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Enhancing Sustainable Geopolymer Concrete with Recycled Concrete Aggregate

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Abstract

This study investigates the development of sustainable geopolymer concrete (GPC) incorporating surface-treated recycled concrete aggregate (RCA) using a modified techniques. Fly ash and ground granulated blast furnace slag (GGBS) were optimized as geopolymer binders to achieve the target strength, while silica powder and chemically treated RCA enhanced the concrete performance. The sodium silicate-treated RCA significantly improved the mechanical strength, durability, and microstructural characteristics of GPC. GPC containing 60% treated RCA exhibited performance comparable to natural aggregate GPC, demonstrating the potential of treated RCA as a sustainable alternative for producing high-performance geopolymer concrete.

Keywords: Multilevel parking; Composite structure; Dynamic analysis; Seismic performance.

1. Introduction

The construction industry is one of the largest consumers of natural resources and a major contributor to global greenhouse gas emissions. Ordinary Portland cement (OPC), the primary binder used in conventional concrete, is responsible for a significant proportion of carbon dioxide (CO_2) emissions due to the energy-intensive clinker production process. Simultaneously, the rapid growth of urbanization and infrastructure development has led to an enormous generation of construction and demolition (C&D) waste, posing serious environmental and economic challenges. The extraction of natural aggregates and disposal of C&D waste not only deplete natural resources but also increase landfill requirements and environmental pollution. Consequently, developing sustainable construction materials that reduce cement consumption and promote the utilization of recycled materials has become a global research priority.

Geopolymer concrete (GPC) has emerged as a promising alternative to conventional Portland cement concrete because it utilizes industrial by-products rich in aluminosilicates, such as fly ash and ground granulated blast furnace slag (GGBS), as binder materials. These materials undergo geopolymerization in the presence of alkaline activators, forming a three-dimensional aluminosilicate network that provides excellent mechanical strength, chemical resistance, and long-term durability. Compared with OPC-based concrete, geopolymer concrete offers substantially lower carbon emissions, reduced energy consumption, and improved resistance to aggressive environments, making it an environmentally sustainable construction material.

In parallel with the development of geopolymer binders, the incorporation of recycled concrete aggregate (RCA) has attracted considerable attention as an effective strategy for conserving natural aggregate resources and minimizing construction waste. RCA is produced by processing demolished concrete and has the potential to replace natural coarse aggregates in new concrete. However, the widespread use of RCA remains limited because of its inferior quality compared with natural aggregates. The presence of adhered old mortar increases porosity, water absorption, and microcracking, resulting in weaker interfacial transition zones and reduced mechanical and durability performance. These inherent deficiencies often restrict the replacement level of RCA in structural concrete.

To overcome these limitations, several surface treatment techniques have been developed to improve the quality of RCA. Mechanical, chemical, and mineral-based treatments are commonly employed to remove or strengthen the adhered mortar, reduce porosity, and enhance the bond between the aggregate and the surrounding matrix. Among chemical treatments, sodium silicate has demonstrated significant potential by penetrating the porous mortar and reacting with calcium hydroxide to form additional calcium silicate hydrate (C–S–H) gel, thereby reducing permeability and improving aggregate strength. Acid treatments, such as hydrochloric acid, are also effective in removing weak adhered mortar and improving the surface characteristics of RCA. These treatments contribute to improved mechanical properties and enhanced durability of recycled aggregate concrete.

Another promising approach for improving recycled aggregate concrete is the modified two-stage mixing approach (M-TSMA). Unlike the conventional mixing method, the M-TSMA allows recycled aggregates to interact with cementitious or geopolymer materials during the initial mixing stage, enabling better penetration of fine particles into the porous surface of RCA. This process strengthens the interfacial transition zone, reduces internal voids, and enhances the homogeneity of the concrete matrix. The incorporation of supplementary cementitious materials such as silica powder and GGBS during the pre-mixing stage further contributes to pore refinement and matrix densification, leading to significant improvements in strength and durability.

Although considerable research has been conducted on geopolymer concrete and recycled aggregate concrete independently, relatively few studies have investigated their combined application. Moreover, limited attention has been given to the synergistic effects of chemically treated RCA and modified two-stage mixing in geopolymer concrete systems. Most previous investigations have focused primarily on compressive strength, while comprehensive evaluations of flexural strength, splitting tensile strength, durability under aggressive environments, and microstructural characteristics remain scarce. Furthermore, the optimum replacement level of treated RCA capable of maintaining performance comparable to natural aggregate geopolymer concrete has not been fully established.

Microstructural characterization plays a vital role in understanding the mechanisms responsible for the enhanced performance of geopolymer concrete containing treated RCA. Techniques such as scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (EDS) provide valuable information regarding matrix densification, elemental distribution, pore structure, and the quality of the interfacial transition zone. Establishing the relationship between microstructural features and engineering properties is essential for optimizing sustainable geopolymer concrete mixtures and ensuring their long-term performance.

The present study addresses these research gaps by developing a sustainable geopolymer concrete incorporating surface-treated recycled concrete aggregate using a modified two-stage mixing approach. Fly ash and GGBS are employed as geopolymer binders, while silica powder is introduced to enhance matrix densification. RCA is chemically treated to improve its physical and mechanical characteristics before incorporation into geopolymer concrete at different replacement levels. The resulting concrete mixtures are evaluated through comprehensive mechanical, durability, and microstructural investigations. The findings provide a practical pathway for maximizing the utilization of recycled concrete aggregates while maintaining high-performance geopolymer concrete, thereby contributing to sustainable construction practices, resource conservation, and reduction of the environmental impact associated with conventional concrete production.

2. Literature Review

The construction industry plays a vital role in global economic development; however, it is also one of the largest contributors to environmental degradation due to its extensive consumption of natural resources and energy. Ordinary Portland cement (OPC), the primary binder used in conventional concrete, is responsible for approximately 7–8% of global anthropogenic carbon dioxide (CO_2) emissions because of the calcination of limestone and the high-temperature clinker production process (Scrivener et al., 2018; Andrew, 2018). In addition to greenhouse gas emissions, the extraction of natural aggregates causes depletion of non-renewable resources, ecosystem disruption, and increased energy consumption. Simultaneously, rapid urbanization and infrastructure renewal generate enormous quantities of construction and demolition (C&D) waste, much of which is disposed of in landfills, creating serious environmental and waste management challenges (Tam et al., 2018). These issues have intensified the demand for sustainable construction materials that minimize environmental impacts while maintaining structural performance. Geopolymer concrete, produced using industrial by-products such as fly ash and ground granulated blast furnace slag (GGBS), has emerged as a promising low-carbon alternative to OPC concrete. Furthermore, the utilization of recycled concrete aggregate (RCA) derived from C&D waste reduces dependence on virgin aggregates and promotes a circular economy through resource conservation. Consequently, integrating geopolymer binders with recycled aggregates offers an effective strategy for reducing carbon emissions, conserving natural resources, and advancing sustainable infrastructure development (Provis, 2018; Shi et al., 2023).

Geopolymer concrete (GPC) is a sustainable alternative to ordinary Portland cement (OPC) concrete, produced by activating aluminosilicate-rich materials such as fly ash, ground granulated blast furnace slag (GGBS), metakaolin, or other industrial by-products with alkaline solutions. The geopolymerization process forms a three-dimensional aluminosilicate network that imparts high compressive strength, low shrinkage, excellent resistance to chemical attack, and superior durability. Compared with OPC concrete, GPC significantly reduces carbon emissions, energy consumption, and reliance on natural resources, making it an environmentally friendly construction material. Owing to these advantages, geopolymer concrete has gained increasing attention for sustainable infrastructure and circular economy applications (Provis, 2018; Davidovits, 2020; Shi et al., 2023).

3. Methodology

The complete experimental investigation was conducted in phases, Phase I involved the characterization of all raw materials, including cement, fly ash, GGBS, fine aggregate, natural coarse aggregate, and superplasticizer. Fly ash–GGBS-based geopolymer concrete (GPC) mixtures were developed using the target strength design approach with a constant binder content. The influence of different mix parameters on workability, compressive strength, and microstructural characteristics was investigated. Phase II focused on the evaluation and modification of recycled concrete aggregate (RCA) obtained from construction and demolition waste. RCA was treated using sodium silicate (Na_2SiO_3) and hydrochloric acid (HCl) solutions to enhance its surface quality and mechanical properties. The optimized treated RCA was further analyzed through microstructural investigation. Recycled aggregate concrete (RAC) mixtures incorporating different percentages of untreated and treated RCA were prepared using various mixing techniques, and their fresh and mechanical properties were assessed. The mechanical performance was further predicted using the SVR model.

Table 1: Percentage of mortar lost adhering to RCA after treatment with HCl

Sr.No	RCA size	0.5 M HCl	0.5 M HCl	1 M HCl	1 M HCl	1.5 M HCl	1.5 M HCl
1	Adhered mortar loss (%)	1 day	7 day	1 day	7 day	1 day	7 day
2	5-20 mm	3.10	2.85	5.10	4.88	7.77	9.99

4. Results and Analysis

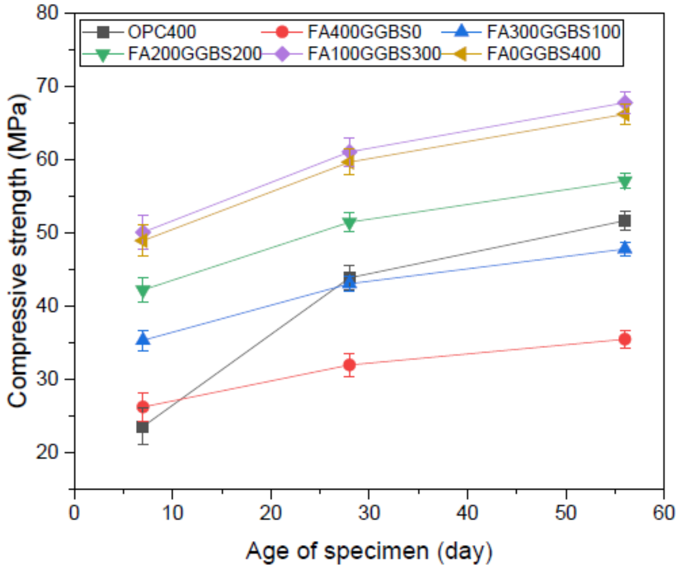

Fig.1 Compressive strength of OPC400 and GPC batches activated with 14 M NaOH and cured at 80°C after 7, 28, and 56 days of ageing.

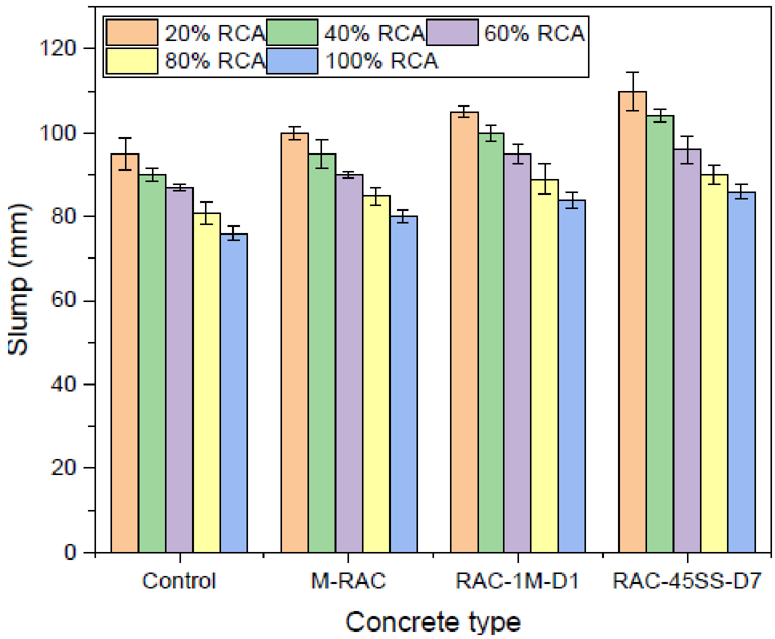

Fig.2 .Slump values of concrete mixes with treated, untreated, and NCA RCA at various replacement amounts.

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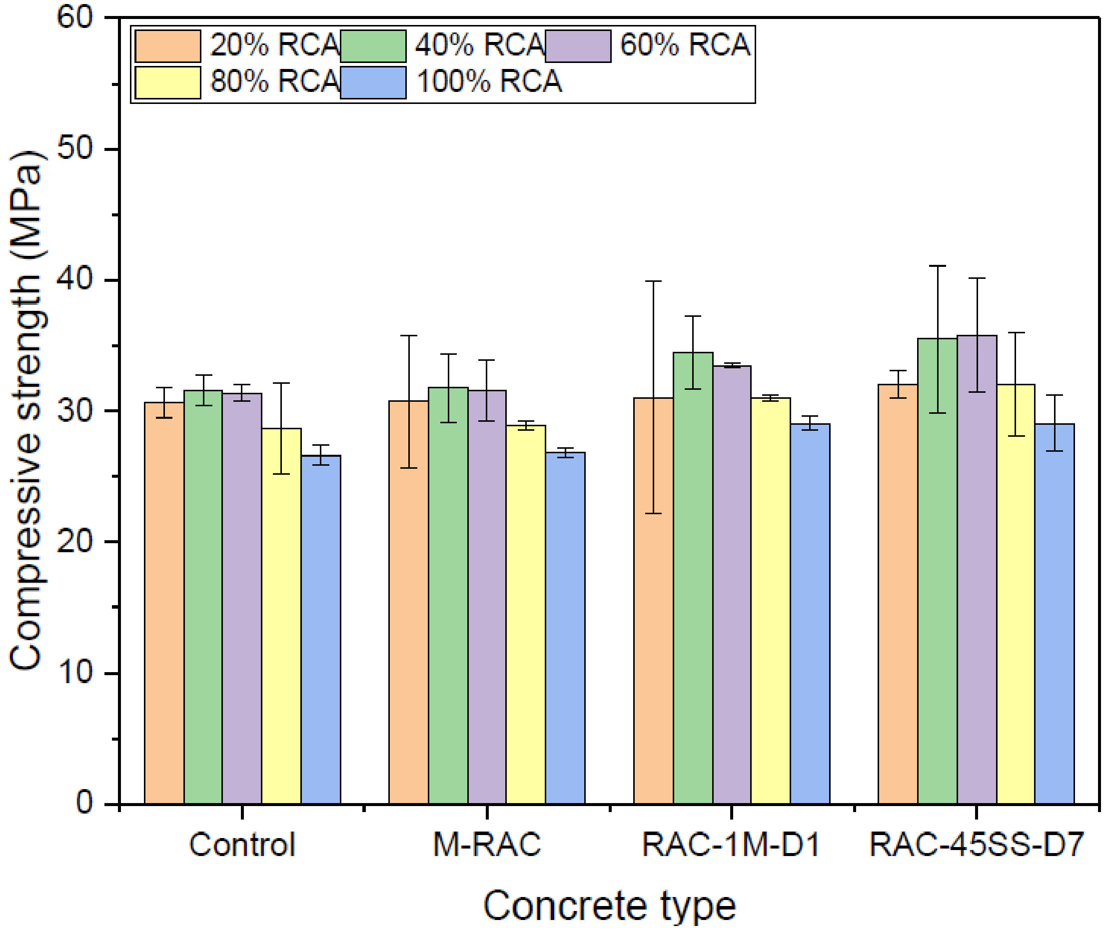

Fig. 3 Compressive strength of verious mix,

5. Conclusion

To attain high compressive strength, a sustainable GPC mix with fly ash and GGBS may be created utilizing the target strength technique with fixed binder content mix design approach.
• After conducting tests with various fly ash and GGBS content ratios, the mix design for the GPC is created. Additionally, three distinct NaOH concentrations (10 M, 12 M, and 14 M) are used to activate each GPC batch. The impact of higher curing temperatures—65°C and 80°C—on the characteristics of GPC batches is examined.

• Every batch of GPC mixes has a workability, or slump value, that falls within the range. It is also noted that when the concentration of NaOH increases, the slump value lowers.

When compared to the control mix, the achieved mechanical strength was marginally better. At 40% RCA content, M-RAC's maximum 28-day compressive strengths were 4%.

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Declaration of Conflicting Interests

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