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Eco-Friendly Tile Production: Transforming Waste Glass into Economic Environmental Value

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Abstract: *The increasing accumulation of glass bottle waste (GBW) in Nigeria presents is a pressing environmental concern due to its non-biodegradable nature and minimal recycling initiatives. Its reuse in construction materials also offers a sustainable solution. This study evaluates the feasibility of using GBW in tile production. By incorporating finely ground waste glass as a primary constituent for fine aggregates in combination with Portland Limestone Cement, experimental tile samples were produced and tested to determine their suitability for construction use. Cement proportions were varied at 10%, 15%, and 20% to examine their influence on physical and mechanical properties such as water absorption, modulus of rupture, surface hardness, and thermal resistance. A series of laboratory tests were conducted to evaluate key physical and mechanical properties, including modulus of rupture, splitting tensile strength, water absorption, apparent relative density, bulk density, moisture expansion, linear thermal expansion, and hardness. The results revealed that tiles containing waste glass exhibited improved mechanical performance, particularly in terms of flexural and splitting tensile strength. This indicates that waste glass contributes positively to the structural integrity of the tiles. However, the tiles also showed increased water absorption, which may affect long-term durability, especially in moisture-prone environments. Despite this limitation, the findings suggest that waste glass can be effectively used as a material in tile production, promoting recycling and reducing reliance on natural raw materials.*

Keywords: *Eco-Friendly, Waste Glass, Powder, Tile, Environmental Value*

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1. INTRODUCTION

Nigeria generates a staggering 2.5 million tons of glass waste annually [1], with the majority ending up in landfills and only a small fraction being recycled [2]. This creates significant environmental challenges, as glass waste occupies substantial space in landfills and doesn't biodegrade, exacerbating waste management issues. The growing volume of glass waste poses a considerable problem [3], threatening to overflow landfills and potentially harming the environment. Effective waste management solutions are crucial to mitigate these issues.

The increasing volume of waste glass from various sources poses environmental challenges due to its non-biodegradable nature and limited recycling options, leading to landfill accumulation and resource waste. However, recycling glass waste into construction materials offers a promising solution, consuming significantly less energy than producing new glass from raw materials. This energy efficiency stems from recycled glass melting at a lower temperature, making it an attractive option for sustainable waste management [4].

Incorporating waste glass into tile production offers a sustainable solution, reducing environmental pollution and conserving natural resources like clay and cement. This approach not only saves energy and resources but also promotes waste reduction. Studies have explored the benefits of using glass in construction, including improved mechanical properties and minimized environmental impact. By using recycled glass or custom glass compositions, tile manufacturers can create sustainable products with enhanced properties, such as strength, colour, or texture, ultimately reducing waste and promoting eco-friendly manufacturing practices. The experiment conducted by Kou and Poon [5], Ismail and AL-Hashmi [6] and Borhan [7] on the effect of replacing natural fine aggregates with recycled fine glass in self-compacting concrete (SCC) yielded an interesting result: the density of the SCC decreased as the percentage of recycled glass replacement increased. This finding is consistent with other studies, which suggest that using waste glass as a partial replacement for fine aggregate in concrete can lead to reduced density. Safarizki *et al* [8] experiment on using glass powder as a partial replacement for sand in concrete mixtures showed promising results, indicating that concrete with glass powder can be safer than conventional concrete. Kaffayatullah *et al* [9] research on concrete containing glass powder revealed that the compressive strength of cement mortar improves with the inclusion of waste glass powder. This finding is consistent with other studies, which suggest that glass powder exhibits pozzolanic characteristics when its particle size is less than 75 µm. This means it can enhance the durability and strength of concrete. Ekwulo and Eme [10] study on the compressive strength of concrete with glass aggregates revealed 20 and 10 % optimal replacement percentages for sand and coarse aggregates with fine glass and coarse glass respectively. Aniket *et al* [11] findings on the compressive strength of concrete with glass powder as a partial cement replacement indicate that; When the proportion of glass is below 30%, the compressive strength is approximately equal to that of normal concrete. The optimum performance of recycled glass concrete (RGC) is achieved by replacing natural fine aggregates with recycled fine glass (RFG) within a specific range. According to researchers Ismail and AL-Hashmi [6], Sakale and Sourabh [12], Ali and Esraa [13], Tuaum *et al* [14] and Park *et al* [15], the recommended replacement range is between 10% to 30%. This range allows for improved mechanical properties and sustainability in concrete production. Gautam *et al* [16] statement that waste glass can effectively replace coarse aggregates up to 50% without substantial change in strength is supported by various studies. Demir [17] research reveals that incorporating waste glass into mixtures yields several benefits. Waste glass additions lower dry and total shrinkage values compared to plain samples. Linear shrinkage increases with rising firing temperatures. Higher firing temperatures and waste glass content reduce porosity and water absorption, enhancing material durability. Crushed and screened waste glass can be used as a partial replacement for fine aggregate in asphalt mixes, with optimal performance achieved at 10-15% incorporation. The study of Al-jameel and Al-Saeedi [18] investigated the effects of incorporating crushed glass into asphalt mixes, replacing conventional materials with glass waste in various forms and percentages. The results showed that glass waste can be effectively used, particularly when 10% of crushed glass replaces coarse aggregate with 40-50 asphalt grades. The study also found that glass waste can substitute conventional flux materials in ceramic masses and be used as a sand substitute in applications like sandblasting, water filtration, aggregates, bricks, and tile production, promoting sustainable waste management and resource conservation. The study of Mouafon *et al* [19] found that adding glass cullet to basic clay mixtures increases linear shrinkage up to 30% glass powder content, while decreasing water absorption in tiles as the glass content increases, indicating improved durability and water resistance.

This study explores the potential of transforming waste glass into valuable materials, such as tiles, to reduce landfill waste and raw material consumption. The research provides insights into the feasibility of using waste glass in tile production, paving the way for sustainable and cost-effective manufacturing processes.

2. MATERIALS AND METHODS

This study evaluates the properties of waste glass used for production of tiles. Several laboratory tests on glass and tiles were conducted. This study focuses on tiles produce with varying proportion of cement/waste glass of 10/ 90, 15/85 and 20/80 %.

2.1 Materials

2.1.1 Cement

The cement employed in this investigation is Portland Limestone Cement, grade 42.5 N with a specific gravity of 3.15 and was obtained locally from Tarauni market in Kano, Nigeria. The cement has the properties to act as a binding agent in the presence of water.

2.1.2 Waste glass powder (WGP)

The glass samples used for this work are the post-consumer glass waste obtained from waste collection points around domestic and hospitals. The glass wastes were gathered, washed with detergent to remove contaminants, dried at room temperature, broken down into pieces and pulverized in a Los Angeles Machine. The powder was sieved through British Standard Sieve size of 300 µm sieve and glass powder was obtained in very fine powder with a specific gravity of 2.44.

2.1.3 Water

Portable water collected from Civil Engineering Laboratory of Bayero University Kano, Nigeria was used for preparing the mix and also for curing the samples. The water conformed to the requirement of [20]. Preliminary investigations (particle size distribution, specific gravity and water absorption) on materials were conducted on the WGP in accordance with [21] for to ascertain their suitability.

2.2 Methods

The proportions of the constituent materials are presented in Table 1.

Table 1: Constituent materials and proportion for tile production

Sample	WGP (%Wt.)	Cement (% Wt.)
A	90	10
B	85	15
C	80	20

The combination of WGS and cement were mixed with water (10 % of the total volume of solid mix) was compacted in molds using a vibrator and cured for 3 days. Various physical and mechanical tests were conducted on the tile samples for their characterization and assessment of conformity with other relevant standards.

i. **Water absorption, apparent porosity, relative density and bulk density:** these tests were conducted in accordance with BS EN ISO 10545-3 [22] using the Equations 1 to 4.

$$Aw = \frac{W-D}{D}\ x\ 100 \tag{1}$$

$$AP = \frac{W-D}{V}\ x\ 100 \tag{2}$$

$$RD = \frac{D}{DW} \tag{3}$$

$$BD = \frac{D}{V} \tag{4}$$

Where; Aw = Water Absorption, AP = Apparent Porosity, BD = Bulk Density, RD = Relative Density, V = Exterior Volume, DW = Loss in Weight in Water, D = Dry Weight, and W = Saturated Weight,

ii. **Moisture expansion:** Moisture expansion is the proportional accelerated expansion that results from subjecting reheated tiles to extended immersion in boiling water. The boil time is usually 24 hours. The test was carried out in accordance to BS EN ISO 10545-10 [23].

iii. **Modulus of rupture (MOR):** The MOR is measured by placing a tile sample on two supports and applying a load at the center until the tile breaks [24]. The maximum load the tile can bear before breaking is used to calculate the Modulus of Rupture thus.

$$MOR = \frac{1.5PL}{bd2} \tag{5}$$

Where; P = Maximum Load , b = width, d = depth, and L = span

iv. **Splitting tensile strength (fs)**: The splitting tensile strength was determined by dividing the maximum applied load by the appropriate geometrical factors as shown in Equation 6. The test was carried out in accordance to ASTM C496/C496M-11 [25].

$$s = \frac{2P}{\pi dl} \tag{6}$$

Where; l = sample length

v. **Linear thermal expansion:** A test method for the measurement of the linear thermal expansion coefficient for the temperature range from ambient to 100°C. Fixed rate of heating was applied, with a uniform distribution of heat. Two specimens were tested, at right angles to one another. The test was carried out in accordance to BS EN ISO 10545-8 [26].

vi. **Resistance to thermal shock:** Thermal shock resistance was determined by cycling between 15°C and 145°C. Defects are assessed by viewing the tiles with the naked eye from a defined distance and light intensity. The test was carried out in accordance to ASTM C484 [27].

vii. **Scratch hardness:** scratching test consists of a simulation where only one abrasive particle acts over the specimen. This technique provides the scratching hardness, specific scratching energy, dynamic brittleness index, and critical stress concentration factor, among other properties [28].

3. RESULTS AND DISCUSSIONS

At least 3 samples were used at each test for all categories and the averages are presented and discussed in this section.

3.1 Tile Materials

The sieve analysis was carried out to know the aggregate gradation of the WGP. The sieve analysis result shows that the WGP contain 93.93% particles between 0.075 to 0.3 mm sizes and 6.07 % fines. The results obtained for specific gravity and water absorption on WGP are presented in Table 2.

Table 2: Physical properties of WGP

Test	Specific gravity	Water absorption (%)
Result	2.44	0.4

3.2 Properties of WGP Tile

3.2.1 Apparent porosity, water absorption, apparent relative density and bulk density of the tiles

The apparent porosity, water absorption, apparent relative density and bulk density of the tiles are presented in Table 3.The apparent porosity and water absorption values of samples A, B, and C followed a similar trend. Sample A showed the highest values, followed by sample B, and the lowest values were recorded for sample C. Water absorption of the WGP tile are influenced by their porosity. When there are more pores or voids in the structure, there is more space for water to enter. The results for apparent relative density and bulk-density supported the observed variations in porosity and water absorption. These variations are closely related to the amount of cement and the extent of hydration that occurred in each sample. When cement reacts with water, it produces hydration products such as calcium silicate hydrate (C-S-H), which helps to fill in pore spaces and make the structure denser. Sample C, with the highest cement content, formed more hydration products, which filled more voids and created a less porous tile with lower water absorption.

Table 3: Apparent porosity, water absorption, apparent relative density and bulk density of the samples

Sample	Apparent porosity (%)	water absorption (%)	Apparent relative density	Bulk density (Kg/m^3)
A	38.70	31.62	1.24	1.91
B	26.67	16.39	1.63	2.24
C	22.49	14.29	1.71	2.31

3.2.2 Linear thermal and moisture expansion

In this study, no measurable expansion was observed across all samples, regardless of the varying glass-to-cement ratios. The absence of expansion can be attributed to the nature of the materials used. Glass, which made up the majority of each sample is a chemically inert and non-porous material that does not absorb water or swell. The tile sample for linear thermal expansion showed no measurable expansion within the temperature range. This may be attributed to the inherently low thermal expansion coefficient of glass-based materials, especially if the tile contains soda-lime or similar glass types.

3.2.3 Modulus of rupture

The Modulus of Rupture (MOR) increased with higher cement content in the WGP tiles as presented in Figure 1. This increase in MOR can be linked to the role of cement in forming hydration products such as calcium silicate hydrate which improves bonding and strengthens the structure, making the tile more resistant to bending forces. The chart presenting the variation of the MOR is shown in Figure 1.

3.2.4 Splitting tensile strength

The splitting tensile strength of the glass powder tiles improved as the cement content increased from Sample A to Sample C as presented in Figure 2. The increased cement proportion allowed for more hydration, resulting in a denser matrix and better bonding between the glass particles. This enhanced the tile's ability to carry tensile loads during the splitting test.

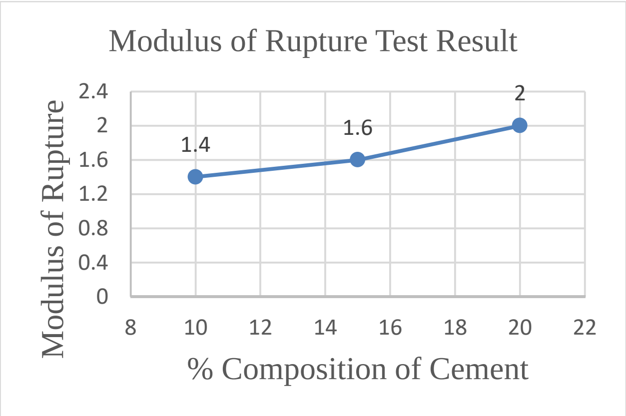

Figure 1: Modulus of rupture test

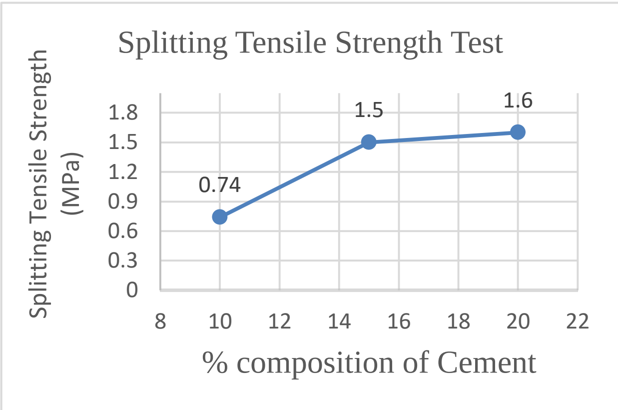

Figure 2: Splitting tensile strength

3.2.5 Thermal shock resistance

The thermal shock resistance of the tiles was evaluated through rapid heating and cooling cycles. No visible cracks or fractures were observed in any of the samples after exposure to temperature fluctuations, indicating that the tiles exhibit excellent resistance to thermal shock. Results of the thermal resistance test of the tiles are presented in Table 5.

Table 5: Thermal shock resistance

Sample	First cycle	Second cycle	Third cycle	fourth cycle	Fifth cycle
A	No visible crack	No visible crack	No visible crack	No visible crack	No visible crack
B	No visible crack	No visible crack	No visible crack	No visible crack	No visible crack
C	No visible crack	No visible crack	No visible crack	No visible crack	No visible crack

3.2.6 Scratch hardness

The hardness of the WGP tiles were assessed using a practical scratch test based on the Mohr scale. Common objects including a fingernail (~2.5), copper penny (~3.5), knife/glass plate (~5.5) and steel nail (~6.5) were used to scratch the tile surface. The results (Table 5) showed that sample A resisted scratch from the fingernail but were scratched by the copper penny, indicating a Mohr hardness of ~3.5. Sample B and C resisted scratched from the fingernail and copper penny but were scratched by the knife and glass plate, indicating a Mohr hardness of ~5.5.

Table-7: Scratch hardness for WGP tiles

Sample	Test object	Mohr Hardness of object	Observation	Scratch hardness of Tile
A	Fingernail	2.5	No scratch	
	Copper penny	3.5	Minor scratch	3.5
B & C	Fingernail	2.5	No scratch	
	Copper penny	3.5	No scratch	5.5
	Knife/glass plate	5.5	Minor scratch	

4. CONCLUSIONS

This research paper presented a preliminary study on using waste glass. The findings show that, the combination of 20% cement and 80% GBW yield the best result. Strength tests, including modulus of rupture and splitting tensile strength, showed that increasing the amount of cement led to higher strength. The 20% cement mix was the strongest. This was shown from the outcome of the durability tests. The water absorption, moisture expansion, apparent porosity, thermal shock resistance, and linear thermal expansion yielded improved result at 20 % cement content. However, the 15% mix is also adequate for use in building tiles. This suggests that using 15% cement is both practical and efficient. Hence, the research presents a profitable way of disposing harmful substance. Using waste glass-cement for floor tiles is an eco-friendly approach. Waste glass is cheap, offsets cement cost, reduces landfill waste, lowers cement usage (lower CO_2 footprint), reduces waste glass in landfills, crushed glass adds decorative appeal (terrazzo-like finish); suitable for interior/exterior tiles. Glass improves abrasion resistance and hardness.

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