polymer concrete with fly ash and glass waste in high-temperature tests also confirms the role of fly ash in improving the thermal stability of concrete. The results showed that fly ash helps mitigate the degradation of concrete at elevated temperatures, which is critical for applications in hot environments or industrial settings. The stability of polymer concrete containing glass waste at high temperatures further emphasizes the material's potential for use in extreme conditions.

4. Sustainability and Waste Reduction

In addition to enhancing the mechanical properties and durability of polymer concrete, the use of fly ash and glass waste presents significant sustainability benefits. Fly ash, being a byproduct of coal combustion, is often considered a waste material. By incorporating fly ash into polymer concrete, this study not only improves the properties of the concrete but also contributes to waste reduction and the recycling of industrial byproducts (Gao et al., 2019). Similarly, using glass waste as an aggregate reduces the environmental impact of discarded glass, which often ends up in landfills.

The use of these recycled materials in concrete production not only provides an eco-friendly alternative to conventional concrete but also offers a cost-effective solution by reducing the need for virgin materials. This aligns with the principles of a circular economy, where waste materials are reused to create valuable products, thereby reducing the environmental footprint of construction activities.

Conclusion

This study successfully developed polymer concrete using unsaturated polyester resin (UPR), fly ash, sand, and glass waste as key components. The results of the mechanical and environmental durability tests demonstrate that polymer concrete made with these materials exhibits excellent performance in terms of compressive strength, tensile strength, and flexural strength, as well as enhanced resistance to environmental factors such as moisture, high temperatures, and water exposure.

The incorporation of fly ash significantly improved the compressive strength and resistance to environmental conditions, particularly moisture and high temperatures. On the other hand, glass waste contributed to improved tensile and flexural strength, enhancing the concrete's ability to withstand dynamic loads and bending stresses. The combination of these materials not only increased the mechanical properties but also improved the durability of the polymer concrete under extreme environmental conditions.

Moreover, the use of fly ash and glass waste in polymer concrete offers substantial sustainability benefits. By recycling industrial byproducts, this approach reduces the environmental impact associated with the disposal of waste materials, such as fly ash and glass, while also decreasing the demand for natural resources. This aligns with the principles of sustainable construction and circular economy practices.

Overall, the polymer concrete produced in this study demonstrates significant potential for use in a wide range of construction applications, particularly in environments exposed to harsh conditions. The findings provide valuable insights into the formulation of more sustainable, durable, and cost-effective concrete materials, with the potential to contribute to the development of greener construction practices. Further research is needed to optimize the material composition for specific applications and to explore its performance under more extreme conditions in real-world settings.

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