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Performance Evaluation of Pervious Concrete Containing Glass Cullet and Glass Powder for Sustainable Construction

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Abstract
The utilization of waste materials in concrete production has gained significant attention due to its potential for sustainable construction and environmental conservation. This study evaluates the performance of pervious concrete incorporating glass cullet as partial replacement fo r coarse aggregate and glass powder as supplementary cementitious material. The experimental program investigated the physical and mechanical properties of the materials, as well as compressive strength, abrasion resistance, water absorption, and permeability of the produced mixes. Results indicate that up to 20% replacement of cement with glass powder improved compressive strength due to its pozzolanic activity, while glass cullet effectively replaced natural aggregates without adversely affecting workability. Pervious concrete with glass powder demonstrated reduced porosity and enhanced durability compared to control mixes. The findings suggest that integrating waste glass into pervious concrete not only improves mechanical and durability properties but also offers a sustainable solution for waste management and eco-friendly construction.

Keywords: *Pervious concrete, glass cullet, glass powder, sustainable construction, compressive strength.*

1.0 Introduction

Concrete is the most widely used construction material worldwide, but its production contributes significantly to environmental challenges such as high energy demand, greenhouse gas emissions, and the depletion of natural resources.

The rising demand for sustainable construction materials has heightened research into alternative components that can mitigate the environmental impact of conventional concrete. Pervious concrete is an innovation characterised by its high porosity, facilitating water infiltration, thereby diminishing surface runoff and enhancing groundwater recharge.

Pervious concrete is increasingly adopted in sustainable infrastructure because of its high porosity, which enables stormwater infiltration, reduces surface runoff, and improves groundwater recharge. However, its relatively low comprehensive strength limits broader application, especially in load-bearing structures.

Simultaneously, waste glass, when finely pulverised into powder (glass powder) or crushed into coarse fragments (glass cullet), demonstrates favourable pozzolanic and aggregate-like characteristics, rendering it a suitable material for concrete production. Silica-rich glass powder can improve the cementitious matrix via secondary hydration reactions, whereas glass cullet can act as a lightweight, durable substitute for natural coarse aggregates [1],[2]. Incorporating supplementary cementitious materials, such as glass powder has demonstrated the ability to alleviate certain detrimental effects linked to waste glass in concrete. The incorporation of glass cullet as an aggregate can improve strength and durability, counteracting possible decreases due to alkali-silica reactions (ASR) associated with glass aggregates [2].

Several studies have demonstrated that crushed and screened waste glass is a reliable, secure, and affordable substitute for sand in concrete. Over the past ten years, it has become evident that the quantity of sheet glass trash generated in factories, construction sites, and retail establishments is substantial and growing annually [3].

This study therefore investigates the combined use of glass cullet and glass powder in pervious concrete. The objectives include evaluating the mechanical and durability properties of the mixes and determining the optimum replacement levels that enhance strength and sustainability while contributing to effective waste management solutions.

2.0 Literature review

Concrete is an artificial material comparable in appearance and properties to some natural lime stone rock. It is a man-made composite, the major constituent being natural aggregate such as gravel, or crushed rock, sand and fine particles of cement powder all mixed with water. Pervious concrete is characterised by interconnected voids

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that allow water infiltration, its properties depend on aggregate size water-cement ratio, and porosity. Studies show that increasing porosity enhances permeability but reduces compressive strength.

Glass powder, rich in silica, reacts with calcium hydroxide to form additional calcium silicate hydrate (C-S-H), improving strength and durability. Previous studies have been on the effects of glass cullet, glass powder and some materials such as fly ash [4], lime powder [5], cement [6][7], treated Rice Husk Ash [8], Nanosilica [9], among others, on the performance of concrete and confirm that fine glass powder enhances mechanical properties and reduces environmental impact. [10] investigated on concrete produced from waste glass with natural aggregate while [3] study on critical effectiveness of waste glass powder in concrete production.

Glass waste was used as partial replacement of binding material (i.e cement) in production of pervious concrete [11][12][13]. [3][14][15][16][17][18] combined glass powder and other pozzolanic materials with concrete; while [19] worked on performance of pervious concrete using marble sludge power. These studies confirmed that glass powder significantly influences both permeability and compressive strength depending on dosage.

Most studies focus on either glass powder or glass cullet independently. Limited research evaluates their combined effect in pervious concrete, especially under varying mix ratios. This study comprehensively evaluates fresh properties of pervious concrete incorporating glass cullet, glass powder as active addition through partial replacement of cement, which acts as binder using different mix ratios.

3.0 Materials and Methods

Pervious concrete was produced using cement, glass cullet (coarse aggregate replacement), glass powder (cement replacement), granite (coarse aggregate) and sand (fine aggregate). Sieve analysis, glass impact value, glass crushing value and SEM/EDS analysis were conducted to determine the physical and chemical properties of pervious concrete. Two mix ratios (1:4 and 1:6) were adopted and the glass powder replaced cement at 0%, 5%, 10%, 15%, and 20%. These proportion were selected in order to study the effect of cements content on the properties of pervious concrete. The glass cullet was used as full aggregate materials while glass powder was incorporated as a supplementary material in the mix. Water was added in a controlled quantity to achieve proper mixing and workable consistency suitable for pervious concrete production. Concrete cubes which were cured and analysed for its compressive strength at 7 and 28 days. Abrasion resistance, permeability test and water absorption tests were conducted to determine the durability properties of the pervious concrete. All laboratory test was conducted in accordance with ASTM and BS EN 933-1 standards.

4.0 Results and Discussion

a. Physical and Chemical Properties of Materials

I. Particle size distribution

Particle size distribution of glass powder and glass cullet were presented with Figure 1(a & b). The results of glass cullet are well graded as 100 percent of the glass fine passed through the 37.5mm and 25mm sieve indicating the absence of very large size particles. A large portion of the material was retained on the 12.5mm sieve (49.6%) indicating that the aggregate is predominately within the size range. Both aggregates are suitable for concrete production and are in accordance to BS 812: part 103 which is in line with the work of [20].

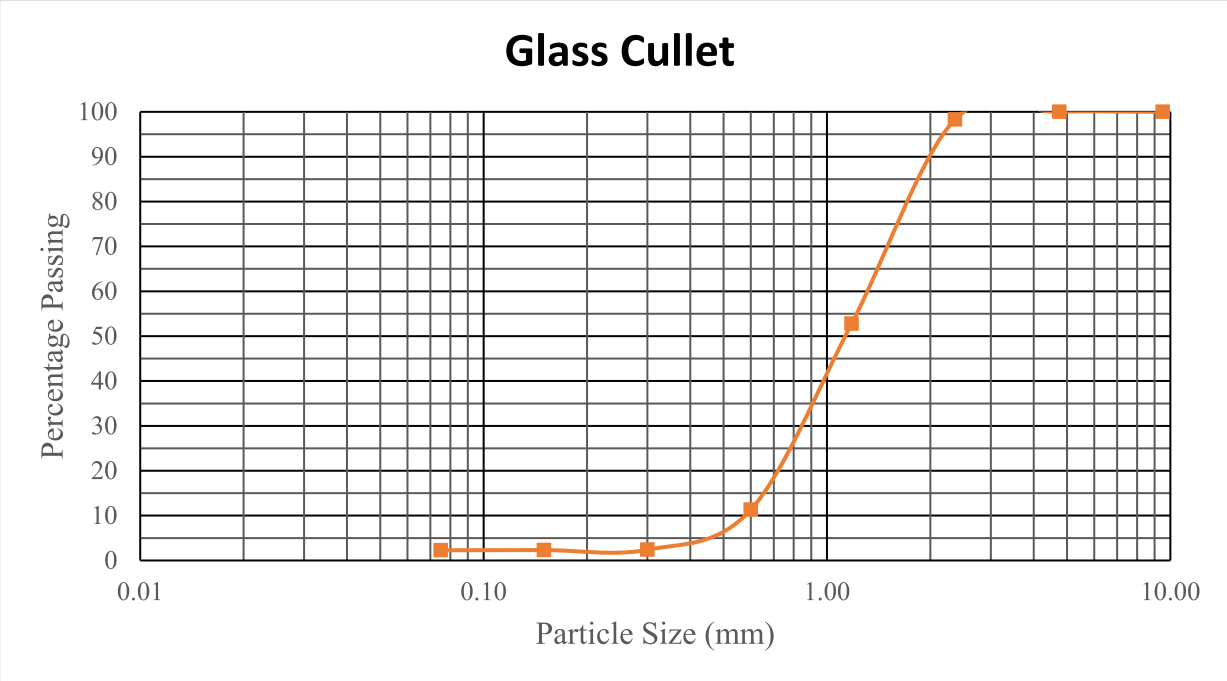

Figure 1a: Particle Size Distribution of Glass Cullet

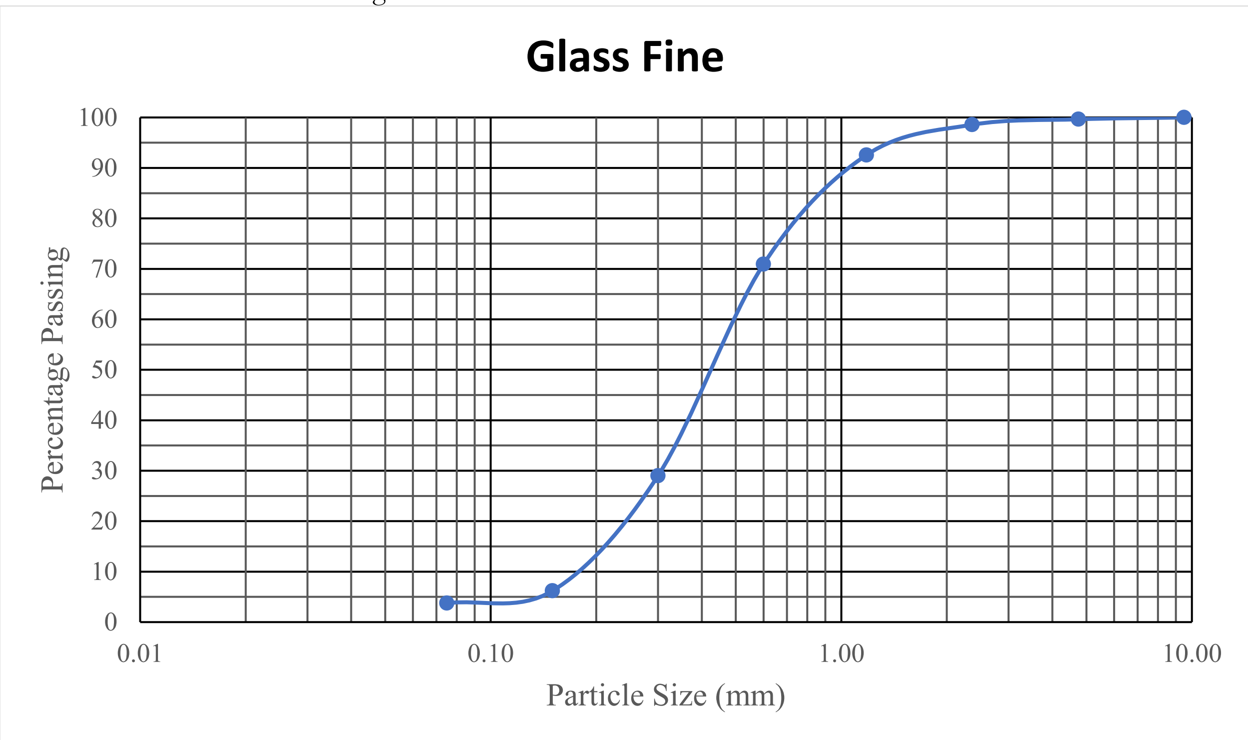

Figure 1b: Particle Size Distribution of Glass Fine

II. Glass Impact and Crushing Test

The results of glass impact value and glass crushing tests were presented in Table 1 and Table 2 respectively. Aggregate with aggregate Impact Value (AIV) of less than 10-20 are considered exceptionally strong while values between 20-30% are satisfactory for road surfacing. A mean glass impact value and glass crushing value of 58.85% and 42.45% obtained respectively indicate lower toughness than natural aggregates. Similar observations were reported in waste glass aggregate studies by [21].

Table 1: Glass Impact Test Results

Description	1	2	3
Empty weight of mould (w) m(g)	1400.00	1400.00	1400.00
weight of sample with steel cup (w_1) (g)	1960.32	1955.91	1971.00
weight of glass passing 2.36mm Is sieve (w_2) (g)	345.87	312.61	334.5

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Description	1	2	3
Glass impact value $\frac{W2}{W1-W} \times 100$	61.73	56.23	58.58
Mean value		58.85	

Table 2: Glass Crushing Test Results

Description	1	2
Weight of glass sample filling in cylinder (W_1) (g)	2000.00	2000.00
Weight of glass sample passing 2.36mm sieve after test (W_2) (g)	840.00	858.00
Aggregate crushing value $\frac{W2}{W1}\times 100$	42	42.9
Average ACV (%)	42.45	

III. SEM/EDM

The Scanning Electron Microscopy image of glass cullet taken at 2000× magnification using a 15kV electron beam is shown in Figure 2. The exterior presents a mostly smooth structure containing several dispersed particles as debris. Processing of the glass cullet appears to have occurred to some extent while residual contaminants and particles remain present. Several irregular particles together with visible surface marks and cracks appear on the surface. Mechanical breakdown or environmental elements have led to the formation of these small irregularly shaped particles and surface scratches or cracks. Thin bright areas appearing in the glass sample might signify both high atomic number elements and elements that enter its composition.

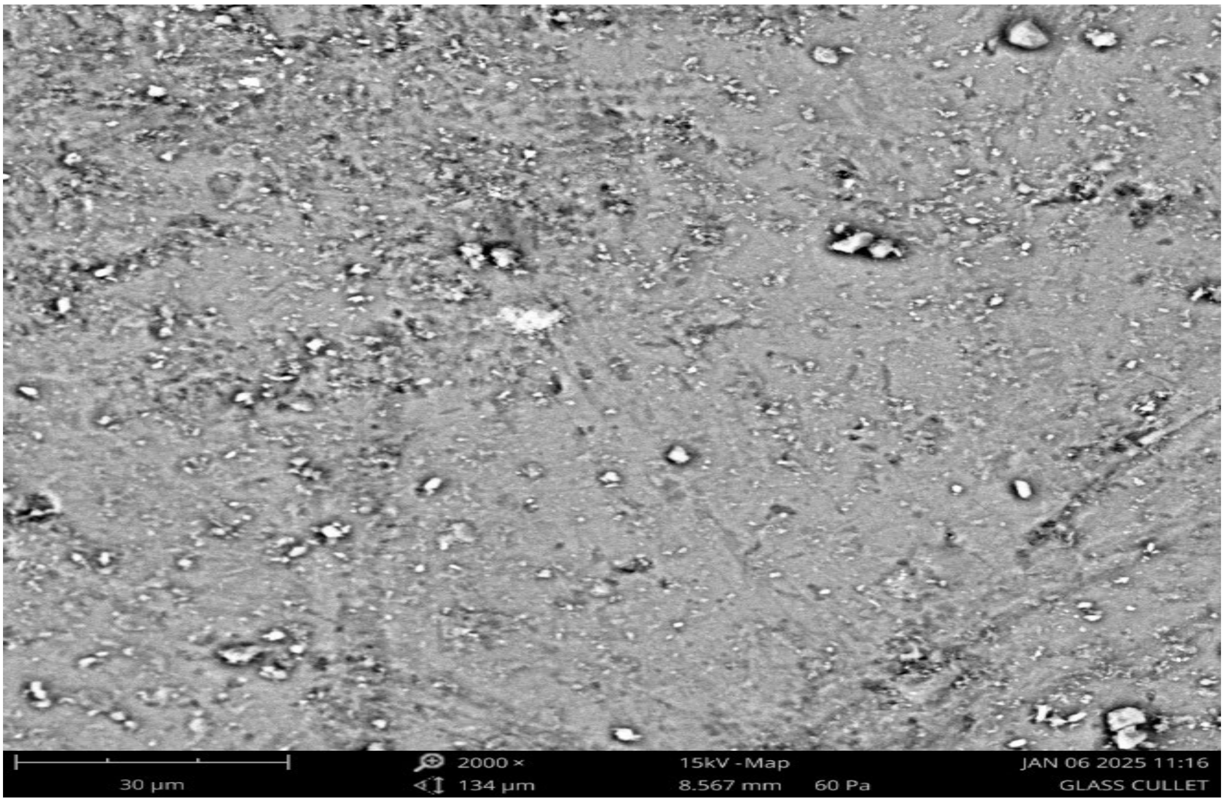

Figure 2: SEM Image of glass cullet

Energy Dispersive X-ray Spectroscopy (EDS) spectrum provides the elemental composition of the analyzed glass cullet sample. The chemical composition of glass cullet used are stated in Table 3.

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Table 3: Element present in glass cullet

Element Number	Element Symbol	Element Name	Atomic Conc.	Weight Conc.
14	Si	Silicon	60.33	54.47
20	Ca	Calcium	11.22	14.45
11	Na	Sodium	16.83	12.44
38	Sr	Strontium	3.83	10.78
12	Mg	Magnesium	4.12	3.22
13	Al	Aluminium	2.04	1.77
26	Fe	Iron	0.69	1.24
19	K	Potassium	0.47	0.60
47	Ag	Silver	0.10	0.36
30	Zn	Zinc	0.12	0.25
22	Ti	Titanium	0.14	0.22
28	Ni	Nickel	0.11	0.21
15	P	Phosphorus	0.00	0.00
16	S	Sulphur	0.00	0.00
17	Cl	Chlorine	0.00	0.00

Minor Elements

Aluminum (Al): Commonly present in glass as Al_2O_3, enhancing strength; Calcium (Ca): Suggests CaO (lime), which improves durability; Strontium (Sr): Often used in specialty glasses, possibly for modifying optical properties; Titanium (Ti): Found in certain glasses to improve UV resistance; Zinc (Zn): May be present for chemical resistance or optical properties; Iron (Fe): Possible impurity or intentional addition for tinting.

Trace Elements

Silver (Ag), Potassium (K), Sulphur, (S), Chlorine (Cl), and Nickel (Ni) are detected at lower levels, possibly as impurities or minor functional additives. Both glass cullet and powder show similar Si, Al, Ca, and Sr peaks, confirming they share the same base composition.

b. Optimum proportion test on glass cullet and glass powder

Glass cullet and powder were added to concrete materials in percentages (0, 5, 10, 15, 20) to ascertain the effects which the glass cullet and powder has on the concrete produced.

i. Estimated quantities for 1:4 mix

The results of the quantities of material for mix design ratio (1:4) of Cement, Glass Cullet, Glass Powder, and Water were presented in Table 4. The materials are batched by weight.

Table 4: Results of estimated quantities of pervious concrete of Mix ratio (1:4)

Materials	0	5	10	15	20
Cement	8.10	7.29	6.48	5.67	4.86
Coarse aggregate (glass cullet)	32.4	32.4	32.4	32.4	32.4
Glass powder	-	0.81	1.62	2.43	1.62
Water	2.84	2.84	2.84	2.84	2.84

The effect of glass powder increases as the cement decreases as glass powder replaces a portion of the cement, the total amount of pure cement reduces from 8.1kg to 4.86kg at 20% replacement. The percentage of coarse aggregate (glass cullet) remain the same (32.4kg), maintaining the bulk volume.

The water/cement materials remain constant throughout the mix and the workability may improve slightly because glass powder particles are very fine and can act like lubricants [1]. The strength up to about 15% replacement, strength may stay the same or slightly improve, due to pozzolanic reaction of glass powder [22] and beyond 20% replacement, a decrease in compressive strength is generally observed if curing is not optimized [23]. The durability of glass powder improves resistance to sulphate attack and reduces permeability because of finer particle packing and pozzolanic action [24].

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ii. Estimated quantities for 1:6 mix

The results of the quantities of material for mix design ratio (1:6) of Cement, Glass Cullet, Glass Powder, and Water were presented in Table 5.

Table 5: Results of estimated quantities of pervious concrete of Mix ratio (1:6)

Materials	0	5	10	15	20
Cement	5.4	4.86	4.32	3.78	3.24
Coarse aggregate (glass cullet)	32.4	32.4	32.4	32.4	32.4
Glass powder	-	0.54	1.08	1.62	1.08
Water	2.84	2.84	2.84	2.84	2.84

At 0% replacement, the control mix contained 5.40kg of cement, 3.24kg of glass cullet, 0.00kg of glass powder and 2.84kg of water. At 5% replacement, the cement content reduced to 4.68kg which the glass powder increased to 0.54kg. At 10% replacement, the cement further reduced to 4.32kg with a corresponding increase in glass powder to 1.08kg. At 15% and 20% replacement, the cement content decrease to 3.78kg and 3.24kg respectively, while the glass powder increased to 1.62kg at 15% and 1.08 at 20%. This trend confirm that glass powder was used as a partial replacement for cement and not as an additional; material. The reduction in cement and corresponding increase in glass powder indicate a systematic substitution within the binder component of the concrete mix.

The glass cullet remains constant at 32.4kg across all the mixes, indicating that the aggregate proportion was maintained in order to isolate the effect of cement replacement on the concrete properties similarly to the water content remain constant at 2.84kg, ensuring a uniform mixing condition and making it easier to compare the effect of glass powder replacement on the concrete performance.

The implication of this result is that the 1:6 concrete mix can successfully accommodate glass powder as a supplementary cementious materials. The fine nature of glass powder may help to fill micro-voids within the concrete matrix, thereby improving particles packing and enhancing the compactness of the mix. This agree with the funding of [24] who reported that finely ground glass powder can act as a pozzolamic materials in concrete and contribute positively to concrete performance.

In terms of straight and durability, moderate replacement level such as 10% to 15% are generally considered beneficial because the pozzolamic reaction of finely ground, glass powder can contribute to the formation of additional cementious compound, thereby improving the internal structure of the concrete. This is in line with the report of [23], who observed that concrete containing glass powder at suitable replacement level showed improved compactness and reduce porosity

Furthermore, the use of glass powder in concrete has been associated with improved durability – related properties, such as reduced permeability, improved resistance to chloride penetration, and better electrical resistivity. This support the finding of [25] who found that fine glass powder enhanced the durability characteristic of concrete by refining its pore structures. However, although increasing the replacement level reduces cement consumption and promotes sustainability excessive replacement may reduce the amount of active cement available for hydration, which can adversely affect strength if the option level is exceeded.

Therefore, based on the mix trends and supporting literature, the optimum replacement level for the 1:6 mix is between 10% to 15%, where both strength and durability performance may be reasonable balanced. Overall, the result of the 1:6 estimated the ratio show that glass powder can be successfully incorporated as a partial replacement for cement, while keeping the aggregate and water content constant. This makes the mix suitable for evaluating the effect of glass powder on the workability, strength and durability of concrete.

c. Compressive Strength of Pervious Concrete with Glass Cullet and Glass Powder

The results of compressive strength of mixes 1:4 and 1:6 at 7 and 28 days of crushing are presented in Figure 3&4 respectively.

The optimum replacement of 20% glass powder at mix 1:4 appears to give the highest compressive strength at both 7 and 28 days and at 20% replacement there was decrease slightly, suggesting too much cement replacement limits available $Ca(OH)_2$ for pozzolanic reactions, and less C-S-H forms [22]. While the strength of mix 1:6 increases from 0% to 15% replacement with glass powder and slightly decrease in strength was recorded with 15 and 20% replacement at both 7 and 28days of curing.

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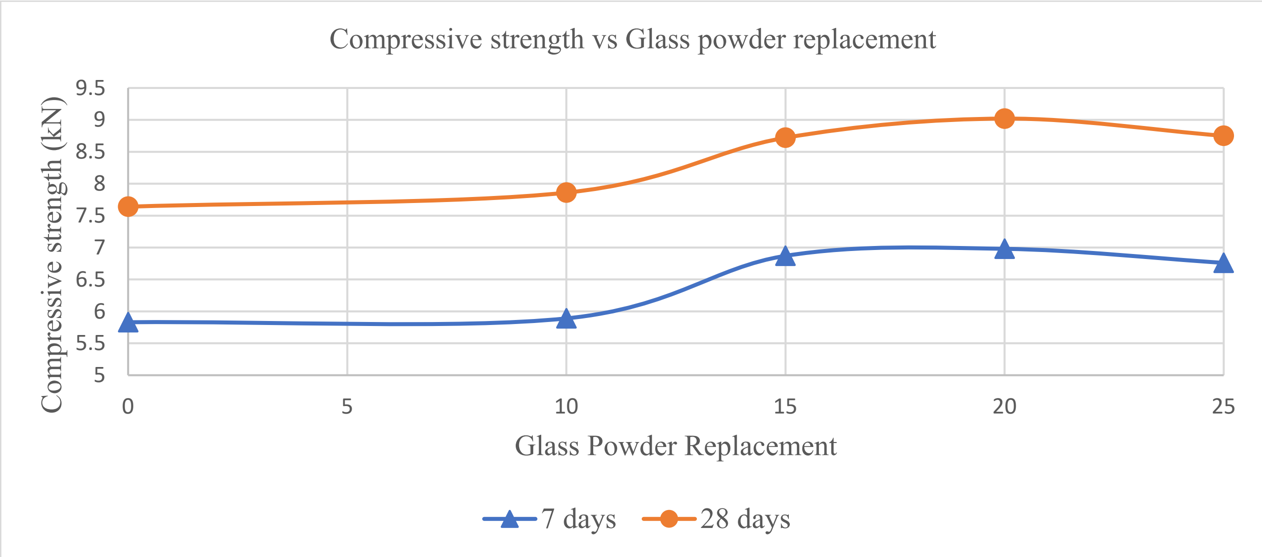

Figure 3: Compressive strength with varying percentages of glass powder replacement with mix 1:4

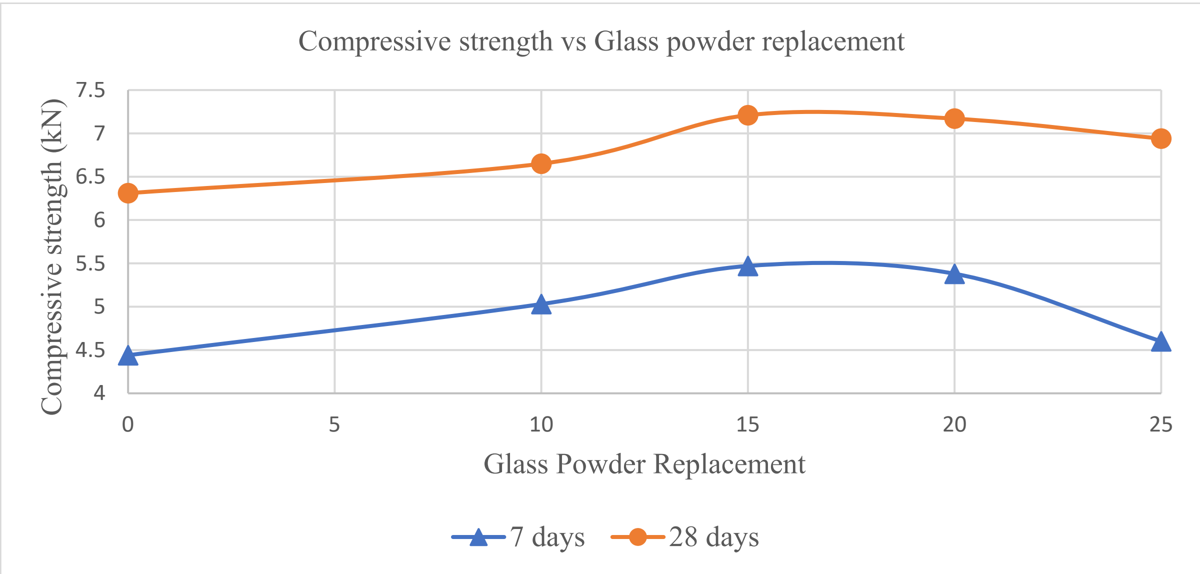

Figure 4: Compressive strength with varying percentages of glass powder replacement with mix 1:6

A constant weight ratio (0.25) of mix 1:4 ensures that changes are only due to material replacement, not water content changes. The steady increase until 20% shows that the fineness and pozzolanic reaction of glass powder positively contribute to strength without significantly affecting the workability or setting time [24]. For the mix 1:6, the pozzolanic reaction of fiber **glass powder** provides additional silica (SiO_2), which reacts with calcium hydroxide ($Ca(OH)_2$) to form more C-S-H gel, contributing to strength [1]. The replacement up to **15% replacement**, the reaction enhances strength due to a good balance between cement hydration and pozzolanic activity. In the work of [24], it is being reviewed that further replacement beyond 15% becomes insufficient, leading to less C-S-H formation and slightly **reduced strength** and also, the reduction in active clinker content slows early hydration.

d. Durability properties of pervious concrete with glass cullet and glass powder

i. Abrasion Test

The abrasion test of the two mixes were presented in Table 6, the abrasion values indicates the aggregate toughness and abrasion characteristics. Lower values indicate an aggregate have high toughness to resist crushing and degradation.

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Table 6: Abrasion test results

Property	Mix 1:4		Mix 1:6	
	A1	A2	B1	B2
Initial weight (W1)	5.40	5.80	5.60	6.00
Final weight (W2)	3.50	4.10	3.40	3.60
Weight loss (DW)	1.90	1.70	2.20	2.40
% Loss	35.19	29.31	39.29	40.00
Average % loss	32.25		39.65	

Abrasion loss can only be influenced by glass content gradation and mix design. The percentage weight loss recorded was approximately 32.25% for mix 1:4 and 39.65 % for mix 1:6, indicating a weak abrasion resistance of the previous concrete sample. Generally, a lower percentage suggest better performance in terms of durability. A lower value closer to 25 % suggest better abrasion resistance, the higher abrasion test values obtained indicate lower durability in terms of wear resistance which is in cordial with the work of [20].

ii. Permeability Test

Permeability of a pervious concrete cube containing glass cullet and glass powder were experimented with two types of mix and their results were analysed in Tables 7 and 8.

Table 7: Result of Permeability Test of Mix Ratio 1:4

K = Permeability (m/s)				
Q = Volume of water collected (liters)	2.40	2.60	2.50	2.00
L = Thickness of the sample (m)	15cm			
A = Cross sectional area of the sample (m²)	15cm x 15cm			
T = Time interval during which water was collected (s)	60 seconds			
H = hydraulic height (height of the water above sample) (m)	20cm			

$$Q = \frac{2.40+2.60+2.50+2.00}{4}$$

$Q = 2.375 \approx 2.4$ liters

$Q = 2.4$ liters $= 0.024m^3$

$L = 15cm = 0.15m$

$A = 15cm \times 15cm = 0.0225m^2$

$t = 60$ seconds

$h = 20cm = 0.2m$

$$K = \frac{Q \, x \, l}{A \, x \, \Delta h \, x \, t}$$

$$K = \frac{0.024m^3 x \, 0.15m}{0.0225m^2 x \, 60 \sec x \, 0.2m} = \frac{0.0036}{0.27}$$

$K = 0.01333m/s$

Table 8: Result of permeability test of mix ratio 1:6

K = Permeability (m/s)				
Q = Volume of water collected (liters)	2.00	1.90	2.10	1.90
L = Thickness of the sample (m)	15cm			
A = Cross sectional area of the sample (m²)	15cm x 15cm			
T = Time interval during which water was collected (s)	60 seconds			
H = hydraulic height (height of the water above sample) (m)	20cm			

$$Q = \frac{2.00+1.90+2.10+1.90}{4}$$

$Q = 1.975 \approx 2.0$ liters

$Q = 2.0$ liters $= 0.020m^3$

$L = 15cm = 0.15m$

$A = 15cm \times 15cm = 0.0225m^2$

$t = 60$ seconds

$h = 20cm = 0.2m$

$$K= \frac{Q\ x\ l}{A\ x\ \Delta h\ x\ t}$$
$$K= \frac{0.020m^3 x\ 0.15m}{0.0225m^2 x\ 60\ \sec x\ 0.2m} = \frac{0.0030}{0.27}$$
$$K = 0.011111 m/s$$

Pervious concrete is engineered to facilitate water passage through its structure, rendering permeability a critical performance metric for its use in sustainable pavement systems. This study analysed two mix ratios: 1:4 and 1:6, yielding permeability values of 0.0133m/s and 0.0111m/s respectively. The observed permeability arises from the fact that an increased cement-to-aggregate ratio generally results in enhanced pore interconnectivity and larger pore sizes in pervious concrete [26].

Increased permeability facilitates swift storm-water infiltration, diminishes surface runoff, and enhances groundwater recharge, in accordance with the principles of sustainable drainage systems (SuDS) [27]. This is in line with the observed permeability for both mixes in this study.

Increasing the aggregate-to-cement ratio generally reduces pore connectivity and obstructs flow paths, resulting in lower permeability [28]. The 1:6 mix enhances mechanical strength through a denser internal structure; however, the notable reduction in permeability may undermine its essential role in pervious concrete applications. The 1:4 mix is more appropriate in contexts requiring high infiltration rates, such as parking lots or pedestrian pathways designed for sustainable surface water management. The 1:6 mix is more suitable for areas that necessitate a balance between moderate permeability and enhanced structural strength, such as lightly trafficked roads. The results underscore the necessity of balancing permeability and strength requirements in the design of pervious concrete mixes for targeted sustainable infrastructure projects.

In general permeability values were 0.01333 m/s for Mix 1:4 and 0.0111 m/s for Mix 1:6, both within the acceptable range for pervious concrete. The slightly higher permeability in Mix 1:4 supports its use in storm-water management applications.

iii. Water Absorption Test

Water absorption test for mix ratio 1:6 and 1:4 was conducted and the results are presented in Tables 9 and 10.

Table 9: Result of water absorption test for mix ratio 1:6

Sample No	**Dry Weight (Kg) (W_1)**	**Wet Weight (Kg) (W_2)**	**Result (%)**
1	10.15	10.31	1.58
2	8.20	8.42	2.68
3	9.18	9.38	2.18

Water absorption (%) = $\frac{W_2 - W_1}{W_1}$ x 100 =

= $\frac{1.58+2.68+2.18}{3}$ = 2.15%

Table 10: Result of water absorption test for mix ratio 1:4

Sample No	Dry Weight (Kg) (W_1)	Wet Weight (Kg) (W_2)	Result (%)
1	9.05	9.23	1.99
2	9.25	9.44	2.05
3	8.97	9.15	2.01

Water absorption (%) = $\frac{W_2 - W_1}{W_1}$ x 100 =

An average absorption of 2.15% was observed for the 1:6 mix, while the mix 1.4 recorded a 2.02% average absorption. The average water absorption results are well within acceptable limit for durable concrete (typically below 5%). The use of glass aggregate tend to reduce water absorption because glass patch are relatively smooth and non-porous, resulting in lower water uptake compare to conventional natural sand and aggregate [29]. Furthermore, studies on concrete with glass aggregate have shown lower overall with the impervious nature of glass particles [30] and difference in concrete microstructure [31].

5.0 Conclusion and Recommendations
5.1 Conclusion

This study assessed the performance of pervious concrete incorporating glass cullet as a partial coarse aggregate replacement and glass powder as a supplementary cementitious material. The results demonstrate that:

i. The glass powder and glass cullet were primarily constituted of silica (SiO_2), indicating pozzolanic activity. The moderate presence of calcium oxide (CaO) contributes to cementitious properties, enhancing the mechanical strength of the concrete matrix.
ii. The glass powder was verified to be well-graded, which is essential for achieving optimal packing density, minimising voids, and improving the overall strength and permeability of the concrete.
iii. The results of abrasion resistance show that mix 1:4 indicate higher resistance to wearing compare to mix 1:6 and shows better surface durability and impact results presents moderate toughness and acceptable load-bearing characteristics for pavement applications.
iv. Compressive strength and load bearing presents a maximum strength at 20% replacement of cement by glass power and glass cullet in both mix ratios and mix 1:4 perform better at both 7 and 28 days with 20% replacement, whereas mix 1:6 performed optimum with 20% at 7 days and 15% replacement at 28days.

5.2 Recommendations

Based on the findings of this research work, the following recommendations are made;

i. For rigid pavement construction using pervious concrete, mix ratio 1:4 with 20% replacement of cement by a combination of glass cullet and glass powder is recommended. This mix provided the best balance between mechanical strength, permeability, and durability.
ii. Given the high silica content and moderate CaO presence, glass powder and cullet should be treated not only as fillers but as active pozzolanic materials and Encourage sourcing well-graded glass waste to ensure consistency in mix performance.
iii. Incorporating glass waste into concrete supports environmental sustainability by reducing landfill usage and lowering cement consumption, thus cutting down CO_2 emissions associated with cement production.
iv. It is recommended to investigate long-term durability factors, such as freeze-thaw resistance, alkali-silica reactivity, and field performance over diverse environmental conditions. Moreover, lifespan cost studies would facilitate wider implementation in infrastructure projects.

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