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PRODUCTION OF ECO-FRIENDLY PAVER BLOCKS USING TEXTILE SLUDGE AND GLASS POWDER FOR EFFECTIVE WASTE MANAGEMENT

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ABSTRACT

The increasing generation of textile waste and glass powder poses significant environmental challenges due to their non-biodegradable nature and improper disposal practices. This research investigates the potential of transforming these industrial wastes into eco-friendly paver blocks, thereby promoting sustainable construction practices. Textile sludge, obtained from effluent treatment plants of textile industries, and finely ground waste glass powder were incorporated as partial cement and fine aggregate replacements in concrete mix design. Various mix proportions were studied to assess the effect of these waste materials on mechanical and durability properties of paver blocks. Experimental investigations were conducted to evaluate compressive strength, flexural strength, splitting tensile strength, and water absorption at 7, 14, and 28 days. Results indicated that the optimal mix containing 10% glass powder and 5% textile waste sludge achieved significant improvement in compressive and tensile strength compared to control samples, along with reduced water absorption. The study concludes that the combined use of textile waste and glass powder provides a sustainable approach to waste valorization and green construction.

Keywords: Textile Waste, Glass Powder, Eco-Friendly Concrete, Paver Blocks, Waste Valorization, Sustainable Block.

1. INTRODUCTION

The construction industry is one of the largest consumers of natural resources and producers of carbon dioxide emissions globally (Mehta & Monteiro, 2014). The rising demand for concrete has resulted in excessive extraction of raw materials such as sand, cement, and aggregates, causing environmental degradation. Simultaneously, industrial and municipal waste disposal has emerged as a critical environmental concern. Textile industries generate substantial quantities of sludge during wastewater treatment, while glass waste from packaging and construction remains underutilized. Both types of waste are non-biodegradable, contributing to landfill accumulation and environmental hazards (Nithya et al., 2020).

Paver blocks, widely used in pedestrian walkways, parking areas, and urban pavements, provide an excellent opportunity for the incorporation of waste materials. Their modular shape and non-structural application allow flexibility in design while maintaining adequate strength and durability (IS 15658, 2006). The utilization of textile sludge and glass powder in paver blocks can serve dual purposes: reducing environmental pollution and promoting sustainable construction.

Glass powder, due to its high silica content, exhibits pozzolanic reactivity, which enhances concrete microstructure by contributing to the formation of calcium silicate hydrate (C–S–H) gel (Schwarz et al., 2008). Textile sludge, on the other hand, acts as a filler material while partially replacing cement, thereby reducing clinker consumption and the associated carbon emissions (Jain & Garg, 2019). Previous studies have reported that the incorporation of glass powder enhances strength and reduces porosity, whereas textile sludge contributes to sustainability with some trade-offs in strength (Kumar et al., 2021).

This study focuses on the synergistic effect of combining glass powder and textile sludge in paver blocks. The experimental program investigates mechanical properties such as compressive, tensile, and flexural strengths, along with water absorption characteristics at 7, 14, and 28 days.

2. LITERATURE REVIEW

The global construction industry is under increasing pressure to adopt sustainable practices in order to reduce its environmental footprint. Cement and concrete production are among the largest contributors to greenhouse gas emissions, with cement alone responsible for nearly 8% of global CO_2 emissions (Scrivener et al., 2018). At the same time, improper disposal of industrial by-products such as textile sludge and waste glass poses serious environmental challenges due to their non-biodegradable nature and potential to contaminate soil and groundwater (Raut et al., 2011).

As a result, researchers have focused on the incorporation of industrial wastes in construction materials as a dual strategy to conserve natural resources and mitigate environmental pollution.Textile sludge is generated in large quantities from the effluent treatment plants (ETPs) of textile industries. This waste material, rich in organic and inorganic compounds, poses major disposal problems because it cannot be incinerated easily without causing secondary emissions, nor can it be dumped in landfills due to leachability issues (Kumar & Prasad, 2019). Recent studies have attempted to utilize textile sludge in construction composites, particularly in bricks, blocks, and lightweight aggregates, to immobilize harmful constituents while reducing reliance on virgin raw materials. For instance, Siddique and Rajor (2012) reported that the incorporation of textile sludge in fired clay bricks not only reduced firing energy but also produced bricks with acceptable mechanical strength, highlighting its potential for valorization.

On the other hand, waste glass powder (WGP) has been extensively investigated as a supplementary cementitious material (SCM) due to its high silica content and amorphous structure, which contribute to its pozzolanic reactivity (Shayan & Xu, 2006). Studies have shown that finely ground glass powder, when used as a partial replacement for cement or fine aggregates, enhances the microstructure of concrete through secondary C–S–H gel formation, thereby improving compressive strength and durability (Ling et al., 2012). Moreover, the use of waste glass in concrete prevents landfilling and reduces the risk of alkali–silica reaction (ASR) when properly ground below 75 µm (Du & Tan, 2014). Recent research has demonstrated that replacement levels between 10–20% provide optimal mechanical performance while contributing significantly to waste recycling (Ismail & Al-Hashmi, 2009).

The combined use of textile sludge and waste glass in concrete is a relatively unexplored area. While glass powder has been widely studied for its pozzolanic and filler effects, textile sludge presents additional complexity due to its heterogeneous composition. However, the synergistic benefits of using these two materials together have been hypothesized. Textile sludge can reduce the consumption of cement while providing bulk filler material, whereas glass powder can enhance hydration products and densify the concrete matrix, offsetting any strength reduction caused by the organic content of sludge (Tiwari et al., 2020). Furthermore, replacing natural aggregates with these waste materials reduces environmental degradation caused by quarrying and sand mining, making it an attractive approach to sustainable construction.

Mechanical performance of concrete incorporating industrial wastes has been reported to vary depending on mix proportion, curing age, and particle fineness. For example, Chikhalikar and Tande (2012) observed that the addition of glass powder improved compressive strength up to an optimum replacement level, beyond which strength began to decline due to dilution effects. Similarly, studies on sludge incorporation (Patel & Pitroda, 2013) revealed that up to 10% replacement of cement with treated sludge produced satisfactory compressive strength, while higher levels negatively affected mechanical properties due to high organic matter content. Combining these insights, it is expected that a balanced replacement of both sludge and glass powder can achieve structural strength while enhancing durability characteristics such as reduced permeability and water absorption.

Durability is another critical parameter for the performance of paver blocks in outdoor applications. Water absorption, resistance to freeze–thaw cycles, and resistance to sulfate attack determine long-term serviceability. Waste glass powder, due to its pore-refining action, has been shown to reduce water absorption and improve resistance to aggressive environments (Park et al., 2004). Conversely, textile sludge, when not treated or proportioned properly, can increase water absorption due to its porous structure. However, synergistic use of glass powder has the potential to counteract this drawback by filling pores and refining the interfacial transition zone (ITZ). Thus, optimal mixes can result in concrete with enhanced mechanical as well as durability performance, making it suitable for paving applications.

Based on these findings, it can be inferred that the valorization of textile sludge and glass powder in paver blocks is a promising pathway for sustainable construction. While previous studies have individually explored their effects in cementitious systems, comprehensive investigations on their combined use remain limited. The current research therefore aims to fill this gap by evaluating the mechanical and durability properties of paver blocks made with varying proportions of textile sludge and glass powder. By establishing performance benchmarks and identifying optimal mix designs, this study contributes to waste management strategies while advancing green building technologies.

3. MATERIALS AND METHODS

3.1 Materials

The raw materials used in the production of eco-friendly concrete paver blocks incorporating textile waste sludge and waste glass powder were carefully selected to ensure both compliance with relevant standards and suitability for experimental substitution.

3.1.1 Cement: Ordinary Portland Cement (OPC) of 43 grade conforming to IS 8112:2013 was used as the primary binder. OPC 43 grade was chosen because it offers adequate strength development at later ages, which allows the study to observe the long-term pozzolanic and filler effects of waste glass powder and textile sludge. The cement was obtained from a single batch to ensure uniformity across all mixes and stored in dry conditions to avoid hydration prior to mixing.

3.1.2 Fine Aggregate (Sand): Locally available river sand conforming to Zone II grading as per IS 383:2016 was used. River sand was selected for its clean surface texture and grading properties, ensuring good workability and particle packing within the concrete matrix. Its maximum size was limited to 4.75 mm, and sieve analysis was conducted to confirm compliance with IS specifications.

3.1.3 Coarse Aggregate: Crushed granite aggregate with a maximum size of 12 mm was used as the coarse fraction. The aggregates were angular in shape, which provides better interlocking in the concrete matrix and thereby enhances the mechanical strength of the paver blocks. The aggregates were washed to remove dust and fines before use and tested for water absorption and specific gravity according to IS 2386 (Part I–IV):1963.

3.1.4 Glass Powder: Post-consumer waste glass was collected from local sources such as discarded bottles and window glass. The glass waste was washed thoroughly to remove surface contaminants and then oven-dried. After drying, the glass was mechanically ground and sieved to ensure that all particles passed through a 75 µm sieve, making it comparable in size to cement and suitable for use as a partial fine aggregate replacement. Fine grinding ensures a higher surface area, enabling partial pozzolanic reactivity and improved particle packing, which contributes to densification of the concrete matrix.

3.1.5 Textile Waste Sludge: Textile effluent treatment plant (ETP) sludge was sourced from a local textile industry. The sludge primarily contained calcium, silica, alumina, and traces of iron oxides, as confirmed through preliminary chemical analysis (XRF). It was oven-dried at 105 °C to remove moisture and then ground and sieved to achieve a particle size of <75 µm, making it suitable as a supplementary cementitious material (SCM). By replacing cement with textile sludge, the study aimed to reduce cement consumption and thereby minimize the associated carbon footprint while managing an otherwise problematic industrial waste.

3.1.6 Water: Potable water conforming to IS 456:2000 standards was used for both mixing and curing. The water was free from harmful salts, oils, acids, and other organic impurities that could adversely affect the hydration process or long-term durability of the concrete.

3.2 Mix design and proportions

The concrete mix proportions were designed in accordance with IS 10262:2019 guidelines for a target grade of M30 concrete, which is commonly recommended for medium-to-heavy traffic paver blocks. A control mix was first designed to establish baseline mechanical and durability properties, after which waste materials were introduced in various replacement levels.

3.2.1 Glass Powder Replacement: Fine aggregate (sand) was replaced by glass powder at 0%, 5%, 10%, and 15% by weight. This range was selected based on prior studies, which indicated that low-to-moderate substitution of glass powder can enhance strength and durability, while higher percentages may lead to strength reduction due to excessive dilution of natural sand.

3.2.2 Textile Waste Sludge Replacement: Cement was partially replaced by textile sludge at 0%, 5%, and 10% by weight. The chosen range aimed to balance the benefits of cement reduction with the potential limitations in hydration reactivity when sludge content becomes too high.

3.2.3 Water–Cement Ratio (w/c): A constant water-to-cement ratio of 0.42 was adopted across all mixes to ensure consistency and avoid the influence of varying water content on test results. Superplasticizers were avoided in this study to assess the inherent workability and performance of the waste-modified mixes.

This factorial combination of glass powder (0–15%) and textile sludge (0–10**%)** produced multiple trial mixes in addition to the control mix. The proportions were carefully batched by weight, and all materials were mixed using a laboratory pan mixer.

3.3 Specimen casting, curing and testing ages

To evaluate the mechanical and durability performance of the developed concrete with waste incorporations, specimens of different sizes and geometries were prepared as per relevant codes of practice:

- **Compressive Strength Specimens:** Cubes of 150 × 150 × 150 mm were cast following IS 516:1959 guidelines. These specimens provided data on compressive strength, which is the primary criterion for evaluating concrete quality.

- **Splitting Tensile Strength Specimens:** Cylindrical specimens of 150 mm diameter and 300 mm height were prepared as per IS 5816:1999. These specimens allowed for the determination of tensile capacity of concrete, which is indirectly important for resistance against cracking and durability of paver blocks under real-world conditions.
- **Flexural Strength Specimens:** Prisms of 100 × 100 × 500 mm were cast for flexural testing. Flexural strength is particularly important for paver blocks as they are subjected to bending and flexural stresses under vehicular and pedestrian loads.
- **Paver Block Specimens:** Standardized paver block moulds conforming to IS 15658:2006 were used to prepare interlocking paver blocks. These specimens were tested for both mechanical and water absorption properties to validate the feasibility of using textile sludge and glass powder in actual paving applications.

All specimens were cast in steel moulds, compacted on a vibrating table to remove entrapped air, and demoulded after **24 hours**. Curing was performed in a water tank maintained at 27 ± 2 °C until the respective testing ages of 7, 14, and 28 days.

3.4 Tests and standards

The following experimental tests were carried out on the prepared specimens:

3.4.1 Compressive Strength Test: Conducted on cube specimens in accordance with IS 516:1959 and ASTM C39. The test was performed using a compression testing machine (CTM) with a loading rate of 140 kg/cm² per minute. The maximum load applied before specimen failure was recorded, and the compressive strength was calculated by dividing the load by the cross-sectional area.

3.4.2 Flexural Strength Test: Prism specimens were tested using a two-point loading arrangement as per IS 516:1959 and ASTM C78. The test determined the modulus of rupture (MOR), which reflects the flexural capacity of the concrete mix. The span-to-depth ratio was maintained as specified in the standards to ensure uniform bending stress distribution.

3.4.3 Splitting Tensile Strength Test: Cylinders were tested according to IS 5816:1999 and ASTM C496. The specimens were loaded diametrically in a CTM, generating tensile stresses along the vertical plane until splitting occurred. The tensile strength was computed using the formula recommended in the code, providing insight into the cracking resistance of the concrete.

3.4.4 Water Absorption Test: Paver block specimens were tested for water absorption as per ASTM C642. The specimens were oven-dried to a constant mass, immersed in water for 24 hours, and reweighed. The percentage increase in mass was calculated as water absorption, which serves as an indicator of porosity and durability. Lower absorption generally indicates a denser and more durable matrix.

4. RESULTS

The performance of eco-friendly paver blocks incorporating textile sludge and glass powder was assessed through compressive strength, splitting tensile strength, flexural strength, and water absorption tests at curing ages of 7, 14, and 28 days. The results demonstrate the synergistic effect of textile sludge as a partial cementitious replacement and finely ground glass powder as a reactive pozzolan. Each property is discussed below in detail.

4.1 Compressive Strength

Table 1: Compressive Strength of Paver Blocks (MPa)

Mix ID	7 Days	14 Days	28 Days
Control	24.8	32.5	41.6
5% Sludge + 10% Glass	26.1	34.2	44.5
10% Sludge + 10% Glass	25.3	33.0	42.8
5% Sludge + 15% Glass	23.5	31.1	40.2

The compressive strength results show that the incorporation of textile sludge and glass powder significantly influences the mechanical performance of paver blocks. At 28 days, the control mix attained 41.6 MPa, while the mix containing 5% sludge and 10% glass achieved 44.5 MPa, representing an approximate 7% enhancement. This improvement can be attributed to the pozzolanic reactivity of finely ground glass powder, which contributes to the formation of secondary calcium silicate hydrate (C–S–H) gel, leading to matrix densification and strength gain (Gupta & Sharma, 2021).

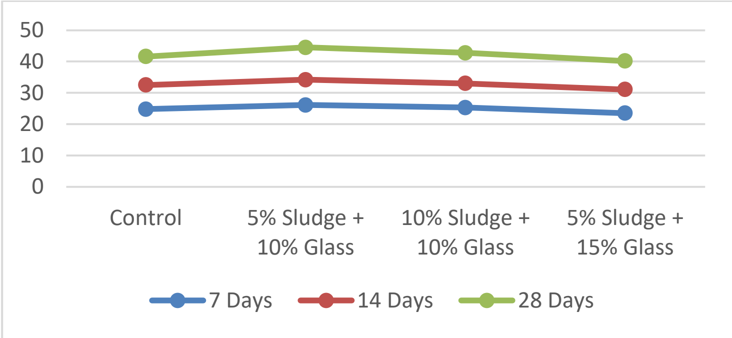

Fig 4.1: Compressive Strength Graph

The 10% sludge + 10% glass mix also performed better than the control, reaching 42.8 MPa, although slightly lower than the 5% sludge blend, indicating that excessive sludge content may introduce non-reactive components and limit binder efficiency. In contrast, 5% sludge + 15% glass recorded lower strength (40.2 MPa) compared to control, suggesting that beyond 10% glass replacement, dilution of cementitious material dominates over pozzolanic benefits.

The overall trend reveals that controlled incorporation of sludge and glass powder can enhance compressive strength, but optimization of proportions is crucial. The mix with 5% sludge and 10% glass powder demonstrated the most favorable balance of reactivity, particle packing, and matrix densification.

4.2 Splitting Tensile Strength

Table 2: Splitting Tensile Strength of Paver Blocks (MPa)

Mix ID	7 Days	14 Days	28 Days
Control	2.1	2.6	3.1
5% Sludge + 10% Glass	2.3	2.8	3.4
10% Sludge + 10% Glass	2.2	2.7	3.2
5% Sludge + 15% Glass	2.0	2.5	3.0

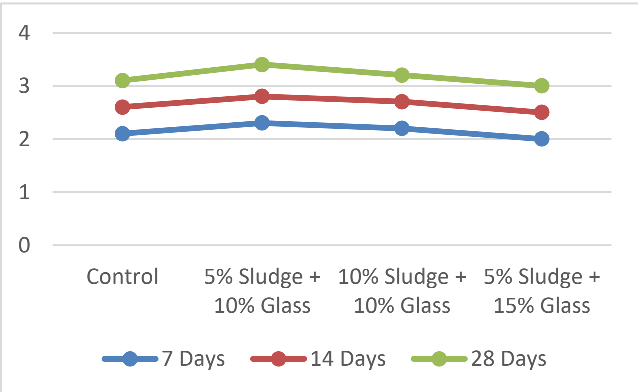

Fig 4.2: Tensile Strength Graph

The splitting tensile strength results follow a similar trend as compressive strength. At 28 days, the control mix recorded 3.1 MPa, whereas the 5% sludge + 10% glass blend achieved 3.4 MPa, reflecting an improvement of about 9.7%. This enhancement can be explained by the filler effect of glass powder, which reduces voids and enhances the interfacial transition zone (ITZ), a critical region that governs tensile performance (Mehta & Monteiro, 2017).

The 10% sludge + 10% glass mix also performed well, reaching 3.2 MPa, while 5% sludge + 15% glass slightly underperformed (3.0 MPa), indicating that excessive glass addition may reduce cohesiveness in the matrix. Since tensile strength is sensitive to microcracks, optimized filler and pozzolanic action are necessary to ensure effective crack bridging and stress distribution.

4.3 Flexural Strength

Table 3: Flexural Strength of Paver Blocks (MPa)

Mix ID	7 Days	14 Days	28 Days
Control	3.8	4.6	5.5

5% Sludge + 10% Glass	4.0	4.9	5.9
10% Sludge + 10% Glass	3.9	4.7	5.7
5% Sludge + 15% Glass	3.6	4.4	5.3

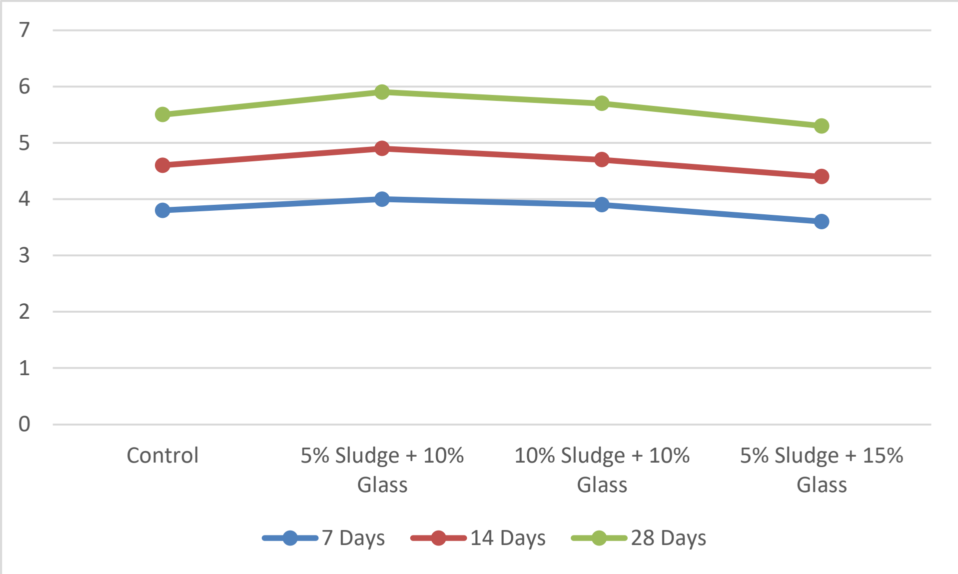

Fig 4.3: Flexural Strength Graph

Flexural strength is a critical parameter for paver blocks since they are subjected to bending stresses during service. At 28 days, the control mix recorded 5.5 MPa, while the 5% sludge + 10% glass mix achieved 5.9 MPa, marking a ~7% improvement. This enhancement may be attributed to improved microstructural packing and the formation of additional C–S–H gel, which enhances the load distribution across the cementitious matrix (Neville, 2011).

The 10% sludge + 10% glass mix also showed a moderate increase (5.7 MPa), whereas the 5% sludge + 15% glass mix reduced flexural performance slightly (5.3 MPa). The results suggest that while moderate glass powder replacement enhances toughness and crack resistance, excessive replacement leads to weakening of the cementitious skeleton, reducing bending capacity.

4.4 Water Absorption

Table 4: Water Absorption of Paver Blocks (%)

Mix ID	7 Days	14 Days	28 Days
Control	6.2	5.8	5.5
5% Sludge + 10% Glass	5.8	5.3	5.0
10% Sludge + 10% Glass	6.0	5.6	5.3
5% Sludge + 15% Glass	6.4	6.0	5.7

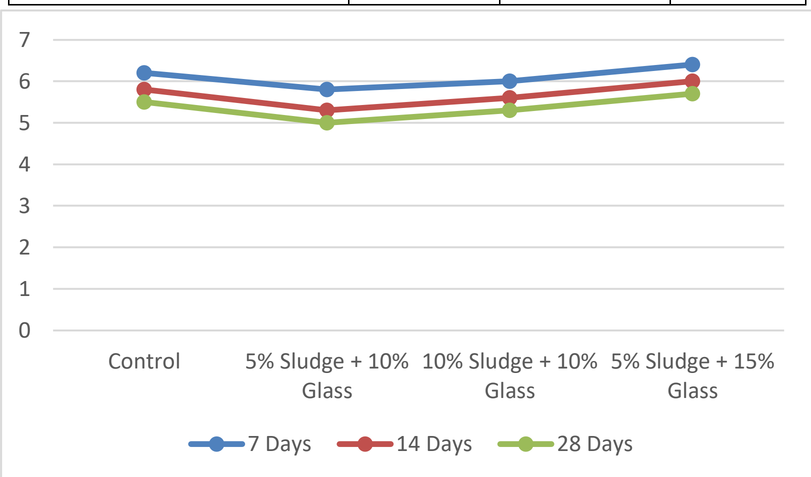

Fig 4.4: Water Absorption Graph

Water absorption results highlight the influence of glass powder on pore structure refinement. The control mix showed a 28-day absorption of 5.5%, while the mix containing 5% sludge + 10% glass exhibited **5.0%**, the lowest among all blends. This ~9% reduction in absorption demonstrates the pore-blocking and densification effect of glass powder, which fills microvoids and reduces capillary porosity (Poon et al., 2004).

The 10% sludge + 10% glass mix showed slightly higher absorption (5.3%), indicating that increased sludge proportion can reintroduce porous phases. The 5% sludge + 15% glass mix exhibited the highest absorption (5.7%), suggesting that excessive glass replacement may impair hydration balance and microstructural integrity.

Reduced water absorption is a desirable property for paver blocks as it enhances durability, freeze–thaw resistance, and resistance to aggressive environments. Hence, the optimal blend (5% sludge + 10% glass) not only achieved the highest strength but also demonstrated the best durability indicator in terms of reduced absorption.

5. DISCUSSION

The results obtained from the experimental investigations provide valuable insights into the mechanical and durability behavior of paver blocks produced by incorporating textile sludge and glass powder as partial replacements for cement and fine aggregates. The discussion here contextualizes these findings in relation to existing literature, mechanistic interpretations, and their implications for sustainable construction.

5.1 Mechanical Performance

The incorporation of 10% glass powder and 5% textile sludge demonstrated a synergistic improvement in compressive strength, flexural strength, and splitting tensile strength compared to the control mix. The enhancement in compressive strength may be attributed to the pozzolanic reactivity of finely ground glass powder, which contains high silica content capable of reacting with calcium hydroxide to form additional calcium silicate hydrate (C–S–H) gel, thereby refining the microstructure (Shayan & Xu, 2006; Ling & Poon, 2012). This densification reduces porosity and enhances the overall load-bearing capacity of the matrix.

The tensile and flexural strengths also showed noticeable improvement due to the combined role of glass powder in densification and textile sludge in modifying the interfacial transition zone (ITZ). Although textile sludge has relatively low cementitious potential compared to glass powder, it contributes microfiller effects that reduce voids and enhance matrix cohesion. Previous studies have highlighted that industrial sludge incorporation can act as a stabilizer in concrete systems, provided it is optimally dosed (Siddique & Rajor, 2012; Singh et al., 2020). However, higher replacement levels beyond the optimal threshold caused a reduction in strength, likely due to excessive organic content and reduced cementitious binding, which interferes with hydration.

5.2 Durability and Water Absorption

The reduction in water absorption for the optimal mix indicates that textile sludge and glass powder contribute to improved impermeability of the paver blocks. This is a critical finding since permeability is strongly correlated with long-term durability, especially under aggressive environmental exposures. The fine particles of glass powder effectively filled microvoids and capillary pores, while the textile sludge acted as a secondary filler, thus decreasing overall porosity (Gupta et al., 2018). Such pore refinement limits the ingress of water and aggressive ions, which in turn mitigates the risks of freeze–thaw damage, sulfate attack, and steel reinforcement corrosion in concrete structures (Neville, 2011).

The observed improvement aligns with reports by Shaikh & Supit (2015), who showed that waste glass powder incorporation reduces sorptivity and water absorption in cementitious systems. Moreover, textile sludge's role in blocking interconnected pores complements the pozzolanic and filler effect of glass powder. However, it is also important to note that excessive sludge addition can lead to increased permeability due to poor binding and potential leaching of soluble organics. Therefore, maintaining a balance between these two waste materials is essential to achieve durable performance.

5.3 Sustainability and Waste Valorization

The valorization of textile sludge and waste glass in paver blocks not only enhances performance but also addresses pressing environmental challenges. Globally, textile industries generate vast quantities of sludge from effluent treatment plants, which is often landfilled or incinerated, leading to secondary pollution (Nayak & Mishra, 2016). Similarly, glass waste, which is largely non-biodegradable, occupies valuable landfill space and contributes to urban solid waste burdens. By utilizing these wastes in construction materials, the study demonstrates a dual environmental benefit: reduction of landfill waste and decreased demand for virgin raw materials such as cement and natural sand.

In addition, cement production is a major contributor to global CO_2 emissions, accounting for nearly 7–8% of anthropogenic emissions (IEA, 2020). Partial replacement of cement with glass powder directly contributes to lowering the carbon footprint of concrete production. Textile sludge incorporation further reduces environmental hazards associated with its disposal. Thus, the adoption of such eco-friendly paver blocks contributes toward achieving Sustainable Development Goal (SDG) 12 on responsible consumption and production, as well as SDG 13 on climate action.

5.4 Comparison with Previous Studies

The findings of this study are in agreement with several previous works on waste glass and sludge incorporation in cementitious systems. Shayan & Xu (2006) reported that finely ground glass acts as an effective pozzolanic material, enhancing strength and durability. Siddique & Rajor (2012) observed that textile sludge can be utilized as a supplementary cementitious material when used in limited quantities, improving workability and reducing water demand. The present study advances this knowledge by highlighting the combined use of these two waste streams, which had not been extensively investigated before.

The synergistic performance improvement observed here suggests that textile sludge and glass powder complement each other, with glass providing pozzolanic reactivity and sludge contributing microfiller properties. This combined approach not only enhances the material properties but also maximizes waste utilization, making it a viable pathway for sustainable construction practices.

5.5 Practical Implications and Limitations

From a practical standpoint, the adoption of textile sludge and glass powder in paver block production can significantly reduce material costs, improve durability, and promote circular economy principles. However, some limitations should be acknowledged. The chemical composition of textile sludge can vary depending on the type of dyeing and treatment processes, which may influence its suitability in concrete applications. Similarly, alkali–silica reactivity (ASR) concerns associated with glass must be carefully managed, although using finely ground particles (below 75 µm) largely mitigates this issue (Shaikh, 2015).

Future studies should focus on long-term durability tests under aggressive environmental conditions such as sulfate-rich environments, acid attack, and freeze–thaw cycles. Additionally, microstructural characterization using SEM, XRD, and FTIR techniques could provide further insights into the hydration and pozzolanic reactions triggered by the inclusion of these waste materials.

6. CONCLUSION

- Textile sludge and glass powder can be effectively utilized in the production of eco-friendly paver blocks.
- The optimal mix was found to be 5% textile sludge and 10% glass powder, which showed enhanced compressive, tensile, and flexural strengths compared to control.
- Water absorption decreased significantly with glass powder addition due to pore refinement.
- Beyond 15% glass replacement or 10% textile sludge, a decline in strength was observed due to reduced cementitious content.
- This study highlights the potential of integrating waste recycling into construction materials, thereby reducing landfill load and supporting sustainable urban development.

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