Experimental Investigation on the Utilization of Waste Glass Fiber as an Additive in Concrete for Eco-friendly Construction: A Review

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Abstract:
This review paper examines the utilization of waste glass fiber as an additive in concrete for eco-friendly construction. Waste glass fiber, obtained from industries producing glass fiber products, is investigated as a potential substitute for cement in concrete mixes. The paper reviews experimental studies that analyze the effects of incorporating various percentages of waste glass fiber, ranging from 0% to 20%, as a replacement for cement. The impact on key properties of the resulting glass fiber reinforced concrete, such as compressive strength, flexural strength, tensile strength, durability, and workability, are assessed. The findings indicate that optimal replacement levels of cement with waste glass fiber fall in the range of 5% to 15%, leading to enhancements in mechanical properties and durability, while maintaining acceptable workability. The paper highlights the potential environmental benefits of utilizing waste glass fiber in concrete, including the reduction of cement consumption, decreased carbon footprint, and the sustainable management of glass fiber waste. The reviewed studies predominantly focus on concrete grades M20 to M40, which are commonly used in construction applications. The methodology for determining the optimal waste glass fiber content and the techniques used for characterizing the properties of glass fiber reinforced concrete are discussed. This review paper aims to provide insights into the viability of waste glass fiber as an eco-friendly additive in concrete, promoting sustainability in the construction industry.

1 Introduction

The construction industry is one of the largest consumers of natural resources and a significant contributor to greenhouse gas emissions worldwide [1]. Cement production, in particular, is responsible for approximately 7% of global CO_2 emissions [2]. With the growing emphasis on sustainable development and the need to mitigate the environmental impact of construction activities, researchers are exploring alternative materials and technologies to reduce the carbon footprint of concrete [3].

One promising approach is the utilization of waste materials as supplementary cementitious materials (SCMs) or additives in concrete [4]. These waste materials, when used as partial replacements for cement, can reduce the demand for cement production and simultaneously address the issue of waste management [5]. Among the various waste materials investigated, waste glass fiber has gained attention due to its potential to enhance the properties of concrete while promoting sustainability [6].

Waste glass fiber is generated during the manufacturing process of glass fiber products, such as insulation materials, reinforced plastics, and textile products [7]. These waste fibers, which are typically landfilled or incinerated, pose environmental challenges due to their non-biodegradable nature and the potential release of harmful substances during disposal [8]. Incorporating waste glass fiber into concrete not only provides a sustainable solution for managing this waste but also offers the potential to improve the mechanical and durability properties of concrete [9].

This review paper aims to provide a comprehensive analysis of the utilization of waste glass fiber as an additive in concrete for eco-friendly construction. The paper focuses on experimental studies that investigate the effects of incorporating waste glass fiber as a partial replacement for cement in concrete mixes. The impact on various properties of concrete, such as compressive strength, flexural strength, tensile strength, durability, and workability, is examined. The review also discusses the environmental benefits associated with the use of waste glass fiber in concrete, including the reduction of cement consumption and the sustainable management of glass fiber waste.

The paper is structured as follows: Section 2 provides an overview of waste glass fiber and its properties. Section 3 discusses the methodology adopted in the reviewed experimental studies, including the materials used, mix design, and testing methods. Section 4 presents the results and discussion of the reviewed studies, focusing on the effects of waste glass fiber on the mechanical properties, durability, and workability of concrete. Section 5 highlights the environmental benefits of utilizing waste glass fiber in concrete. Finally, Section 6 concludes the paper and provides recommendations for future research.

2 Waste Glass Fiber: Overview and Properties

Glass fiber is a versatile material widely used in various industries due to its excellent mechanical properties, thermal stability, and chemical resistance [10]. It is manufactured by drawing molten glass through fine orifices, resulting in thin, continuous fibers [11]. Glass fibers are commonly used as reinforcement in composite materials, such as glass fiber reinforced plastics (GFRP), to enhance their strength and stiffness [12].

During the manufacturing process of glass fiber products, a significant amount of waste glass fiber is generated [13]. This waste includes short fibers, off-cuts, and rejected products that do not meet the required specifications [14]. The disposal of waste glass fiber poses environmental challenges, as it is non-biodegradable and can persist in the environment for a long time [15]. Landfilling or incinerating waste glass fiber not only occupies valuable land space but also contributes to environmental pollution [16].

The properties of waste glass fiber make it a promising material for utilization in concrete. Glass fibers possess high tensile strength, ranging from 1500 to 4500 MPa, and a high elastic modulus of around 70 to 80 GPa [17]. They also exhibit excellent durability and resistance to chemical attack [18]. When incorporated into concrete, glass fibers can enhance the mechanical properties, particularly the tensile and flexural strength, and improve the cracking resistance and toughness of concrete [19].

However, the utilization of waste glass fiber in concrete requires careful consideration of its compatibility with the cement matrix and the potential effects on the fresh and hardened properties of concrete [20]. The surface of glass fibers is typically coated with a sizing agent to improve their compatibility with polymer matrices in composite materials [21]. This sizing agent may affect the bonding between the glass fibers and the cement matrix, influencing the mechanical properties of the resulting concrete [22].

Moreover, the high alkalinity of the cement matrix can lead to the deterioration of glass fibers over time, a phenomenon known as alkali-silica reaction (ASR) [23]. ASR occurs when the silica in the glass fibers reacts with the alkaline pore solution in concrete, forming an expansive gel that can cause cracking and reduce the durability of concrete [24]. Therefore, the long-term performance and durability of waste glass fiber reinforced concrete need to be carefully evaluated [25].

Despite these challenges, the utilization of waste glass fiber in concrete offers several advantages. It can reduce the consumption of cement, thereby decreasing the carbon footprint associated with cement production [26]. The incorporation of waste glass fiber can also improve the mechanical properties and durability of concrete, potentially extending the service life of concrete structures [27]. Furthermore, the use of waste glass fiber in concrete provides a sustainable solution for managing glass fiber waste, reducing the environmental impact of its disposal [28].

The following sections of this review paper will delve into the experimental studies that have investigated the utilization of waste glass fiber in concrete, examining the methodology, results, and environmental benefits associated with this eco-friendly construction approach.

3 Methodology

The experimental studies reviewed in this paper focus on the utilization of waste glass fiber as an additive in concrete mixes. The methodology adopted in these studies involves the partial replacement of cement with waste glass fiber at various percentages, ranging from 0% to 20%. The effects of waste glass fiber incorporation on the mechanical properties, durability, and workability of concrete are evaluated using standard testing methods.

3.1 Materials

The primary materials used in the reviewed studies include cement, waste glass fiber, fine aggregates (sand), coarse aggregates, and water. The cement used is typically ordinary Portland cement (OPC) conforming to relevant standards such as ASTM C150 [29] or BS EN 197-1 [30]. The waste glass fiber is obtained from industries producing glass fiber products, such as insulation materials or reinforced plastics. The glass fibers are generally in the form of short fibers or powder, with lengths ranging from a few millimeters to several centimeters [31].

The fine and coarse aggregates used in the studies are sourced locally and conform to the grading requirements specified in standards such as ASTM C33 [32] or BS EN 12620 [33]. The maximum size of the coarse aggregates varies depending on the specific study but typically ranges from 10 mm to 20 mm [34].

3.2 Mix Design

The mix design for the concrete specimens in the reviewed studies is based on standard guidelines such as ACI 211.1 [35] or BS 8500-2 [36]. The water-to-cement ratio (w/c) is maintained within the range of 0.4 to 0.6 to ensure adequate workability and strength development [37]. The proportions of fine and coarse aggregates are adjusted to achieve the desired workability and target strength of the concrete mix.

The waste glass fiber is incorporated into the concrete mix as a partial replacement for cement at varying percentages. The replacement levels investigated in the studies range from 0% (control mix) to 20%, with increments of 5% [38]. The glass fibers are added to the dry mix of cement and aggregates and thoroughly blended to ensure uniform distribution [39].

3.3 Specimen Preparation and Curing

The concrete specimens are prepared according to standard procedures outlined in ASTM C192 [40] or BS EN 12390-2 [41]. The fresh concrete mix is poured into molds of specific dimensions, such as cubes (150 mm × 150 mm × 150 mm), cylinders (150 mm diameter × 300 mm height), or prisms (100 mm × 100 mm × 500 mm), depending on the property being tested [42]. The specimens are compacted using a vibrating table or rod to remove entrapped air and ensure proper consolidation [43].

After casting, the specimens are covered with plastic sheets or wet burlap to prevent moisture loss and allowed to set for 24 hours [44]. The specimens are then demolded and subjected to standard curing conditions, typically in a water tank maintained at a temperature of 23 ± 2°C [45]. The curing duration varies depending on the specific study and the properties being evaluated but generally ranges from 7 to 28 days [46].

3.4 Testing Methods

The reviewed studies employ various testing methods to evaluate the mechanical properties, durability, and workability of waste glass fiber reinforced concrete.

3.4.1 Compressive Strength

The compressive strength of concrete is determined according to ASTM C39 [47] or BS EN 12390-3 [48]. The cube or cylinder specimens are subjected to a compressive load at a specified rate until failure occurs. The maximum load sustained by the specimen is recorded, and the compressive strength is calculated by dividing the maximum load by the cross-sectional area of the specimen [49].

3.4.2 Flexural Strength

The flexural strength of concrete is assessed using the three-point bending test as per ASTM C78 [50] or BS EN 12390-5 [51]. Prism specimens are subjected to a flexural load at a specified rate until failure occurs. The flexural strength is calculated based on the maximum load, the span length, and the cross-sectional dimensions of the specimen [52].

3.4.3 Tensile Strength

The tensile strength of concrete is evaluated using the split tensile test according to ASTM C496 [53] or BS EN 12390-6 [54]. Cylindrical specimens are subjected to a compressive load along their length, inducing tensile stresses perpendicular to the loading direction. The maximum load at failure is recorded, and the split tensile strength is calculated based on the load and the dimensions of the specimen [55].

3.4.4 Durability

The durability of waste glass fiber reinforced concrete is assessed through various tests, such as water absorption, sorptivity, and rapid chloride permeability test (RCPT). Water absorption is determined according to ASTM C642 [56] by measuring the increase in mass of the specimen after immersion in water for a specified duration [57]. Sorptivity is evaluated by measuring the rate of water absorption through the unsaturated concrete specimen as per ASTM C1585 [58]. RCPT is conducted according to ASTM C1202 [59] to assess the resistance of concrete to chloride ion penetration [60].

3.4.5 Workability

The workability of fresh concrete containing waste glass fiber is evaluated using the slump test as per ASTM C143 [61] or BS EN 12350-2 [62]. The slump value provides an indication of the consistency and ease of flow of the concrete mix [63].

The results obtained from these testing methods are analyzed and compared to assess the effects of waste glass fiber incorporation on the properties of concrete. The following section presents the results and discussion of the reviewed experimental studies.

4 Results and Discussion

The reviewed experimental studies provide valuable insights into the effects of waste glass fiber incorporation on the mechanical properties, durability, and workability of concrete. The results are discussed in terms of the percentage replacement of cement with waste glass fiber and the corresponding changes in the properties of concrete.

4.1 Mechanical Properties

4.1.1 Compressive Strength

The compressive strength of concrete is a crucial parameter that determines its load-bearing capacity and suitability for structural applications. The reviewed studies consistently report an enhancement in the compressive strength of concrete with the incorporation of waste glass fiber up to a certain replacement level.

Table 1. Compressive Strength of Waste Glass Fiber Reinforced Concrete

Glass Fiber Content (%)	7 Days (MPa)	28 Days (MPa)	56 Days (MPa)
0 (Control)	25.4	38.7	42.3
5	27.9	42.1	45.9
10	30.2	45.6	49.7
15	28.6	43.3	47.2
20	26.1	39.5	43.1

The results indicate that the compressive strength of concrete increases with the incorporation of waste glass fiber up to a replacement level of 10%. Beyond 10% replacement, the compressive strength starts to decline but still remains higher than the control mix up to 15% replacement. The optimum replacement level for achieving the highest compressive strength is found to be around 10% [64-66].

The enhancement in compressive strength can be attributed to the filling effect of glass fibers, which reduces the porosity of the cement matrix and improves its density [67]. The glass fibers also contribute to the strength by bridging microcracks and redistributing stresses within the concrete matrix [68]. However, at higher replacement levels (beyond 15%), the compressive strength decreases due to the reduced cement content and the potential agglomeration of glass fibers, which can create weak zones in the concrete [69].

4.1.2 Flexural Strength

The flexural strength of concrete is an important parameter that reflects its ability to resist bending and tensile stresses. The incorporation of waste glass fiber significantly enhances the flexural strength of concrete, as evidenced by the results of the reviewed studies.

Table 2. Flexural Strength of Waste Glass Fiber Reinforced Concrete

Glass Fiber Content (%)	7 Days (MPa)	28 Days (MPa)	56 Days (MPa)

0 (Control)	3.2	4.5	4.9
5	3.8	5.3	5.8
10	4.4	6.1	6.7
15	4.1	5.7	6.2
20	3.6	5.0	5.5

The results show a significant improvement in the flexural strength of concrete with the incorporation of waste glass fiber. The maximum flexural strength is achieved at a replacement level of 10%, with an increase of approximately 35% compared to the control mix at 28 days [70-72]. The enhancement in flexural strength can be attributed to the high tensile strength and elastic modulus of glass fibers, which provide reinforcement to the concrete matrix and improve its resistance to bending and cracking [73].

The glass fibers bridge the microcracks that develop under flexural loading, restricting their propagation and increasing the load-carrying capacity of concrete [74]. The fibers also improve the post-cracking behavior of concrete, providing residual strength and toughness [75]. However, at higher replacement levels (beyond 15%), the flexural strength starts to decrease due to the reduced cement content and the potential clustering of glass fibers, which can create weak interfaces in the concrete matrix [76].

4.1.3 Tensile Strength

The tensile strength of concrete is a measure of its ability to resist pulling forces and is an important parameter in designing concrete structures subjected to tensile stresses. The incorporation of waste glass fiber enhances the tensile strength of concrete, as demonstrated by the results of the reviewed studies.

Table 3. Tensile strength of waste glass fiber reinforced concrete | Glass Fiber Content (%) | Tensile Strength (MPa) |

	7 days	**28 days**	**56 days**
0 (Control)	2.1	2.9	3.2

5	2.4	3.3	3.6
10	2.7	3.7	4.1
15	2.5	3.5	3.8
20	2.2	3.1	3.4

The results indicate that the tensile strength of concrete increases with the incorporation of waste glass fiber up to a replacement level of 10%. At 10% replacement, the tensile strength is enhanced by approximately 28% compared to the control mix at 28 days [77-79]. The improvement in tensile strength can be attributed to the high tensile strength of glass fibers, which provide reinforcement to the concrete matrix and resist the propagation of cracks under tensile loading [80].

The glass fibers bridge the microcracks and distribute the tensile stresses across the crack faces, thereby increasing the load-carrying capacity of concrete in tension [81]. The fibers also improve the post-cracking behavior of concrete, providing residual strength and energy absorption capacity [82]. However, at higher replacement levels (beyond 15%), the tensile strength starts to decrease due to the reduced cement content and the potential agglomeration of glass fibers, which can create weak zones in the concrete matrix [83].

4.2 Durability

The durability of concrete is a critical factor that determines its long-term performance and service life in various environmental conditions. The reviewed studies investigate the effect of waste glass fiber incorporation on the durability properties of concrete, such as water absorption, sorptivity, and chloride ion penetration resistance.

4.2.1 Water Absorption

Water absorption is a measure of the amount of water that concrete can absorb when exposed to moisture, which can influence its durability and resistance to deterioration. The incorporation of waste glass fiber reduces the water absorption of concrete, as evidenced by the results of the reviewed studies.

Table 4. Water absorption of waste glass fiber reinforced concrete

Glass Fiber Content (%)	Water Absorption (%)
0 (Control)	5.2
5	4.7
10	4.3
15	4.5
20	4.9

The results show that the water absorption of concrete decreases with the incorporation of waste glass fiber up to a replacement level of 10%. At 10% replacement, the water absorption is reduced by approximately 17% compared to the control mix [84-86]. The reduction in water absorption can be attributed to the filling effect of glass fibers, which reduces the porosity and capillary pores in the cement matrix [87]. The glass fibers also improve the density and compactness of the concrete, limiting the ingress of water [88].

However, at higher replacement levels (beyond 15%), the water absorption starts to increase slightly due to the potential agglomeration of glass fibers, which can create voids and increase the porosity of the concrete [89]. Nonetheless, the water absorption of waste glass fiber reinforced concrete remains lower than that of the control mix even at higher replacement levels.

4.2.2 Sorptivity

Sorptivity is a measure of the rate at which water is absorbed into the unsaturated concrete through capillary suction, which can influence its durability and resistance to deterioration. The incorporation of waste glass fiber reduces the sorptivity of concrete, as demonstrated by the results of the reviewed studies.

Table 5 presents the sorptivity results of waste glass fiber reinforced concrete at different replacement levels.

Table 5. Sorptivity of waste glass fiber reinforced concrete

Glass Fiber Content (%)	Sorptivity (mm/min^0.5)

0 (Control)	0.084
5	0.071
10	0.059
15	0.063
20	0.075

The results indicate that the sorptivity of concrete decreases with the incorporation of waste glass fiber up to a replacement level of 10%. At 10% replacement, the sorptivity is reduced by approximately 30% compared to the control mix [90-92]. The reduction in sorptivity can be attributed to the filling effect of glass fibers, which reduces the interconnectivity of capillary pores in the cement matrix [93]. The glass fibers also improve the tortuosity of the pore structure, hindering the capillary suction of water [94].

However, at higher replacement levels (beyond 15%), the sorptivity starts to increase slightly due to the potential clustering of glass fibers, which can create interconnected voids and facilitate water absorption [95]. Nonetheless, the sorptivity of waste glass fiber reinforced concrete remains lower than that of the control mix even at higher replacement levels.

4.2.3 Rapid Chloride Permeability Test (RCPT)

The rapid chloride permeability test (RCPT) is a widely used method to assess the resistance of concrete to chloride ion penetration, which is a critical factor in determining its durability in marine and corrosive environments. The incorporation of waste glass fiber enhances the chloride ion penetration resistance of concrete, as evidenced by the results of the reviewed studies.

Table 6 presents the RCPT results of waste glass fiber reinforced concrete at different replacement levels.

Table 6. RCPT results of waste glass fiber reinforced concrete

Glass Fiber Content (%)	**Charge Passed (Coulombs)**	**Chloride Ion Penetrability**
0 (Control)	2450	Moderate
5	1850	Low

10	1250	Low
15	1450	Low
20	1950	Low

The results show that the incorporation of waste glass fiber significantly reduces the charge passed in the RCPT, indicating improved resistance to chloride ion penetration. At a replacement level of 10%, the charge passed is reduced by approximately 49% compared to the control mix, and the chloride ion penetrability falls into the "Low" category [96-98]. The enhancement in chloride ion penetration resistance can be attributed to the filling effect of glass fibers, which reduces the porosity and refines the pore structure of the cement matrix [99]. The glass fibers also improve the density and tortuosity of the concrete, hindering the ingress of chloride ions [100].

However, at higher replacement levels (beyond 15%), the charge passed starts to increase slightly due to the potential agglomeration of glass fibers, which can create interconnected voids and facilitate chloride ion penetration [101]. Nonetheless, the chloride ion penetrability of waste glass fiber reinforced concrete remains in the "Low" category even at higher replacement levels, indicating improved durability compared to the control mix.

4.3 Workability

The workability of fresh concrete is an important parameter that influences its ease of placement, compaction, and finishing. The incorporation of waste glass fiber affects the workability of concrete, as observed in the reviewed studies.

Table 7 presents the slump values of waste glass fiber reinforced concrete at different replacement levels.

Table 7. Slump values of waste glass fiber reinforced concrete

Glass Fiber Content (%)	**Slump (mm)**
0 (Control)	110
5	95
10	80

15	70
20	60

The results indicate that the slump value of concrete decreases with the incorporation of waste glass fiber, indicating a reduction in workability. The decrease in slump can be attributed to the increased surface area and water absorption of glass fibers, which reduces the free water available for lubrication and flow [102]. The glass fibers also increase the cohesiveness and viscosity of the concrete mix, resulting in a stiffer consistency [103].

However, the reduction in workability can be mitigated by adjusting the mix design parameters, such as increasing the water-to-cement ratio or using suitable plasticizers [104]. The reviewed studies suggest that a slight increase in the water-to-cement ratio (within the acceptable range) or the use of superplasticizers can help maintain the desired workability while incorporating waste glass fiber [105].

It is important to note that the workability requirements may vary depending on the specific application and the placement method of concrete. The acceptable range of slump values should be determined based on the project specifications and the desired performance characteristics of the concrete [106].

5. Environmental Benefits

The utilization of waste glass fiber as an additive in concrete offers several environmental benefits, contributing to sustainable construction practices. The reviewed studies highlight the potential environmental advantages associated with the incorporation of waste glass fiber in concrete.

5.1 Reduction of Cement Consumption

Cement production is a highly energy-intensive process that contributes significantly to greenhouse gas emissions and environmental pollution [107]. The incorporation of waste glass fiber as a partial replacement for cement in concrete reduces the demand for cement production, thereby decreasing the associated environmental impacts [108].

The reviewed studies demonstrate that waste glass fiber can effectively replace cement up to a certain percentage (typically around 10-15%) without compromising the mechanical properties and durability of concrete [109]. This substitution of cement with waste glass fiber leads to a reduction in the overall cement consumption, which in turn lowers the carbon footprint of concrete production [110].

5.2 Sustainable Waste Management

Glass fiber waste generated from various industries, such as insulation materials and reinforced plastics, poses environmental challenges due to its non-biodegradable nature and the potential release of harmful substances during disposal [111]. The utilization of waste glass fiber in concrete provides a sustainable solution for managing this waste, diverting it from landfills and reducing the environmental burden [112].

By incorporating waste glass fiber into concrete, the reviewed studies showcase the potential to valorize this waste material and give it a second life in construction applications [113]. This approach promotes the circular economy concept, where waste materials are repurposed and reused, minimizing the need for virgin raw materials and reducing the environmental impact of waste disposal [114].

5.3 Reduced Environmental

Impact of Concrete Concrete is one of the most widely used construction materials worldwide, and its production and use have significant environmental implications [115]. The incorporation of waste glass fiber in concrete contributes to reducing the overall environmental impact of concrete in several ways.

Firstly, the partial replacement of cement with waste glass fiber reduces the embodied energy and carbon emissions associated with cement production [116]. The reviewed studies highlight the potential to lower the carbon footprint of concrete by utilizing waste glass fiber as a supplementary cementitious material [117].

Secondly, the enhanced mechanical properties and durability of waste glass fiber reinforced concrete can lead to improved service life and reduced maintenance requirements of concrete structures [118]. This, in turn, minimizes the need for frequent repairs and replacements, conserving resources and reducing the environmental impact over the life cycle of the structure [119].

Furthermore, the improved durability characteristics of waste glass fiber reinforced concrete, such as reduced water absorption and increased resistance to chloride ion penetration, contribute to enhanced resistance against deterioration mechanisms and prolonged service life [120]. This extends the lifespan of concrete structures, reducing the environmental burden associated with demolition and reconstruction [121].

6. Conclusion

This review paper has systematically analyzed the experimental studies investigating the utilization of waste glass fiber as an additive in concrete for eco-friendly construction. The findings of the reviewed studies consistently demonstrate the potential benefits of incorporating waste glass fiber in concrete, both in terms of mechanical properties and durability.

The results indicate that the optimal replacement level of cement with waste glass fiber falls in the range of 5% to 15%, with 10% replacement exhibiting the most favorable enhancements in compressive strength, flexural strength, and tensile strength. The incorporation of waste glass fiber also improves the durability properties of concrete, such as reduced water absorption, decreased sorptivity, and enhanced resistance to chloride ion penetration.

The environmental benefits associated with the utilization of waste glass fiber in concrete are significant. The partial replacement of cement with waste glass fiber reduces the cement consumption and the associated carbon footprint. The sustainable management of glass fiber waste is achieved by diverting it from landfills and repurposing it in construction applications. Moreover, the improved mechanical properties and durability of waste glass fiber reinforced concrete contribute to reduced environmental impact over the life cycle of concrete structures.

However, it is important to note that the workability of concrete is affected by the incorporation of waste glass fiber, with higher replacement levels leading to reduced slump values. This aspect should be considered during mix design and placement of concrete, and appropriate adjustments should be made to maintain the desired workability.

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