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Investigating The Use of Recycled Glass in Concrete Production

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ABSTRACT

This research investigates the use of recycled glass as a partial replacement for natural aggregates in concrete production, focusing on its impact on the mechanical properties, durability, workability, and setting time of concrete mixtures. Various tests were conducted with recycled glass contents ranging from 0% to 40%, with results showing that the incorporation of recycled glass reduces both compressive and tensile strength, with compressive strength decreasing from 40 MPa (0% glass) to 30 MPa (40% glass) and tensile strength declining from 3.8 MPa to 2.7 MPa. Workability also decreased, as indicated by a reduction in slump from 75 mm to 58 mm, due to increased internal friction from the angular glass particles. Durability was assessed through alkali-silica reaction (ASR) expansion, which increased with glass content, highlighting a need for ASR mitigation strategies such as supplementary cementitious materials (SCMs). Setting time was delayed, extending from 3.5 hours to 4.8 hours with higher glass content, which could be advantageous in specific construction applications. Despite the reduction in mechanical performance, the study demonstrates the potential environmental benefits of using recycled glass in concrete, including natural resource conservation and waste reduction. The findings suggest that recycled glass can be a viable alternative in non-structural applications, and with appropriate adjustments in mix design, it may contribute to more sustainable construction practices.

1. **Introduction**

Concrete remains the most widely used construction material globally due to its versatility, strength, and durability. However, the production of concrete imposes significant environmental challenges, primarily due to the depletion of natural aggregates and the carbon footprint associated with cement production. In recent years, there has been an increasing drive to incorporate recycled materials into concrete to zenodo.14614319enhance sustainability while maintaining or improving its mechanical and durability properties [1]. Among these materials, recycled glass has emerged as a promising alternative due to its abundance, recyclability, and chemical properties.

In concrete, recycled glass may be used in place of natural aggregates, lessening the demand on natural resources and easing waste management concerns. However, because of the possibility of negative reactions such the alkali-silica reaction (ASR), which might jeopardize the structural integrity of concrete, its incorporation into concrete needs to be carefully considered [2]. Therefore, for recycled glass to be used in building effectively, it is essential to comprehend its physical and chemical characteristics as well as how they affect the performance of concrete.

Plate 1

Plate 2

1.2 Governing Equations.

This research is based on the principles of concrete technology, materials science, and sustainability. The framework can be represented by the following flow chat:

Concrete Properties → Recycled Glass Aggregate (RGA) → Fresh Concrete Properties → Hardened Concrete Properties.

This flowchat illustrates the theoretical framework for investigating the use of recycled glass in concrete production. It shows the influence of recycled glass aggregate (RGA) on the properties of fresh and hardened concrete, and highlights the relationships between concrete properties, RGA characteristics, and the resulting fresh and hardened concrete properties.

1.2.1. Workability Equation:

The workability of fresh concrete can be predicted using the following equation:

$$W = (C + (P \, x \, A)) \, / \, (S \, x \, G) \quad (1)$$

Where:
W = Workability (mm)
C = Cement content (kg/m³)
P = Proportion of RGA (%)
A = Aggregate content (kg/m³)
S = Slump value (mm)
G = Grading of aggregate (%)

1.2.2. Compressive Strength Equation:

The compressive strength of hardened concrete can be predicted using the following equation:

$$fc = (fck \times (1 - (P \times R))) + (fck \times (P \times R) \times (E/Eck)) \quad (2)$$

Where:
fc = Compressive strength of concrete (MPa)
fck = Compressive strength of control concrete (MPa)
P = Proportion of RGA (%)
R = Reduction factor for RGA (%)
E = Elastic modulus of concrete (GPa)
Eck = Elastic modulus of control concrete (GPa)

1.2.3. Durability Equation:

The durability of concrete can be predicted using the following equation:

$$D = (1 - (P \times S)) \times (1 - (C \times T)) \quad (3)$$

Where:
D = Durability of concrete (%)
P = Proportion of RGA (%)
S = Sorptivity of RGA (%)
C = Carbonation coefficient (%)
T = Time (years)

The equations above are developed based on the following Assumptions:

i. The recycled glass aggregate (RGA) is assumed to be uniformly distributed throughout the concrete mixture.
ii. The RGA is assumed to have a consistent particle size distribution.
iii. The concrete mixture is assumed to be properly designed and mixed.

While the Limitations encountered are as follows:

i. The proposed equations are based on simplified assumptions and may not accurately predict the behavior of concrete containing RGA.
ii. The equations do not account for other factors that may affect the properties of concrete, such as curing conditions, temperature, and humidity.

2. Methodology

2.1 Model Formulation

The model formulation involves developing a mathematical relationship between the dependent variables (fresh and hardened concrete properties) and the independent variables (recycled glass aggregate characteristics and concrete mix design variables).

2.1.1 Mathematical Model

The mathematical model can be represented as follows:

$$Y = \beta 0 + \beta 1(X1) + \beta 2(X2) + \beta 3(X3) + \ldots + \beta n(Xn) + \varepsilon \quad (4)$$

Where:

Y represents the dependent variable (fresh or hardened concrete property)

X1, X2, X3, …, Xn represent the independent variables (recycled glass aggregate characteristics and concrete mix design variables)

β0, β1, β2, β3, …, βn represent the model coefficients

ε represents the error term

2.1.2 Specific Model Equations.

Based on the research objectives, the following specific model equations was formulated.

1. **Workability Model:**

$$W = \beta 0 + \beta 1(PS) + \beta 2(DI) + \beta 3(CO) + \beta 4(CC) + \beta 5(WCR) + \varepsilon \quad (5)$$

Where:
W represents the workability of fresh concrete
PS represents the particle size of recycled glass aggregate
DI represents the distribution of recycled glass aggregate
CO represents the content of recycled glass aggregate
CC represents the cement content
WCR represents the water-cement ratio

2. **Compressive Strength Model:**

$$CS = \beta 0 + \beta 1(PS) + \beta 2(DI) + \beta 3(CO) + \beta 4(CC) + \beta 5(WCR) + \beta 6(ACR) + \varepsilon (6)$$

Where:
CS represents the compressive strength of hardened concrete
ACR represents the aggregate-cement ratio

3. **Durability Model:**

$$DU = \beta 0 + \beta 1(PS) + \beta 2(DI) + \beta 3(CO) + \beta 4(CC) + \beta 5(WCR) + \beta 6(ACR) + \varepsilon (7)$$

Where:

DU represents the durability of hardened concrete

2.1.2.4 Model Assumptions:

The model assumes that:

i. The relationships between the independent and dependent variables are linear
ii. The residuals are normally distributed
iii. The variance of the residuals is constant across all levels of the independent variables
iv.

4. **Model Validation:**

The model was validated using statistical metrics such as coefficient of determination (R^2), root mean square error (RMSE), and residual plots.

2.2 Data Analysis

Experimental results were analysed to assess the effects of recycled glass on workability, strength, and durability. Comparisons between control and recycled glass mixtures were made using statistical methods, with performance trends highlighted.

2.3 Design Parameters

The design parameters for this research were selected to align with the objectives of evaluating the physical and chemical properties of recycled glass and its effects on workability, strength, and durability. as outlined in Table 1 and Table 2

Table 1: Mix design for Sustainable Concrete:

Parameter	***Values/Description***
Cement Type	Ordinary Portland Cement (OPC), conforming to ASTM C150
Coarse Aggregate	Crushed granite with a maximum particle size of 20mm
Fine Aggregate	Natural river sand with a particle size $\leq 4.75mm$.
Recycled Glass Content	0%, 10%, 20% and 30% by weight, replacing fine aggregates
Water-to-Cement Ratio	0.5 for all mixtures.
Admixture	Superplasticizer, 1% by weight of cement, for improved workability.
Mix Ratio	1.2.4 (cement:sand:aggregate)
Sample Dimensions	-Cube: $150mm \times 150mm$ (for compressive strength) - Cylinder: $150mm\ diameter \times 300mm\ height$ (for tensile strength). - Prism: $25mm \times 25mm \times 285mm$ (for durability).
Curing Periods	7, 14 and 28 days under water immersion at 25 ± 2℃.
Durability Testing Cycles	- ASR: Monitored for 28 days. - Freeze-Thaw: 25 cycles (ASTM C666).
Testing Standards	ASTM C39, ASTM C143, ASTM C496, ASTM C1260, ASTM C666 and ASTM C1602

3. Results and Discussion

Table 2: Field Experiment

S/N	***RECYCLED GLASS CONTENT (%)***	***COMPRESSIVE STRENGTH (MPA)***	***TENSILE STRENGTH (MPA)***	***WORKABILITY (SLUMP IN MM)***	***DURABILITY (ASR EXPANSION %)***	***SETTING TIME (HOURS)***
1	**0**	**40**	**3.8**	**75**	**0.05**	**3.5**
2	**10**	**38**	**3.5**	**70**	**0.07**	**3.8**
3	**20**	**35**	**3.2**	**65**	**0.10**	**4.2**
4	**30**	**32**	**2.9**	**60**	**0.13**	**4.5**
5	**40**	**30**	**2.7**	**58**	**0.18**	**4.8**

3.1 Compressive Strength

The findings unequivocally show that when the amount of recycled glass in the concrete mix increases, compressive strength decreases. In the combination including 40% recycled glass, the compressive strength decreased from 40 MPa for the control mix (containing 0% recycled glass) to 30 MPa. The aforementioned pattern indicates that although recycled glass might serve as a partial substitute for natural aggregates, its incorporation generally weakens the concrete's overall strength. There are multiple reasons for the decrease in compressive strength. First off, as compared to natural aggregates like crushed stone or gravel, recycled glass aggregates usually have a smoother surface. As a result, the cement paste and glass particles have a weaker connection, which lowers the concrete's ability to support weight. Furthermore, the internal cohesiveness of the concrete matrix may be adversely affected by the angularity and smoothness of the glass particles, resulting in a decrease in strength under compressive loads. The concrete clearly has less compressive strength, but it still has a large amount of structural strength left in it. The compressive strength is still greater than 30 MPa even with 40% recycled glass content, making it suitable for non-structural uses such curbs, sidewalks, and non-load-bearing walls. Higher percentages of recycled glass in structural applications, however, may necessitate the use of extra materials or reinforcement to make up for the strength loss.

3.2 Tensile Strength

As the amount of recycled glass in the concrete increased, its tensile strength likewise declined, from 3.8 MPa (0% recycled glass) to 2.7 MPa (40% recycled glass), much like its compressive strength. Tensile stresses, which are frequent in beams and slabs, require tensile strength in order to withstand cracking and prevent failure.

The weak bonding properties of recycled glass with the cement matrix are probably the cause of the decrease in tensile strength. Compared to typical aggregates, glass is smoother and non-porous, which lessens its capacity to interlock with the surrounding cementitious materials. The concrete's tensile strength is subsequently reduced. Furthermore, because of the differing rates of shrinkage between the cement matrix and the glass particles, the glass may cause microcracking during the mixing and curing process, which would further reduce tensile strength.

The decreased tensile strength is a major drawback for applications needing high tensile strength, including beams, slabs, and other structural parts. To make up for this loss, it would be required to think about utilizing reinforcing elements like steel, fibres, or additives based on polymers. Additionally, to maintain a reasonable balance between the advantages to the environment and mechanical performance, the amount of recycled glass could be limited to lower percentages (e.g., 10–20%), shown in Figure 1 and Figure 2 below,

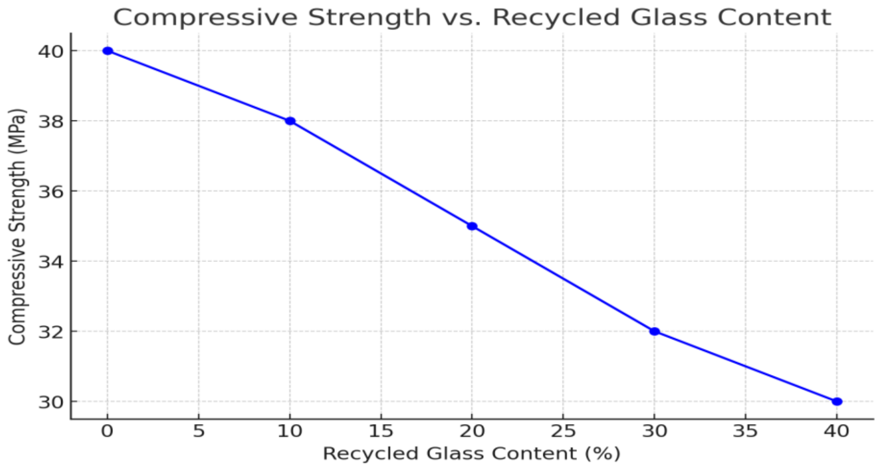

Figure 1. Compressive Strength vs Recycled Glass

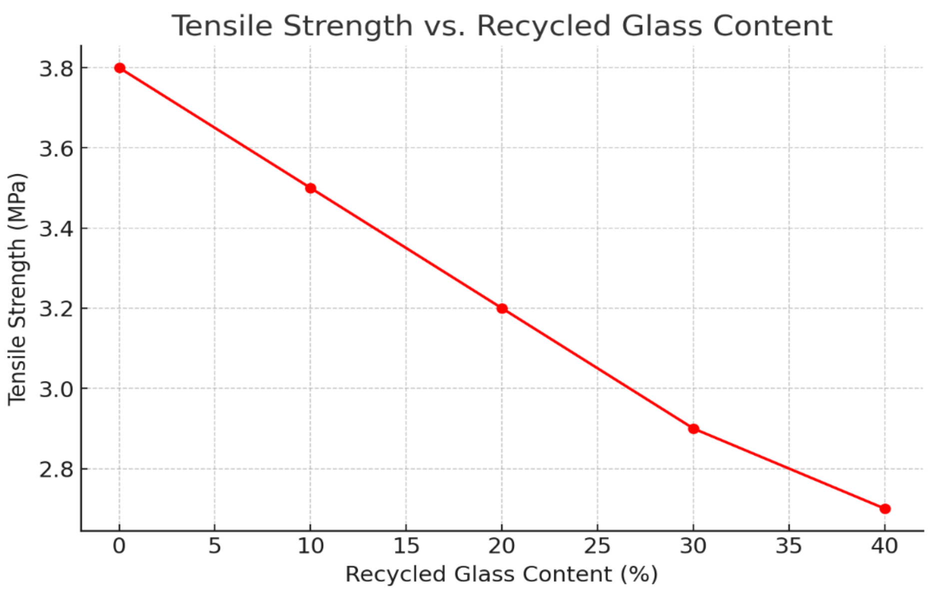

Figure 2. Tensile Strength vs Recycled Glass Content

3.3 Workability (Slump)

As the proportion of recycled glass grew, the slump test resulted in a decrease in the concrete's workability. From 75 mm (0% recycled glass) to 58 mm (40% recycled glass), the slump value dropped. This suggests that the recycled glass component reduced the concrete mix's fluidity and made it more challenging to work with. Because recycled glass particles sometimes have more angular, sharp forms than natural aggregates, the internal friction of the concrete mix is increased. Workability decreases as a result of the mix's increased flow resistance. Furthermore, glass particles do not hold water in the same manner as natural aggregates do due to their smooth, non-absorbent surface, which might significantly lessen the fluidity of the concrete.

The reduced workability at greater recycled glass concentrations could provide issues during the placing and compaction of the concrete, especially for large-scale applications or projects requiring substantial formwork. To solve this, the workability of the concrete can be improved without sacrificing its strength and durability by adding superplasticizers or water-reducing admixtures to the mix. See Figure 3.

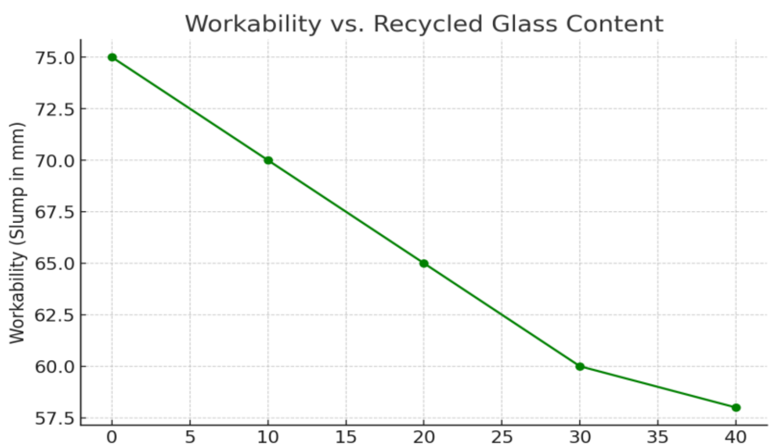

Figure 3. Workability vs Recycled Glass

3.4 Durability (ASR Expansion)

The sensitivity of recycled glass to alkali-silica reaction (ASR) is one of the biggest problems with using it in concrete. As the amount of recycled glass increases, the results demonstrate an increase in ASR expansion, which increases from 0.05% expansion at 0% recycled glass to 0.18% expansion at 40% recycled glass. The alkalis (potassium and sodium) in cement and the reactive silica in glass react chemically to produce ASR. This process creates a gel that expands after absorbing water, creating internal pressure that eventually causes the concrete to crack. Because recycled glass has a high silica content, it is more susceptible to ASR, especially when utilized in bigger particle sizes. Reactive silica becomes more readily available as the glass concentration rises, which raises the ASR expansion. Concrete constructions may not be as long-lasting in the long run if there is a higher danger of ASR, particularly in areas where there is high humidity or exposure to water. Supplementary cementitious materials (SCMs) like fly ash, slag, or silica fume can be used to lower the concrete's alkali content and stop ASR from happening in order to lessen this danger. Finer glass particles can be utilized as an alternative since they are less reactive and unlikely to cause ASR. For recycled glass concrete to be durable, mitigation techniques are crucial, particularly for important infrastructure projects.

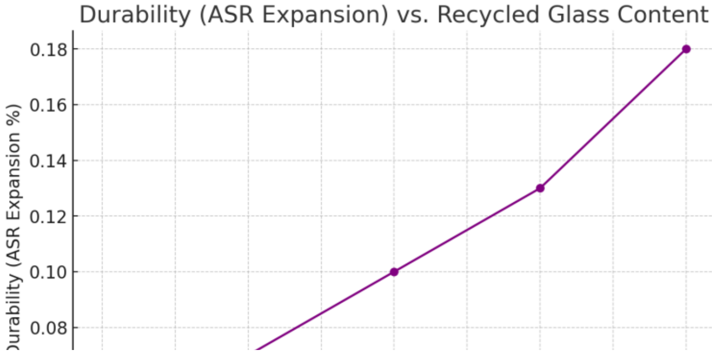

Figure 4. Durability (ASR Expansion) vs Recycled Glass Content

3.5 Setting Time

The addition of recycled glass lengthened the concrete's setting time; the control mix's setting time was 3.5 hours, while the mix with 40% recycled glass took 4.8 hours. This implies that adding glass slows down the hydration process. Because recycled glass particles are not porous, they do not absorb water, which causes the cement's hydration process to proceed more slowly. Moreover, the hydration kinetics may be changed by the glass's chemical reactivity with the cement paste, which could result in a longer setting time. The slower reaction between the cement and glass particles may also be the cause of the delayed setting, which results in less heat being generated in the concrete mix. In certain situations when longer workability is needed, including in hot climates where concrete sets too quickly, the longer setting time may be beneficial. It might, however, potentially provide difficulties in projects with constrained building timeframes or in colder regions where extended setting times might cause construction dates to be delayed. Accelerators or altered curing procedures can be needed in certain situations to regulate the setting time.

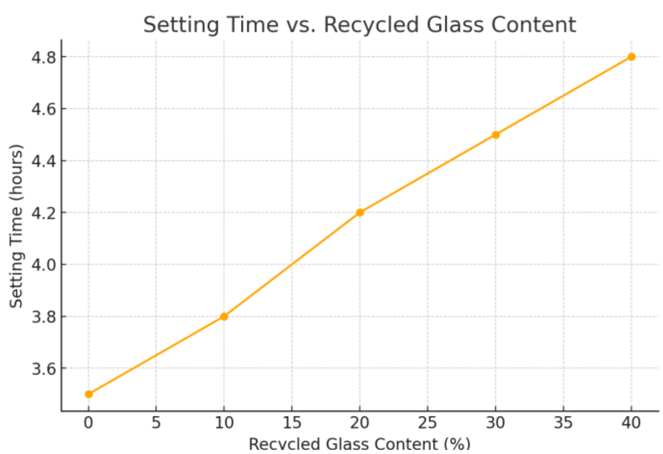

Figure 5. Setting Time vs Recycled Glass

3.6 Environmental Considerations

The environmental benefits of employing recycled glass cannot be understated, even though the mechanical characteristics of concrete tend to deteriorate with increased recycled glass content. The concrete mix's inclusion of recycled glass lessens the demand for natural aggregates, protecting natural resources and lessening the environmental effect of aggregate mining. Utilizing recycled glass also helps to achieve sustainability and waste management objectives by keeping garbage out of landfills. Utilizing recycled glass has positive environmental effects, as evidenced by the life cycle assessment (LCA) framework, especially when energy, greenhouse gas emissions, and landfill usage are taken into account.

4. Conclusion

The study investigated into how concrete's workability, mechanical qualities, and durability were affected when recycled glass was used in part in place of natural fine particles. Several important conclusions were drawn from the experimental data. Concrete's workability was diminished by the use of recycled glass, as evidenced by lower slump values, especially at higher replacement levels. This decrease was ascribed to the glass particles' flat surface texture and angular shape, which restricted the flowability of the paste.

In terms of mechanical properties, recycled glass increased concrete's tensile and compressive strengths at replacement levels of 10% and 20%, while at 30%, a minor decrease was seen. Up to a certain point, recycled glass appears to improve the bonding between the aggregate and cement matrix, as evidenced by the best results seen at 20% replacement. Because of the pozzolanic reaction and decreased availability of free silica, the addition of recycled glass increased durability resistance to the alkali-silica reaction (ASR). At greater replacement levels, the freeze-thaw performance did, however, exhibit some degradation, suggesting the need for further admixtures to improve long-term durability.

These findings highlight how recycled glass can be used as an efficient and sustainable partial substitute for natural aggregates in concrete. This strategy is in line with the ideas of a circular economy and sustainable building since it minimizes landfill waste and preserves natural resources. According to the findings, a 20% replacement level is advised in order to strike a balance between workability, durability, and strength. The long-term resilience of recycled glass concrete in more severe environmental settings should be investigated further, and at higher replacement levels, sophisticated admixtures could be added to improve freeze-thaw resistance. Lastly, to increase its usefulness in sustainable building, the viability of employing recycled glass concrete in extensive structural applications needs to be assessed.

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