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Recycled aggregate with GGBS geopolymer concrete behaviour on elevated temperatures

Pramod Kumar
Department of Civil Engineering, Mohan Babu University (SVEC), Tirupati, India
Bheem Pratap
Department of Civil Engineering, Graphic Era Deemed to be University, Dehradun, India, and
Anasuya Sahu
Department of Civil Engineering, National Institute of Technology Jamshedpur, Jamshedpur, India

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Abstract

Purpose – This study explored the effects of incorporating RA into geopolymer concrete, particularly examining its performance under ambient and elevated temperatures ranging from ambient temperature to 700°C.

Design/methodology/approach – The current study incorporates RA to replace conventional aggregates in the mix, with replacement levels ranging from 0 to 50%. Each mix designation is identified by a unique ID: RA0, RA10, RA20, RA30, RA40 and RA50, representing the percentage of RA used. The alkaline-to-binder ratio adopted for this study is 0.43.

Findings – The compressive strength starts at 50.51 MPa for 0% RA and decreases to 39.12 MPa for 50% RA after 28 days. It is highest with 0% RA and diminishes as the RA content increases. All mixes show a slight increase in compressive strength when heated to 100°C. However, the compressive strength starts to decrease for all mixes at 300°C. At 700°C, there is a drastic drop in compressive strength for all mixes, indicating significant structural degradation at this temperature.

Originality/value – The study evaluates the qualitative impact of RA on the properties of geopolymer concrete when exposed to severe temperatures. The experimental setup included several tests to assess the concrete mixes' mechanical properties and responses. Specifically, the researchers conducted compressive, flexural and split tensile strength tests.

Keywords Geopolymer concrete, Recycle aggregate, Elevated temperature, Mass loss

Paper type Research paper

Introduction

Urbanization in developing countries has surged, worsening the environmental impact of cement production (Alaloul *et al.*, 2020). Cement manufacturing is a significant source of greenhouse gases (GHGs), contributing to global warming. Therefore, sustainable alternatives to cement are essential to mitigate environmental degradation (Zeyad *et al.*, 2021). Various industrial waste materials can be repurposed to replace conventional cement materials. Utilizing these wastes in sustainable cement alternatives can significantly lower GHG emissions, reduce costs, and reduce reliance on natural raw materials (Mikulčić *et al.*, 2016).

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One promising alternative to conventional cement is using alkali-activated materials, which lead to the production of geopolymer concrete (Das *et al.*, 2020). Geopolymers are inorganic polymers formed by the reaction of aluminosilicate materials with alkaline solutions. These materials can completely replace cement in concrete, offering a sustainable and eco-friendly solution. Using industrial wastes, such as fly ash, slag, and rice husk ash, as raw materials for geopolymers further enhances their environmental benefits (Wainwright and Rey, 2000; Gogineni *et al.*, 2024a, b). These waste materials are often by-products of other industrial processes and would otherwise contribute to landfill waste.

Geopolymers are innovative alternative binders that provide an eco-friendly solution for concrete production by utilizing industrial by-products (Kumar *et al.*, 2024a, b, c; Pratap *et al.*, 2024). Creating a geopolymer binder involves the reaction between an alkaline solution and industrial waste materials rich in silica and aluminium, such as fly ash, blast furnace slag, and metakaolin. The geopolymerization process starts when an alkaline solution is chemically reacted with the waste materials containing silicon (Si) and aluminium (Al) atoms. The development and application of geopolymers in concrete have been extensively studied (Chithambaram *et al.*, 2019), demonstrating their potential to enhance concrete's durability and mechanical properties while promoting sustainability in the construction industry. Ground granulated blast furnace slag (GGBS) is extensively used in geopolymer concrete due to its sustainable and performance-enhancing properties (Kumar *et al.*, 2024a, b, c; Sharma *et al.*, 2024). As a by-product of the steel industry, GGBS is an eco-friendly alternative to traditional Portland cement (Paswan *et al.*, 2024). It enhances mechanical properties, including compressive and tensile strength (Pratap *et al.*, 2023).

Construction and demolition (C&D) waste has become a significant environmental challenge globally, with the production of such waste surpassing 30 billion tons per year (Liang *et al.*, 2020). This immense waste necessitates effective management strategies to mitigate its environmental impact. A promising approach to addressing this issue is recycling C&D waste into recycled aggregates (RA), which can be used in concrete production (Lopez-Uceda *et al.*, 2020). In 2016, India alone generated approximately 15 billion tonnes of C&D waste. However, the country struggled with low utilization rates, recycling less than 10% of this waste (Jain *et al.*, 2019). This low recycling rate exacerbates landfill overflow and environmental degradation, highlighting the urgent need for improved waste management practices. Integrating RA into concrete composites as a partial or complete replacement for natural aggregates presents a sustainable engineering solution (Wang *et al.*, 2016; Kurda *et al.*, 2017). RA is classified based on its composition and physical-mechanical qualities, focusing on particle size distribution. A significant challenge in using RA in conventional concrete is the reduced compressive strength, as RA contains highly porous mortar around its surface. This porosity leads to higher water absorption, adversely affecting the concrete's performance.

Fire has played a fundamental role in the development of human civilization (Dunning, 1996), acting as both a crucial resource and a potential hazard. From its initial discovery, fire enabled early humans to cook food, stay warm, and fend off predators, thus becoming an integral part of daily life and societal progress. However, despite its numerous benefits, fire is also capable of causing significant disasters (Joshi and Saini, 2023), particularly in modern contexts such as high-rise buildings, tunnels, fuel vessels, and nuclear plants. In the aftermath of earthquakes, the fires that often break out can cause more damage than the quake (Ibragimov and Jabbarov, 2023), underscoring the dual-edged nature of fire. Structures incorporate active and passive fire protection systems to mitigate the risks associated with fire. Despite these measures, fire resistance remains a critical consideration in the design of structural systems (Kodur *et al.*, 2012). Concrete is widely regarded as a fire-resistant material; however, this belief is only partially accurate. Concrete undergoes significant changes in its physical and chemical properties at high temperatures. Ordinary Portland cement (OPC) concrete, for instance, experiences dihydroxylation of calcium hydroxide ($Ca(OH)_2$) at temperatures between 400–500°C (John and Lothenbach, 2023). Furthermore, the differential thermal expansion of the aggregates and the cement paste generates stress at the interface transition zone (ITZ), forming cracks (Zhou and Xu, 2023). Cracks in concrete facilitate the rapid transfer of heat, exacerbating damage when exposed to high temperatures (Yu *et al*., 2024). At around 1,000°C, concrete can lose more than 90% of its strength (Bao *et al*., 2023), making it significantly weaker and more susceptible to structural failure.

Recycle aggregate concrete (RAC) is increasingly used in structural and non-structural applications owing to its sustainability and cost-effectiveness (Behera *et al*., 2014). RAC is produced by recycling demolition waste, which is then processed into a coarse RA. At ambient temperatures, various studies have assessed the mechanical properties of RAC, such as its compressive strength, tensile strength, and elasticity (Dhir *et al*., 1999; Pedro *et al*., 2014). These properties are crucial for determining the suitability of RAC in different construction applications. However, for RAC to be reliably used in building construction, evaluating its performance under elevated temperatures and after exposure to high temperatures is essential (Salau *et al*., 2015; Salahuddin *et al*., 2019). Sarhat and Sherwood (2013) partially replaced natural aggregates with recycled aggregates to create concrete specimens. These specimens were then exposed to temperatures of 20°C, 250°C, 500°C, and 750°C to simulate conditions such as those encountered during a fire. The study concluded that the residual mechanical properties of concrete containing varying percentages of recycled aggregates were generally comparable to conventional concrete, though there were some variations. Specifically, while the recycled aggregate concrete exhibited similar behaviour to traditional concrete at lower temperatures, differences became more noticeable at higher temperatures. Chang *et al*. (2006) conducted an experimental study in which they substituted up to 30% of natural aggregates in concrete with RA. The concrete specimens were then exposed to elevated temperatures of 200°C, 400°C, and 600°C to observe the effects on their compressive strength. The results showed a gradual improvement in compressive strength from 200°C to 450°C. This increase in strength can be attributed to the densification and possible recrystallization processes occurring within the concrete matrix at these temperatures. However, beyond 450°C, a steady decline in compressive strength was observed. Vieira *et al*. (2011) explored the residual mechanical performance of concrete using varying percentages of RA, focusing on compressive strength, splitting tensile strength, and elastic modulus. The concrete samples were exposed to various temperatures: ambient, 400°C, 600°C, and 800°C. The investigation aimed to understand how RA affected the concrete's mechanical properties after being subjected to high temperatures. The results showed no significant differences in the residual mechanical behaviour between concrete made with RA and the control mixture, which was made with natural aggregates.

In this investigation, the primary objective is to explore the performance of geopolymer concrete incorporating RA when subjected to elevated temperatures. This study builds upon prior research conducted by Pratap and Kumar (2024), extending their findings to include the influence of RA on geopolymer concrete under extreme thermal conditions. In the study, Pratap and Kumar (2024) optimized fly ash and GGBS in geopolymer concrete under elevated temperature conditions. Initially, concrete specimens were prepared using locally sourced natural aggregates and coarse RA. These specimens were then exposed to varying levels of temperature, including ambient conditions and elevated temperatures of 100°C, 300°C, 500°C, and 700°C. The study evaluates the qualitative impact of RA on the properties of geopolymer concrete when exposed to severe temperatures. The experimental setup included several tests to assess the concrete mixes' mechanical properties and responses. Specifically, the researchers conducted compressive, flexural, and split tensile strength tests. These tests were crucial in understanding how the concrete's performance changes with varying percentages of RA (0%–50%). In addition to mechanical tests, the researchers also measured the mass loss of the concrete specimens during exposure to elevated temperatures. The study aims to provide qualitative insights into the potential benefits or challenges of using RA in geopolymer concrete under extreme thermal conditions.

Materials and methodology

Materials used

In the present study, various materials, including GGBS, fly ash (FA), sand, coarse aggregate (CA), recycled aggregate (RA), and a superplasticizer, are utilized to produce concrete (Figure 1). The GGBS and FA are key components with cementing properties sourced from Tata Steel in Jamshedpur. These materials are chosen due to their potential to improve the cementitious characteristics of the concrete. An X-ray fluorescence (XRF) analysis is conducted to verify the suitability of GGBS and FA. This analysis provides detailed information about the chemical compositions of these materials, which are presented in Table 1.

The sand used in the study is obtained from the Kharkai River in Jamshedpur. The specific gravity of river sand is determined to be 2.67. Coarse aggregate (CA) is procured from

Figure 1. Descriptions of materials used in the present study

Source(s): Authors' own work

Table 1. The major composition of GGBS and FA obtained from XRF

Major chemical compositions	Fly ash (%)	GGBS (%)
SiO_2	44.76	31.24
Fe_2O_3	5.71	11.45
Al_2O_3	23.53	15.61
CaO	14.41	34.38
Na_2O	0.45	0.56
MgO	1.14	5.65

Source(s): Authors' own work

a local supplier to ensure it meets the standard quality requirements for concrete production. The specific gravity of CA is measured at 2.78. In addition, recycled aggregate (RA) is extracted from construction demolition waste. The specific gravity of RA is found to be 2.27, slightly lower than that of the CA.

A poly-carboxylic ether-based superplasticizer is incorporated to enhance the workability and mechanical properties of the concrete. An alkali solution with a concentration of 12 M NaOH is prepared and used to produce a geopolymer concrete mix.

Mix design

In the study by Pratap and Kumar (2024), a previous investigation optimized the mix design of materials. The current study incorporates RA to replace conventional aggregates in the mix, varying from 0% to 50% replacement. Each mix designation is denoted by a unique ID: RA0, RA10, RA20, RA30, RA40, and RA50, indicating the percentage of RA used in the mix. The alkaline-to-binder ratio adopted for this study is 0.43. Table 2 in the present study outlines the specific mix designs, detailing the proportions of GGBS, FA, sand, CA, RA, and alkali solutions.

Sample casting

The mix design of the geopolymer concrete has been specified in Table 2. The mixing process ensures a uniform blend, which is crucial for the desired properties of the concrete. The mixed concrete is poured into moulds of cubes, prisms, and cylinders (Figure 2). Specimens were cast into cubes with 150 × 150 × 150 mm dimensions for compressive strength testing. Split tensile strength was tested using cylindrical samples with a diameter of 150 mm and a height of 300 mm. Flexural strength was determined using prism-shaped specimens with 100 × 100 × 300 mm dimensions. Initially, the samples are cured in an oven at 65°C for 24 h. This thermal curing phase is essential for accelerating the polymerization process. After the 24-h oven curing period, the samples were demoulded and cured at ambient temperature. A total of 21 specimens were cast for each type of test to assess the mechanical properties comprehensively. These specimens were tested at different ages, 3 days, 7 days, and 28 days, and samples at different temperatures (100°C, 300°C, 500°C, and 700°C) to understand how the strength of concrete evolves.

Tests

The study investigates the mechanical properties of geopolymer concrete by conducting tests on samples 28 days after casting. The tests are being performed under two temperature conditions: ambient temperature (23°C) and elevated temperatures. The selected elevated temperatures for the study are 100°C, 300°C, 500°C, and 700°C. The evaluated mechanical

Materials	Mix designation RA0	RA10	RA20	RA30	RA40	RA50
Fly ash (kg/m^3)	336	336	336	336	336	336
GGBS (kg/m^3)	84	84	84	84	84	84
Sand (kg/m^3)	580	580	580	580	580	580
Superplasticizer (kg/m^3)	2.95	2.95	2.95	2.95	2.95	2.95
Coarse aggregate (CA) (kg/m^3)	1,190	1,071	952	833	714	595
Recycle aggregate (kg/m^3)	0.00	119	238	357	476	595
NaOH (kg/m^3)	180	180	180	180	180	180

Source(s): Authors' own work

Table 2.
Mix design of geopolymer concrete

Figure 2.
Preparation of the samples for testing

Source(s): Authors' own work

properties include compressive, flexural, and split tensile strength. These tests are crucial for understanding how geopolymer concrete performs under different thermal conditions, which is essential for applications where exposure to elevated temperatures is a concern. Additionally, mass loss measurements are being performed to determine any changes in the weight of the samples after exposure to elevated temperatures. The setup for mechanical strength testing equipment is depicted in Figure 3, illustrating the apparatus used to measure compressive, flexural, and split tensile strengths. Figure 4 shows the muffle furnace subjecting the samples to elevated temperatures. The muffle furnace ensures controlled heating up to 700°C, allowing researchers to simulate and study the effects of high temperatures on the concrete samples.

Results and discussion

Compressive strength

Figure 5 presents the compressive strength variation with RA for 3, 7, and 28 days. The compressive strength decreases as the percentage of recycled aggregates increases. This trend is consistent across all curing periods (3 days, 7 days, and 28 days). The compressive strength starts at 21.42 N/mm^2 for 0% RA and drops to 14.45 N/mm^2 for 50% RA at 3 days. This represents a decrease of about 32.5%. The strength is more significantly impacted at early ages by including recycled aggregates. This could be due to the slower hydration process and the weaker initial bond formation in the presence of recycled materials. The compressive strength starts at 37.11 N/mm^2 for 0% RA and drops to 30.15 N/mm^2 for 50% RA at 7 days. This represents a decrease of about 18.7%. The compressive strength starts at 50.51 N/mm^2 for 0% RA and drops to 39.12 N/mm^2 for 50% RA at 28 days. This represents a decrease of about 22.6%. Although the strength continues to decrease with higher recycled

Source(s): Authors' own work

Figure 3.
Equipment employed for the different tests of (a) compressive strength test, (b) flexural strength test, and (c) split tensile strength test

aggregate content, the rate of decrease is less pronounced at 7 and 28 days compared to 3 days. This indicates that as the concrete cures, the hydration process helps somewhat mitigate the initial strength loss caused by recycled aggregates. At lower percentages (10%–30%), the drop in compressive strength is less severe, indicating that small amounts of recycled aggregates can be used without drastically compromising the concrete strength (Akbarnezhad *et al.*, 2015; Kumar *et al.*, 2024a, b, c). At higher percentages (40% and 50%), the drop in strength is more significant, suggesting that high levels of recycled aggregates might not be suitable for applications requiring high compressive strength. Similar types of decline in compressive strength with an increase in RA are observed by Topal *et al.* (2022) and Mohammadinia *et al.* (2016).

Recycled aggregates often contain residual mortar and other impurities, which can weaken the concrete matrix. The ITZ between the aggregate and the cement paste might be weaker with recycled aggregates, leading to lower compressive strength. Using recycled aggregates in concrete reduces compressive strength, with the extent of reduction increasing with the percentage of recycled aggregates. While recycled aggregates can be used to some extent, careful consideration must be given to the required compressive strength and the appropriate percentage of recycled aggregates to use in the mix.

Flexural strength

Figure 6 presents the flexural strength variation with RA for 3, 7, and 28 days. The flexural strength decreases as the percentage of recycled aggregates increases. This trend is consistent across all curing periods (3 days, 7 days, and 28 days). The flexural strength starts at 2.81 N/mm^2 for 0% RA and drops to 1.31 N/mm^2 for 50% RA after 3 days of curing periods. This represents a decrease of about 53.4%. The flexural strength starts at 4.95 N/mm^2 for 0% RA and drops to 2.20 N/mm^2 for 50% RA after 7 days of curing periods. This represents a decrease

Figure 4.
Muffle furnace used in experimental program

Source(s): Authors' own work

of about 55.6%. The flexural strength starts at 7.15 N/mm^2 for 0% RA and drops to 3.17 N/mm^2 for 50% RA after 28 days of curing periods. This represents a decrease of about 55.7%.

Although the flexural strength continues to decrease with higher recycled aggregate content (Ganesh and Muthukannan, 2019; Ojha and Gupta, 2020), the rate of decrease is consistent over the curing periods. This indicates that even as the concrete cures and the hydration process progresses, the inherent weakness introduced by recycled aggregates persists. At lower percentages (10%–30%), the drop in flexural strength is less severe, indicating that small amounts of recycled aggregates can be used without drastically compromising the flexural strength (Kumar *et al.*, 2024a, b, c). At higher percentages (40% and 50%), the drop in strength is more significant, suggesting that high levels of recycled aggregates might not be suitable for applications requiring high flexural strength. The use of recycled aggregates in concrete results in a reduction in flexural strength, with the extent of reduction increasing with the percentage of recycled aggregates. The impact on flexural strength is more pronounced compared to compressive strength, likely due to the nature of flexural forces which are more sensitive to weaknesses in the concrete matrix.

Split tensile strength

Figure 7 presents the split tensile strength variation with RA for 3, 7, and 28 days. The split tensile strength decreases as the percentage of recycled aggregates increases. This trend is consistent across all curing periods (3 days, 7 days, and 28 days). The split tensile strength

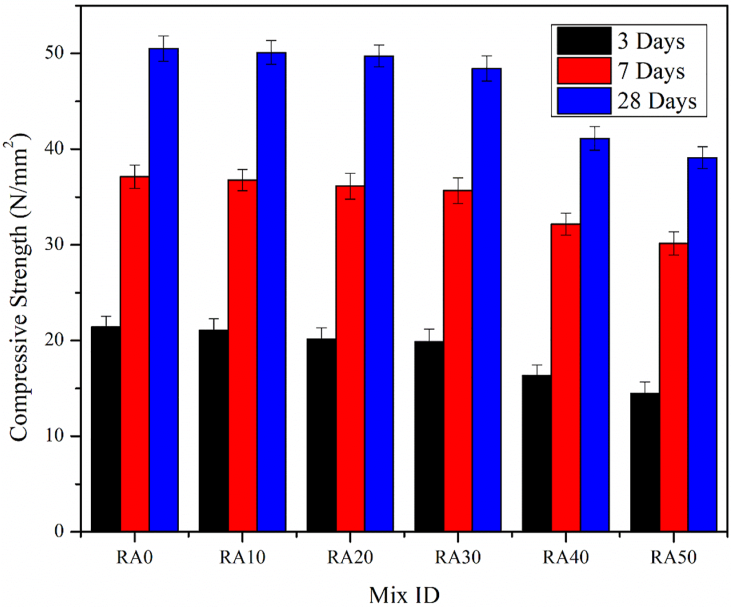

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Figure 5.
Compressive strength variation with RA

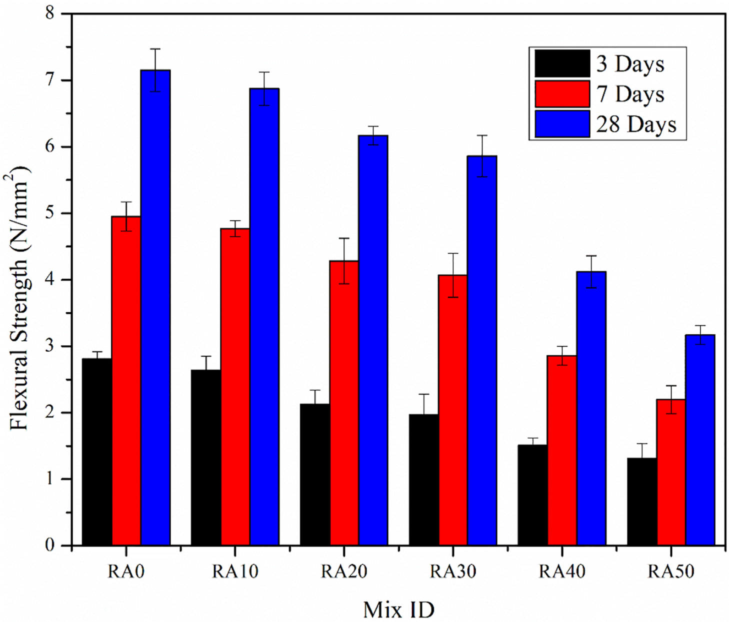

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Figure 6.
Flexural strength variation with RA

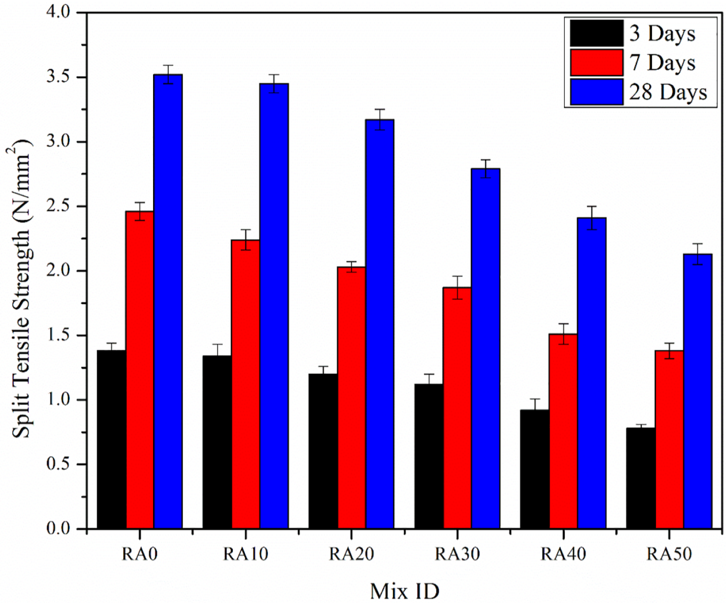

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Figure 7.
Split tensile strength variation with RA

starts at 1.38 N/mm^2 for 0% RA and drops to 0.78 N/mm^2 for 50% RA for 3-day curing periods. This represents a decrease of about 43.5%. The split tensile strength starts at 2.46 N/mm^2 for 0% RA and drops to 1.38 N/mm^2 for 50% RA for 7-day curing periods. This represents a decrease of about 43.9%. The split tensile strength starts at 3.52 N/mm^2 for 0% RA and drops to 2.13 N/mm^2 for 50% RA for 7-day curing periods. This represents a decrease of about 39.5%.

Similar to the compressive and flexural strengths, the presence of recycled aggregates leads to a reduction in split tensile strength. The split tensile strength shows a significant reduction at early ages by including recycled aggregates (Ren and Zhang, 2019). This could be due to the slower rate of hydration and weaker initial bond formation in the presence of recycled aggregates. Although the split tensile strength continues to decrease with higher recycled aggregate content, the rate of decrease is somewhat consistent over the curing periods. This indicates that even as the concrete matures and undergoes further hydration, the weaknesses introduced by the recycled aggregates remain impactful. At lower percentages (10%–30%), the decrease in split tensile strength is less severe, suggesting that small amounts of recycled aggregates can be used without drastically compromising the split tensile strength (Kumar *et al.*, 2024a, b, c). The decrease is more significant at higher percentages (40% and 50%), indicating that high levels of recycled aggregates might not be suitable for applications requiring high split tensile strength. Using recycled aggregates in concrete reduces split tensile strength, with the extent of reduction increasing with the percentage of recycled aggregates. The split tensile strength is affected similarly to compressive and flexural strengths, with recycled aggregates introducing weaknesses in the concrete matrix.

Relation between mechanical properties

The Figure 8 illustrates the relationship between compressive, flexural, and split tensile strength for recycled aggregate concrete. The x-axis represents compressive strength in the

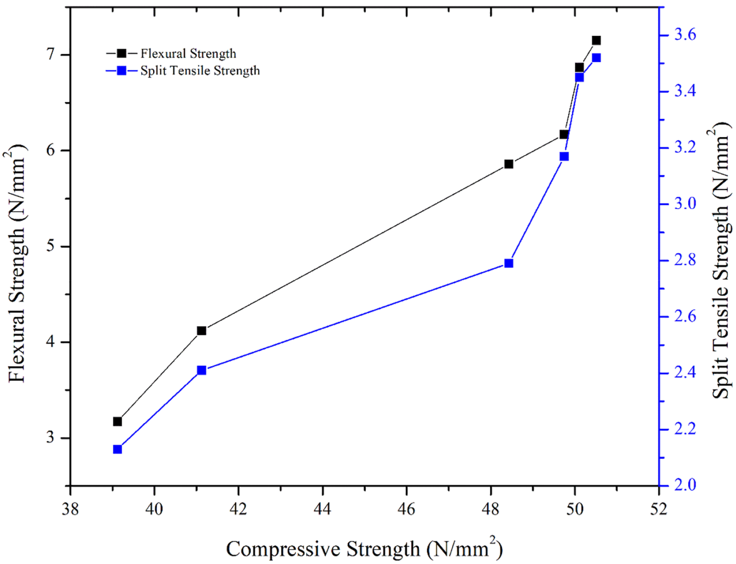

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Figure 8.
Relation between the compressive, flexural, and split tensile strength of recycled aggregate concrete

range of 38 N/mm^2 to 52 N/mm^2. The left y-axis indicates flexural strength and the right y-axis denotes split tensile strength. As the compressive strength increases, the flexural and split tensile strengths exhibit an upward trend, suggesting a positive correlation between these mechanical properties. The flexural strength begins at approximately 3.5 N/mm^2 when the compressive strength is around 40 N/mm^2. With an increase in compressive strength to about 42 N/mm^2, the flexural strength rises to around 4.5 N/mm^2. A more substantial increase is observed between compressive strengths of 44–50 N/mm^2, where the flexural strength peaks at approximately 7 N/mm^2. This pattern suggests that as the compressive strength of recycled aggregate concrete increases, its flexural strength improves significantly.

The split tensile strength also shows a positive correlation with compressive strength, although the rate of increase is more gradual than that of flexural strength. At a compressive strength of about 40 N/mm^2, the split tensile strength is approximately 2.4 N/mm^2. As the compressive strength rises to 42 N/mm^2, the split tensile strength increases to nearly 2.6 N/mm^2. The upward trend continues steadily, reaching around 3.6 N/mm^2 when the compressive strength is 50 N/mm^2. This steady progression implies that while split tensile strength improves with increasing compressive strength, it does so at a more modest pace than flexural strength.

Effect of elevated temperature on the compressive strength

Figure 9 shows the compressive strength loss at elevated temperatures from 23°C to 700°C. The compressive strength starts highest with 0% RA at 50.51 N/mm^2 and decreases with increasing RA content. This is consistent with previous observations where higher recycled aggregate content leads to lower compressive strength. There is a slight increase in compressive strength for all mixes when heated to 100°C (Tanyildizi and Yonar, 2016; Albidah *et al.*, 2022; Pratap and Kumar, 2024). This can be attributed to the additional hydration of cement particles due to moisture. The compressive strength starts to decrease at

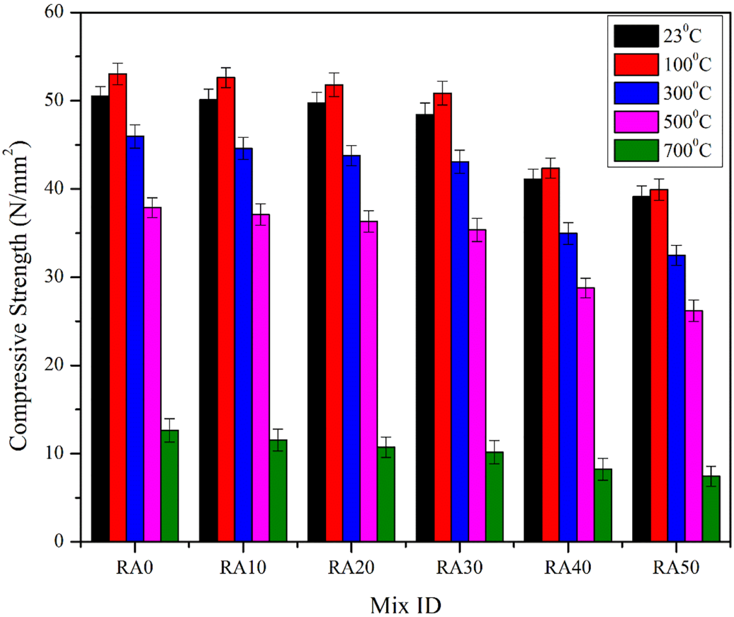

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Figure 9.
Compressive strength variation with elevated temperature

300°C for all mixes. The reduction is more pronounced in mixes with higher RA content. The compressive strength continues to decrease significantly at 500°C. Concrete with higher RA content shows a greater strength reduction than concrete with lower RA content. The compressive strength drops drastically at 700°C for all mixes. The reduction is most severe, indicating significant structural degradation at this temperature.

At elevated temperatures, concrete undergoes physical and chemical changes that degrade its mechanical properties (Özbayrak *et al.*, 2023). The loss of free water, decomposition of calcium hydroxide, and disruption of the aggregate-cement paste bond contribute to strength loss. Recycled aggregates have residual mortar and impurities, leading to a weaker concrete matrix. The presence of these weaker components exacerbates the reduction in strength at elevated temperatures. At lower temperatures (up to 100°C), there might be some beneficial effects due to further hydration. As the temperature increases beyond 100°C, the negative effects of thermal stress, dehydration, and micro-cracking become more pronounced. The concrete retains more of its original strength at lower RA percentages (10%–30%) than at higher RA percentages. At higher RA percentages (40% and 50%), the concrete significantly reduces compressive strength at all temperature levels.

Effect of elevated temperature on the flexural strength

Figure 10 shows the flexural strength loss at elevated temperatures from 23°C to 700°C. The flexural strength decreases as the temperature increases. The reduction in flexural strength is more significant at higher temperatures (500°C and 700°C). The presence of recycled aggregates generally leads to a lower flexural strength at all temperatures. The flexural strength starts highest with 0% RA at 7.15 N/mm^2 and decreases with increasing RA content. This is consistent with previous observations where higher recycled

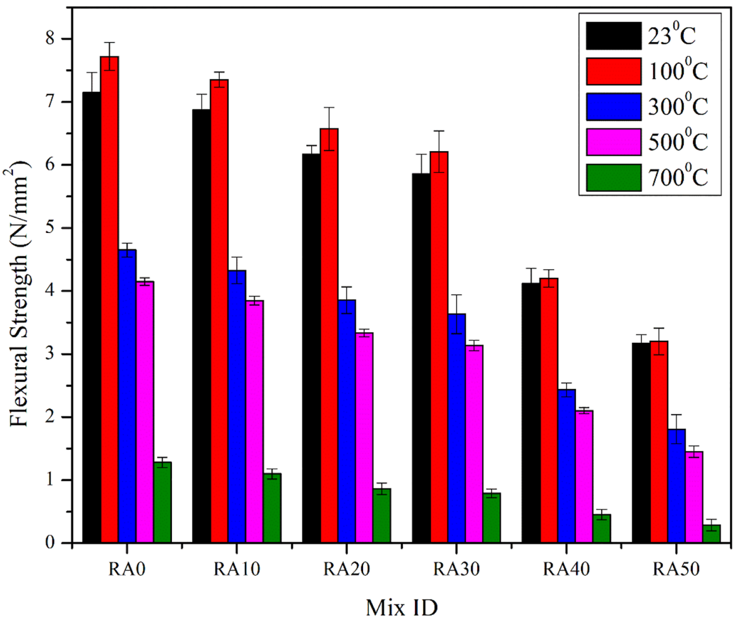

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Figure 10. Flexural strength variation with elevated temperature

aggregate content leads to lower flexural strength. There is a slight increase in flexural strength for all mixes when heated to 100°C (Pratap and Kumar, 2024). This increase can be attributed to the additional hydration of cement particles due to moisture. The flexural strength starts to decrease at 300°C for all mixes. The reduction is more pronounced in mixes with higher RA content. The flexural strength decreases significantly at 500°C (Tayeh *et al.*, 2021). Concrete with higher RA content shows a greater strength reduction than concrete with lower RA content. The flexural strength drops drastically at 700°C for all mixes. The reduction is most severe, indicating significant structural degradation at this temperature.

Recycled aggregates have residual mortar and impurities, leading to a weaker concrete matrix. The presence of these weaker components exacerbates the reduction in strength at elevated temperatures. At lower temperatures (up to 100°C), there might be some beneficial effects due to further hydration. As the temperature increases beyond 100°C, the negative effects of thermal stress, dehydration, and micro-cracking become more pronounced. At lower percentages (10%–30%), the decrease in flexural strength is less severe, suggesting that small amounts of recycled aggregates can be used without drastically compromising the flexural strength. The decrease is more significant at higher percentages (40% and 50%), indicating that high levels of recycled aggregates might not be suitable for applications requiring high flexural strength. The flexural strength of concrete decreases with increasing temperature, with significant losses observed beyond 300°C. Including recycled aggregates in the mix results in a lower flexural strength at all temperatures, with the effect becoming more pronounced at higher temperatures. While recycled aggregates can be used in concrete, their percentage should be carefully controlled, especially for applications exposed to elevated temperatures where flexural strength is a concern.

Effect of elevated temperature on the split tensile strength

Figure 11 shows the split tensile strength loss at elevated temperatures from 23ºC to 700ºC. As the temperature increases from 230°C to 700°C, the split tensile strength decreases significantly for all percentages of recycled aggregates. This reduction in split tensile strength is more pronounced at higher temperatures, with the largest drop occurring from 500°C to 700°C. Generally, as the percentage of recycled aggregates increases, the split tensile strength decreases at each temperature. This trend is consistent across all temperatures. Combining higher temperatures and higher percentages of recycled aggregates results in the lowest split tensile strength values. For instance, at 700°C, RA50 (50% recycled aggregates) shows the lowest split tensile strength of 0.3195 N/mm^2. At 230°C, the split tensile strength ranges from 2.13 N/mm^2 (RA50) to 3.52 N/mm^2 (RA0). At 700°C, the split tensile strength ranges from 0.3195 N/mm^2 (RA50) to 0.915 N/mm^2 (RA0) (Pavithra *et al.*, 2016; Albidah *et al.*, 2022). The data demonstrates the detrimental effect of elevated temperatures and increased recycled aggregate content on the split tensile strength of concrete. Both factors contribute to reduced split tensile strength, with higher temperatures exacerbating the effect. Therefore, it is crucial to consider these factors in designing concrete mixes for applications exposed to elevated temperatures and incorporating recycled aggregates.

Mass loss on elevated temperatures

The mass loss study is a critical aspect of fire safety research, especially when examining the behaviour of construction materials such as concrete under high temperatures. This study focuses on how different shapes and compositions of concrete samples—cubes, prisms, and cylinders—react to elevated temperatures ranging from 100°C to 700°C. By comparing the mass of these samples at ambient conditions with their mass after exposure to high temperatures, researchers can gain valuable insights into the thermal

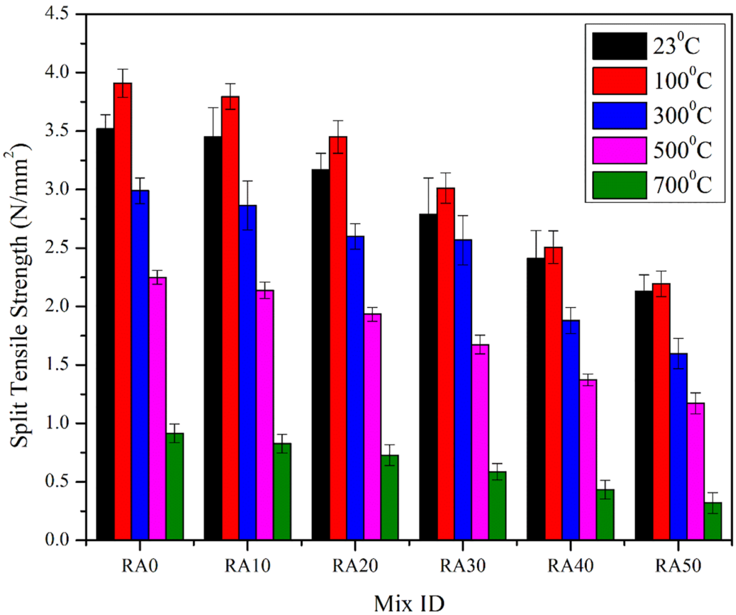

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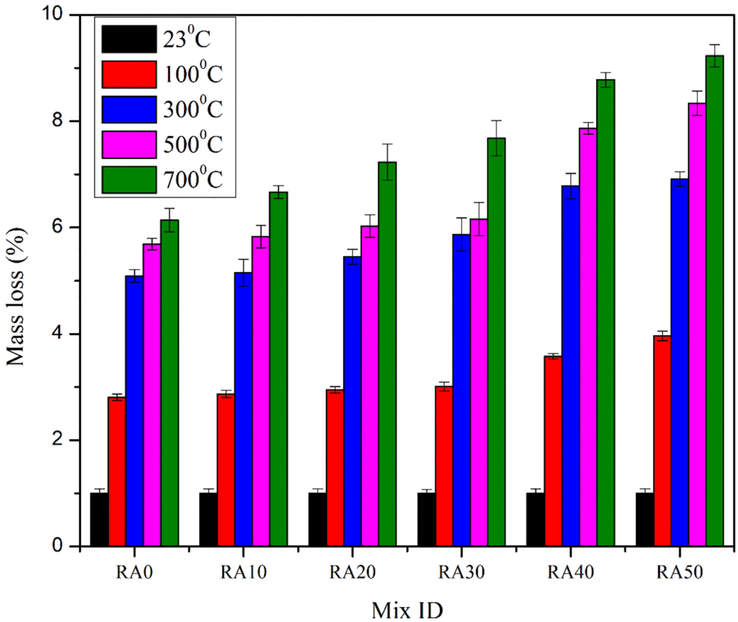
Figure 11.
Split tensile strength variation with elevated temperature

stability and durability of the materials. As the temperature increases, all types of concrete samples—regardless of shape—exhibit a significant loss in mass. This trend is clearly illustrated in Figures 12–14, demonstrating the mass loss for cube, prism, and cylinder samples. The primary reason for this mass loss is the increased temperature, which causes the moisture within the concrete to evaporate and the chemical bonds within the material to break down. However, the mass loss is not uniform across all samples. It is influenced by several factors, including the composition of the concrete mix, particularly the fraction of RA present.

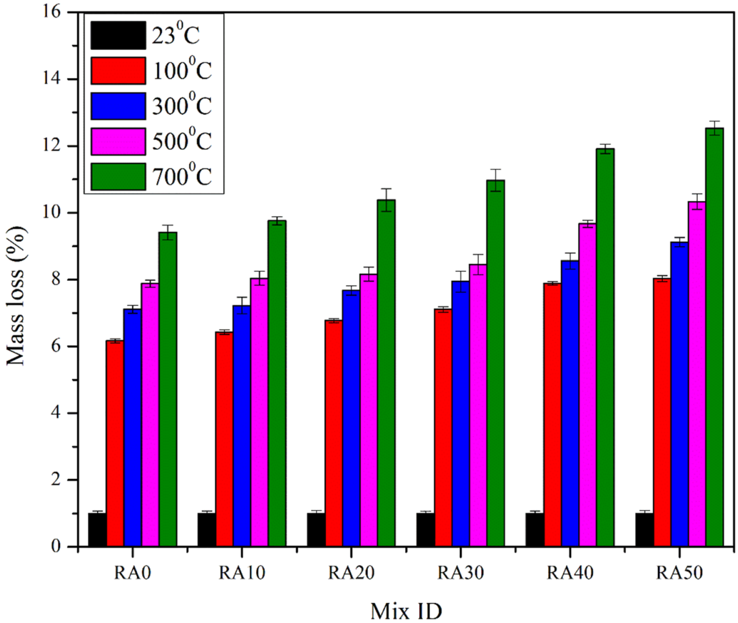
Concrete samples containing higher fractions of RA exhibit a greater mass loss at all temperatures. For instance, at 100°C, the mass loss ranges from 1.5% to 7.5%, depending on the percentage of RA in the mix. As the temperature rises to 300°C, the mass loss increases to between 2.4% and 8.5%. At 500°C, the mass loss further increases, ranging from 5.4% to 7.6%, and at 700°C, it reaches between 6.2% and 12%. These findings indicate that higher temperatures lead to more severe concrete deterioration, as evidenced by increased cracking and surface degradation. The impact of RA on mass loss is particularly pronounced at higher percentages. The mass loss is relatively less severe when the RA content in the concrete mix is between 10% and 30%. However, mass loss becomes significantly more pronounced when the RA content increases to 40% or 50%. This suggests that While RA can be used in concrete, their percentage should be carefully controlled.

Recycled aggregates typically contain residual mortar and impurities, contributing to increased mass loss when the concrete is exposed to elevated temperatures. These impurities can create voids and weak bonds within the concrete, increasing porosity and a greater susceptibility to thermal degradation. As a result, concrete containing higher percentages of RA may experience more severe mass loss and reduced structural integrity when exposed to high temperatures.



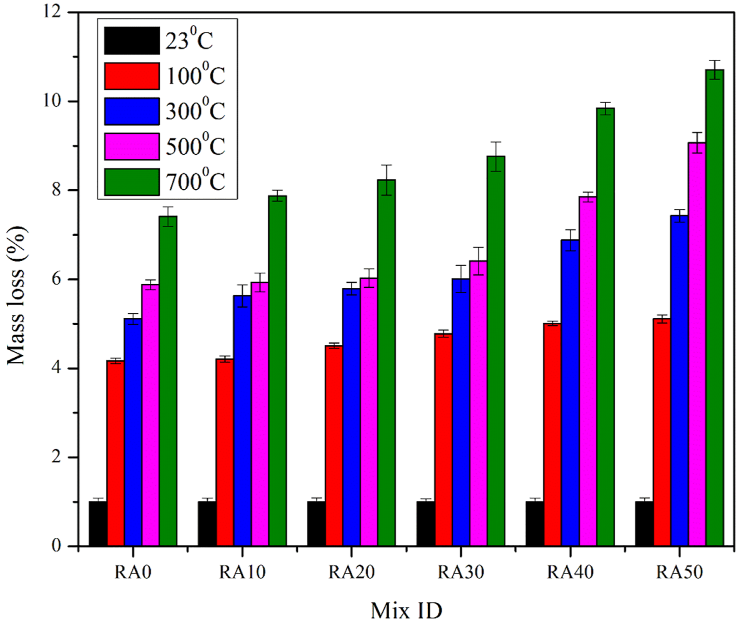
Source(s): Authors' own work

Figure 12.
Mass loss variation for the cube at elevated temperature



Source(s): Authors' own work

Figure 13.
Mass loss variation for prism at elevated temperature



Source(s): Authors' own work

Figure 14.
Mass loss variation for the cylindrical beam at elevated temperature

Conclusions

This study examines elevated temperatures' effects on recycled aggregate (RA) geopolymer concrete. The mechanical properties, including compressive strength, flexural strength, split tensile strength, and mass loss, have been methodically analysed to draw the following conclusions:

(1) At ambient temperature, it is observed that increasing the percentage of RA in the geopolymer concrete results in a decline in compressive strength, flexural strength, and split tensile strength.

(2) The rate of strength reduction remains relatively modest, less than 4% when the RA content is up to 30%. However, when the RA content exceeds 30%, the rate of strength loss becomes significantly higher, exceeding 18%.

(3) Under elevated temperature conditions, the behaviour of the concrete changes notably. At a temperature of 100°C, the strength of the concrete samples increases by more than 3–10%. This initial increase in strength could be attributed to the further polymerization and improved bonding within the geopolymer matrix at this moderate temperature. However, as the temperature rises from 100°C to 700°C, the concrete loses strength substantially.

(4) By the time the temperature reaches 700°C, the loss in compressive strength is up to 80%, the loss in flexural strength is up to 82%, and the loss in split tensile strength is as high as 90%.

(5) The mass loss analysis further supports these findings. Among the different shapes and sizes of samples tested, the prism samples exhibited the highest mass loss. This is likely due to their larger exposed surface area, which increases their vulnerability to temperature-induced dehydration and other material degradation.

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Corresponding author
Bheem Pratap can be contacted at: bheempratapbind009@gmail.com

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