

Mechanical Behaviour and Infiltration Characteristics of Tyre-Rubber-Modified Pervious Geopolymer Concrete for Ground Improvement Using a Multi-Waste Binder

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Abstract - The development of sustainable materials for ground improvement requires solutions that combine mechanical performance with effective water transmission while reducing dependence on conventional construction materials. This study investigates tyre-rubber-modified pervious geopolymer concrete as a potential material for ground-improvement applications. A multi-component binder comprising 45% fly ash, 30% ground granulated blast-furnace slag (GGBS), 15% rice husk ash (RHA), and 10% eggshell powder (ESP) is used, with natural coarse aggregate partially replaced by waste tyre-rubber crumbs at 0%, 5%, 10%, 15%, and 20% by weight. Specimens are heat-cured at 70°C for 24 hours and subsequently subjected to ambient curing. Compressive strength and infiltration tests are performed to evaluate the effects of rubber incorporation on the mechanical and hydraulic performance of the concrete. The results show that increasing rubber content decreases compressive strength while increasing infiltration rate, demonstrating the trade-off between load-bearing capacity at the material level and water transmission. By integrating recycled tyre rubber with industrial and agricultural waste-derived binder constituents, this study explores an alternative pervious geopolymer concrete system with potential relevance to ground-improvement piles and columns in weak soils

Key Words: Pervious geopolymer concrete, Fly ash, Ground-granulated blast-furnace slag (GGBS), Rice husk ash (RHA), Egg shell powder (ESP), Compressive strength, Infiltration rate

1. INTRODUCTION

The presence of weak, compressible, or low-bearing-capacity soil presents a significant challenge in geotechnical engineering because the natural ground may not possess adequate strength or stiffness to safely support imposed loads. When the available soil has insufficient bearing capacity, excessive settlement or undesirable deformation may occur under foundations and other infrastructure. Ground-improvement techniques are therefore commonly employed to modify the

engineering behavior of the existing soil rather than completely replacing the weak stratum.

One established approach to ground improvement is use of stone columns or granular piles. In this technique, columns consisting primarily of compacted granular material are introduced into weak soil. The resulting composite ground system consists of the original soil and the inserted columns, which can increase the shear resistance and bearing capacity of the reinforced ground. Stone columns can also provide drainage paths through the soil, thereby contributing to the dissipation of excess pore-water pressure and consolidation of suitable soft soils. Previous research has demonstrated that stone columns can improve the bearing capacity and settlement behavior of foundations constructed on weak cohesive soils (Etezzad et al., 2014).

The conventional stone-column concept provides an important basis for the present study. Instead of filling a drilled or formed column with only compacted natural stones and repeatedly tamping the material, the present research proposes the potential use of pervious geopolymer concrete as the material forming a ground-improvement pile or column. The proposed element is intended to act as a relatively stiff and interconnected porous inclusion within the soil mass. Therefore, the objective is not to develop a conventional structural concrete pile for direct structural load transfer, but to investigate a sustainable material that could potentially function as a ground-improvement element for enhancing engineering behavior and bearing capacity of weak soil.

The use of pervious concrete is particularly relevant to this concept because, unlike conventional dense concrete, pervious concrete contains an interconnected pore network that permits the movement of water through the material. This characteristic may be advantageous in ground-improvement applications where drainage and consolidation are important considerations. The interconnected pores can provide pathways for water movement, while the solid skeleton of the concrete can provide resistance against deformation. Consequently, a

pervious concrete ground-improvement element has the potential to combine two desirable characteristics: mechanical reinforcement of the surrounding soil and provision of a preferential pathway for water movement. The infiltration characteristics of the material are therefore relevant in addition to its mechanical strength.

The concept of using pervious geopolymer concrete in pile applications has previously been investigated by **Zhang and Hadi (2019)**. They developed a geogrid-confined pervious geopolymer concrete pile (GPGCP) with an FRP-PVC-confined normal geopolymer concrete core. Their composite pile consisted of a circular geogrid outer tube, pervious geopolymer concrete surrounding the core, and an FRP-PVC-confined geopolymer concrete core. The authors incorporated pervious geopolymer concrete to promote water movement and increase the rate of consolidation, while the confined core was used to enhance compressive strength and ductility. Their experimental investigation focused primarily on the axial compression behavior of the resulting composite pile (Zhang and Hadi, 2019).

This previous investigation provides an important conceptual foundation for the present research. However, the objective and configuration of the present study are different. Zhang and Hadi investigated a highly engineered composite pile consisting of geogrid, FRP-PVC confinement, normal geopolymer concrete, and pervious geopolymer concrete. The present research instead concentrates on the development and characterization of the pervious geopolymer concrete material itself, with emphasis on its compressive strength and infiltration characteristics and with the intention of evaluating its potential for subsequent use as a ground-improvement pile or column. The present study do not attempt to reproduce the complete geogrid-FRP-PVC composite pile system.

Another important aspect of the present research is the replacement of conventional cement-based binder technology with geopolymer technology. Geopolymer concrete can be produced using aluminosilicate-rich industrial by-products and other supplementary waste-derived materials activated using alkaline solutions. This provides an opportunity to reduce dependence on conventional Portland cement while simultaneously utilizing waste resources. This study extends that concept by integrating several waste materials into a single binder system.

The binder adopted in the present investigation consists of 45% fly ash, 30% ground granulated blast-furnace slag (GGBS), 15% rice husk ash (RHA), and 10% eggshell powder (ESP). Fly ash and GGBS constitute the principal reactive components of the binder system, while rice husk ash contributes a silica-rich waste component and eggshell powder provides a calcium-rich waste-derived

constituent. The combination therefore represents a multi-waste binder approach in which industrial, agricultural, and food-derived waste materials are incorporated into a single geopolymer system.

In addition to the multi-waste binder, waste tyre rubber is incorporated into the pervious geopolymer concrete by partially replacing natural coarse aggregate. The accumulation of waste tyres is an important environmental concern because discarded tyres are difficult to manage and can create disposal and environmental problems. Their incorporation into concrete provides an opportunity for waste valorization while potentially modifying the density, deformation characteristics, and water-flow behavior of the resulting material.

However, tyre rubber generally possesses a lower stiffness than natural mineral aggregate and may exhibit weaker interfacial bonding with the geopolymer matrix. Consequently, increasing rubber content can influence the compressive strength of the concrete. At the same time, the incorporation of rubber can modify the aggregate packing arrangement and internal pore structure, which may affect the movement of water through the interconnected void network. Therefore, the influence of rubber content needs to be evaluated experimentally in terms of both mechanical and infiltration characteristics, rather than considering strength.

2. LITERATURE REVIEW

2.1 Stone Columns and Pervious Concrete for Ground Improvement

Stone columns and granular piles are established ground-improvement techniques for weak soils. They improve the behaviour of soft ground by providing relatively stiffer inclusions that can increase shear resistance, stiffness, and bearing capacity. Their interconnected granular structure can also provide drainage paths, helping to dissipate excess pore-water pressure and promote consolidation under suitable soil conditions. These characteristics provide the basic concept for investigating an engineered porous material as an alternative ground-improvement element.

Pervious concrete is relevant to this concept because its interconnected pore structure permits water movement while its hardened matrix provides greater structural integrity than an unbound granular column. The material therefore has the potential to combine mechanical resistance with water-transmitting capability. However, an increase in interconnected voids can also influence compressive strength, creating a balance between mechanical and hydraulic behaviour.

2.2 Pervious Geopolymer Concrete

Geopolymer concrete uses reactive alumino-silicate materials that are activated by alkaline solutions to form a hardened binder. Fly ash and GGBS are commonly used geopolymer constituents. Previous studies have demonstrated that pervious geopolymer concrete can retain the interconnected pore structure required for water movement while developing useful mechanical strength. Its behaviour depends on factors such as binder composition, aggregate skeleton, curing conditions, porosity, and activator characteristics.

The use of geopolymer technology in pervious concrete is therefore relevant to the present study because it allows the development of a porous material using waste-derived constituents while maintaining the mechanical and infiltration characteristics required for the proposed application.

2.3 Pervious Geopolymer Concrete for Pile Applications

Zhang and Hadi (2019) investigated a composite pile incorporating pervious geopolymer concrete, a geogrid outer tube, and an FRP-PVC-confined geopolymer concrete core. The pervious geopolymer concrete was incorporated to promote consolidation, while the confined core enhanced the mechanical behaviour of the pile. Their study established the feasibility of incorporating pervious geopolymer concrete into a pile-based ground-improvement concept.

The present research differs from that work because it does not reproduce the composite geogrid-FRP-PVC pile configuration. Instead, it investigates the material properties of the pervious geopolymer concrete itself, particularly its compressive strength and infiltration characteristics, as a preliminary material-development stage for potential ground-improvement application.

2.4 Multi-Waste Geopolymer Binder

The environmental potential of geopolymer concrete can be further increased through the incorporation of multiple waste-derived materials. Fly ash and GGBS provide the principal geopolymer-reactive constituents, while rice husk ash contributes a silica-rich agricultural waste component and eggshell powder provides a calcium-rich waste-derived constituent. The behaviour of a multi-component binder depends on the chemical composition, particle characteristics, reactivity, and interaction of the individual materials.

In the present study, a binder comprising 45% fly ash, 30% GGBS, 15% rice husk ash, and 10% eggshell powder is adopted. This combination provides a multi-waste

binder system incorporating industrial, agricultural, and food-derived waste materials. The specific behaviour of this combination requires experimental evaluation because the combined effect of four constituents cannot be directly inferred from studies involving individual materials or different proportions.

2.5 Tyre Rubber in Pervious Concrete: Strength and Infiltration

Waste tyre rubber has been widely investigated as a partial replacement for natural aggregate because of the need for tyre-waste utilization and reduction of natural aggregate consumption. Rubber differs from mineral aggregate in stiffness, density, surface characteristics, and interfacial bonding. These differences commonly influence the compressive strength of the concrete.

When rubber is incorporated into pervious concrete, its influence extends to the internal pore structure and water-transmitting behaviour. Previous investigations have shown that rubber replacement can modify both mechanical and hydraulic characteristics. **Gesoglu et al. (2014)** reported changes in the mechanical and permeability characteristics of rubberized pervious concrete, while **Cole, Bakheet, and Akib (2020)** reported changes in both compressive strength and infiltration characteristics with recycled-rubber replacement.

The reported behaviour is not necessarily uniform with increasing rubber content. Changes in rubber particle arrangement, aggregate packing, pore connectivity, and compaction can produce different infiltration responses for different mixtures. Therefore, the effect of rubber on infiltration must be determined experimentally for the specific material system rather than assumed from a single trend.

That is particularly relevant to the present study, where tyre-rubber replacement varies from 0% to 20%. The investigation therefore evaluates the effect of progressive rubber incorporation on both compressive strength and infiltration rate, allowing the relationship between mechanical and water-transmitting behavior to be examined.

2.6 Research Gap

Previous research has established the usefulness of stone columns for ground improvement, the feasibility of pervious geopolymer concrete as a porous material, and the potential incorporation of pervious geopolymer concrete into specialized pile systems. Studies have also demonstrated that waste tyre rubber can modify the mechanical and hydraulic characteristics of pervious concrete.

However, the present study focuses on a different material configuration combining a multi-waste geopolymer binder of fly ash, GGBS, rice husk ash, and eggshell powder with progressive tyre-rubber replacement. The study further evaluates the material simultaneously in terms of compressive strength and infiltration characteristics. Thus, the research provides a material-level investigation of the mechanical and water-transmitting behavior of the developed previous geopolymer concrete as a potential material for future ground-improvement pile or column applications.

3. MATERIAL AND METHODOLOGY

3.1 Materials

3.1.1 Fly Ash

Fly ash is an industrial by-product generated during combustion of pulverised coal in the thermal power plants. It is widely investigated as a precursor for geopolymer concrete because it can contain substantial quantities of reactive silica and alumina, which participate in geopolymerisation under suitable alkaline conditions. The properties of fly ash depends on the source of coal, combustion conditions, collection process, and fineness. In the present study, fly ash constitutes 45% of the total binder mass and serves as the principal aluminosilicate precursor. Its incorporation is intended to facilitate the formation of the geopolymer binding matrix. The general chemical compositions of fly ash [15] are shown in table 1



Fig -1: Fly Ash

Table -1: Chemical Compositions of Fly ash

Chemical composition	Perscentages (%)
SiO ₂	48
Al ₂ O ₃	23.1
Fe ₂ O ₃	12.5
CaO	3.3
MgO	1.5

Na ₂ O	0.0
Other constituents	10.5
LOI	1.1

3.1.2 Ground-Granulated Blast-Furnace Slag (GGBS)

Ground-granulated blast-furnace slag (GGBS) is produced by rapidly cooling the molten slag generated during the iron production, followed by drying and grinding to obtain a finely divided material. GGBS is a calcium- and aluminosilicate-rich supplementary cementitious material that can contribute to binder reaction and strength development in alkali-activated systems. Its behaviour is influenced by its chemical composition, fineness, glassy phase content, and activation conditions. In the present study, GGBS constitutes 30% of the total binder mass and is combined with fly ash, rice husk ash, and eggshell powder to form the multi-waste geopolymer binder. The chemical compositions of GGBS [15] are shown in table 2



Fig -2: Ground-Granulated Blast-Furnace Slag

Table -2: Chemical Compositions of GGBS

Chemical composition	Perscentages (%)
SiO ₂	27.8
Al ₂ O ₃	58.6
Fe ₂ O ₃	8.1
CaO	1.3
MgO	6.0
Na ₂ O	0.2
Other constituents	0.3
LOI	0.9

3.1.3 Rice Husk Ash (RHA)

Rice husk ash (RHA) is derived by controlled burning of rice husk, an agricultural residue generated during rice processing. Its chemical and physical characteristics depend on the source of the rice husk and the combustion and processing conditions, particularly burning temperature, duration, cooling conditions, and subsequent

grinding. RHA can contain a high proportion of silica, which may exist in amorphous or crystalline form depending on the processing history. Its potential contribution to alkali-activated binder systems is therefore influenced by its silica content, phase composition, fineness, and other physical characteristics.

The oxide composition confirms the silica-rich nature of the material and provides a basis for describing its suitability as a silica-bearing constituent in the blended geopolymer binder. In the present study, RHA constitutes 15% of the total binder mass and is incorporated together with fly ash, GGBS, and eggshell powder to develop the multi-waste geopolymer binder. The chemical compositions of RHA [9] are shown in table 3



Fig -3: Rice Husk Ash

Table -3: Chemical compositions of Rice husk ash

Chemical composition	Perscentages (%)
SiO ₂	92.8
Al ₂ O ₃	0.21
Fe ₂ O ₃	0.12
CaO	0.51
MgO	0.75
Na ₂ O	0.15
SiO ₃	0.14
K ₂ O	1.35

3.1.4 Eggshell Powder (ESP)

Eggshell waste is generated from households and food-processing activities and consists primarily of a calcium-rich mineral shell structure. After cleaning, drying, and grinding, the waste can be processed into a fine powder for use as a constituent in cement-based and alkali-activated binder systems. The characteristics and potential contribution of eggshell powder depend on its chemical composition, particle size, processing method, and replacement level.

The composition provides the basis for describing the calcium-rich nature of the material and its suitability as a waste-derived constituent of the blended binder. In the present study, eggshell powder constitutes 10% of the

total binder mass and is incorporated together with fly ash, GGBS, and rice husk ash to develop the multi-waste geopolymer binder. Based on its measured composition, the eggshell powder provides a calcium-rich component that may influence the reaction environment and the development of the hardened binder matrix.. The chemical compositions of eggshell powder [10] are shown in table 4



Fig -4: Egg shell powder

Table -4: Chemical compositions of Egg shell powder

Chemical compositions	Percentages (%)
CaO	93.20
SiO ₂	0.24
Al ₂ O ₃	0.23
MgO	0.85
Na ₂ O	0.13
P ₂ O ₅	0.47
SrO	0.28
K ₂ O	0.07
SO ₃	0.57

3.1.5 Coarse Aggregate

Coarse aggregate forms the primary granular skeleton of the pervious concrete and plays an important role in determining its pore structure and mechanical behaviour. Unlike conventional dense concrete, pervious concrete is generally produced with limited or no fine aggregate so that interconnected voids can be retained within the hardened material. Aggregate size, particle shape, grading, surface texture, and compaction influence particle contact, packing arrangement, void connectivity, and mechanical interlocking.

In the present investigation, 20 mm nominal maximum-size coarse aggregate is used as the principal aggregate constituent at a total aggregate content of 1600 kg/m³. Tyre-rubber crumb is used as a partial replacement of the natural coarse aggregate by weight of the total aggregate at replacement levels of 0%, 5%, 10%, 15%, and 20%. Accordingly, the control mixture contains 1600 kg/m³ of natural coarse aggregate, while the 5%, 10%, 15%, and 20% replacement levels correspond to 80, 160, 240, and

320 kg/m³ of tyre-rubber crumb, respectively, with the natural coarse aggregate content reduced to 1520, 1440, 1360, and 1280 kg/m³, respectively. This replacement approach maintains a constant total aggregate mass of 1600 kg/m³ across all mixtures and allows the influence of tyre-rubber incorporation on the compressive strength and infiltration characteristics of the developed pervious geopolymer concrete to be evaluated.

3.1.6 Tyre-Rubber Crumbs

Tyre-rubber crumbs are produced by processing end-of-life tyres into smaller rubber particles. Their incorporation into concrete is investigated as a means of utilising waste tyres and reducing the consumption of conventional mineral aggregate. Rubber particles differ from natural stone in density, stiffness, surface characteristics, and deformation behaviour. Consequently, replacing coarse aggregate with rubber crumbs may alter particle interaction, interfacial bonding, compaction response, and compressive strength. These effects depend on the rubber particle size, replacement proportion, aggregate characteristics, and mixture composition. In the present study, tyre-rubber crumbs are incorporated at replacement levels of 5%, 10%, 15%, and 20% with respect to mass, in addition to a control mixture containing no rubber.



Fig -5: Tyre-rubber Crumbs

3.1.7 Alkaline Activators

Sodium silicate and sodium hydroxide solutions are used as alkaline activators in the present geopolymer concrete. The alkaline environment facilitates the dissolution of reactive aluminosilicate species from suitable precursor materials, followed by reaction and the formation of binding products. Sodium silicate supplies soluble silicate species, while sodium hydroxide provides the required alkalinity. The resulting reaction products depend on precursor chemistry, activator composition, liquid content, curing conditions, and reaction temperature. In this study, a 12 M sodium hydroxide solution is used, with a sodium silicate-to-sodium hydroxide solution mass ratio of 2.5 and an activator-to-binder mass ratio of 0.40. In

order to make 1 L sodium hydroxide solution of 12 M we need to add 480 grams of sodium hydroxide pellets into water and mix it well with stirring rod, due to the highly exothermic nature of sodium hydroxide dissolution the solution was prepared 24 hours prior to casting and allowed to equilibrate to ambient laboratory temperature to ensure thermal stability during the geopolymerization process. Then this sodium hydroxide solution which has been allowed to equilibrate to ambient temperature was thoroughly mixed with the liquid sodium silicate to form the alkaline activator. This combined activator solution was then immediately incorporated into the dry geopolymer concrete. It should be noted that the blending of the sodium hydroxide and sodium silicate solution is accompanied by mild exothermic heat of mixing.



Fig -6: Sodium silicate and Sodium hydroxide

3.1.8 Additional Water

Additional water is used in accordance with the adopted mixture proportions and laboratory procedure. Its quantity can influence the coating and distribution of binder around aggregate particles, fresh-mixture handling, compaction, and the development of the hardened material. Because the activator solutions also contain water, the quantity of additional water should be distinguished from the water contributed by those solutions. In the present study, the quantity of additional water used in each mixture is 20 kg/m³.

3.2 Binder Composition and Mix Proportions

The binder comprises fly ash, GGBS, RHA, and ESP in proportions of 45%, 30%, 15%, and 10%, respectively, by total binder mass. The combined binder is used in all mixtures to maintain a consistent binder composition while investigating the effect of tyre-rubber aggregate replacement. The nominal binder content is 400 kg/m³.

Five mixtures are considered: a control mixture without rubber crumbs and four modified mixtures containing 5%, 10%, 15%, and 20% tyre-rubber replacement of the coarse aggregate by mass. The nominal aggregate content

is 1600kg/m³. All the information is shown in table 5 and table 6

3.3 Preparation of Geopolymer Concrete Mixtures

The constituent materials are proportioned according to the selected mix design. The dry binder constituents are blended to obtain a uniform mixture. The alkaline activator is prepared using sodium hydroxide and sodium silicate solutions in the specified proportions, following the actual preparation and cooling procedure adopted in the laboratory. The coarse aggregate and tyre-rubber crumbs are proportioned according to the replacement level of each mixture. The aggregate constituents are combined with the binder, followed by the gradual addition of the alkaline activator and the specified additional water, where applicable. Mixing continues until the constituents are adequately distributed throughout the mixture. As pervious concrete relies on a connected system of voids, the mixing and compaction procedures should be controlled consistently across all mixtures. The Geopolymer concrete mixture is shown in fig. 7



Fig -7: Geopolymer Concrete Mixture

3.4 Specimen Preparation and Curing

Prior to the casting the surface of the moulds needs to be coated with a thin layer of oil to serve as a release agent and facilitate clean demoulding. Concrete specimens are then cast in cube moulds measuring 150 mm × 150 mm × 150 mm. The fresh mixtures are placed into the moulds, and compaction needs to be light.

Like conventional cement-based concrete which requires standard water curing the geopolymer concrete in this study was cured without water exposure. The caste specimens were subjected to an initial ambient rest period of 24 hours at room temperature then the moulds were transferred to the laboratory oven for thermal curing at 70 °C for a duration of 24 hours upon completion of the heat curing the specimens were demoulded withdrawn from the oven and maintained under ambient curing conditions until the designated ages.



Fig. -8 Samples in oven for curing and demoulded sample

3.5 Compressive Strength Testing

The compressive strength of the hardened pervious geopolymer concrete was evaluated at 7 days and 28 days using cube specimens. For each tyre-rubber replacement level of 0%, 5%, 10%, 15%, and 20%, three specimens

Table -5: Mix proportions of Binders, Activators ratio and Activators to binder ratio

S. No.	Designation	Activators(A) NaOH/Na ₂ SiO ₃	Binders(B) (FA, GGBS, RHA and ESP) (kg/m ³)	A/B
1	PGNAC	2.5	400	0.4
2	PGCA95R5	2.5	400	0.4
3	PGCA90R10	2.5	400	0.4
4	PGCA85R15	2.5	400	0.4
5	PGCA80R20	2.5	400	0.4

Table -6: Mix proportions of aggregates, tyre rubber crumbs and Activators

S. No.	Designation	Aggregates (kg/m ³)	Tyre rubber crumbs (kg/m ³)	NaOH (kg/m ³)	Na ₂ SiO ₃ (kg/m ³)
1	PGNAC	1600	0	45	115
2	PGCA95R5	1520	80	45	115
3	PGCA90R10	1440	160	45	115
4	PGCA85R15	1360	240	45	115
5	PGCA80R20	1280	320	45	115

were tested at 7 days, and three separate specimens were tested at 28 days for each mix design.

Compression testing machine (CTM) is used to perform the test. Prior to testing, each specimen was visually inspected and positioned centrally between the loading plates of the machine. Load was applied continuously until specimen fails. The compression testing machine automatically recorded the maximum load and corresponding compressive strength in MPa for each specimen.

The compressive-strength values obtained from the machine were recorded for all individual specimens. The mean compressive strength was subsequently determined from the three replicate specimens for each tyre-rubber replacement level at both 7 and 28 days. The compressive testing machine along with the placed specimen is shown in the figure below.



Fig -9 Compression Testing Machine

3.6 Infiltration Testing

The infiltration characteristics of the hardened pervious geopolymer concrete were evaluated using 150 mm x 150 mm x 150 mm to investigate the movement of water through the interconnected voids within the concrete matrix. The test was conducted on specimens incorporating tyre-rubber replacement levels of 0%, 5%, 10%, 15%, and 20%. For each mixture, the infiltration measurements were recorded under the same test conditions to facilitate comparison between the control mix and the rubber-modified mixes.

During the test, a known volume of water was applied to the specimen, and the duration of the water to infiltration into the concrete was monitored. The recorded infiltration data were used to evaluate the influence of tyre-rubber content on the water infiltration behaviour of pervious geopolymer concrete. The formula used to calculate the infiltration rate is as follows

$$\text{Infiltration Rate (I)} = \frac{V}{At} \times 3600$$

Here, V is the measured volume of water that infiltrates the cube, A is the area of the cross-section of the cube and t is time in seconds



Fig -10: Infiltration testing

4. RESULTS

4.1 Compressive Strength

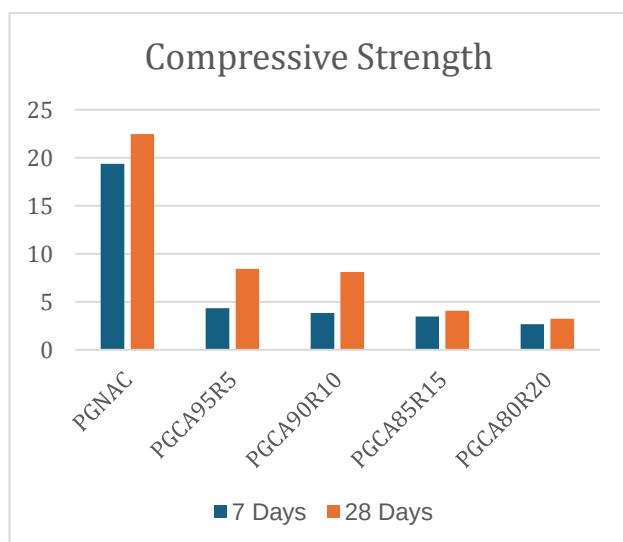
The compressive strength results of pervious geopolymer concrete incorporating different percentages of waste tyre rubber are presented in Table 7 and Table 8. The compressive strength results indicate that the pervious geopolymer concrete developed a substantial proportion of its 28-day compressive strength within the first seven days of ambient curing. The 7-day compressive strength was approximately 60-80% of the corresponding 28-day strength, indicating significant early-age strength development. The remaining strength gain occurred between 7 and 28 days, demonstrating continued strength development during the later curing period. This behavior may be attributed to the ongoing geopolymerisation reactions within the binder system, which contribute to the formation and development of the binding matrix over time. The results suggest that the developed geopolymer concrete achieved considerable early-age strength.

Table -7: Compressive strength results in 7 days

S.No	Designations	Compressive strength at 7 days (mpa)			Average Compressive strength at 7 days (mpa)
		1	2	3	
1	PGNAC	21.56	17.42	19.2	19.39
2	PGCA95R5	4.84	4.76	3.41	4.33
3	PGCA90R10	4.68	3.05	3.78	3.83
4	PGCA85R15	4.04	2.81	3.52	3.45
5	PGCA80R20	2.65	3.1	2.21	2.65

Table -8: Compressive strength results in 28 days

S.N o.	Designatio ns	Compressive strength at 28 days (mpa)			Average Compressi ve strength at 28 days (mpa)
		1	2	3	
1	PGNAC	23.80	22.45	21.16	22.47
2	PGCA95R5	8.62	7.12	9.48	8.44
3	PGCA90R1 0	7.58	11.24	5.5	8.1
4	PGCA85R1 5	3.71	3.80	4.65	4.05
5	PGCA80R2 0	3.56	3.2	2.97	3.24


Chart -1 Comparison between compressive strength at 7 days and 28 days

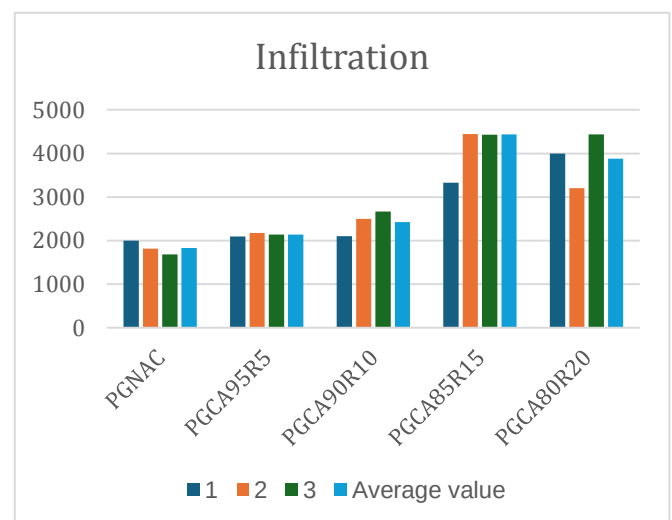
4.2 Infiltration Test Results and Discussion

The infiltration test was performed three times for each mix, and the average infiltration rate was calculated. The results for the different rubber replacement levels (0%, 5%, 10%, 15%, and 20%) are presented in Table 9 and Chart 2. The results showed an increasing trend in the infiltration rate with increasing waste tyre-rubber content up to 15% replacement. However, a slight decrease in the infiltration rate was observed at 20% rubber replacement compared with the 15% mix. Despite this reduction, the infiltration rate at 20% replacement remained higher than that of the control mix. The initial increase in infiltration rate may be associated with changes in aggregate packing and the connectivity of voids within the concrete matrix due to rubber incorporation. The slight reduction at the highest replacement level may indicate that the relationship between rubber content and infiltration

performance is not entirely linear, potentially due to changes in the distribution and connectivity of voids. Overall, the results indicate that incorporating waste tyre rubber improved the infiltration performance of pervious geopolymer concrete within the tested replacement levels, although the improvement did not continue beyond 15% replacement.

Table -9: Infiltration Data

S.No .	Designation s	Infiltration (mm/h)			Average infiltratio n (mm/h)
		1	2	3	
1	PGNAC	200 0	181 8	168 0	1832.6
2	PGCA95R5	209 4	217 3	213 9	2135.3
3	PGCA90R10	210 5	250 0	266 6	2423.6
4	PGCA85R15	333 0	444 5	553 3	4436
5	PGCA80R20	400 0	320 0	444 0	3880


Chart -2: Infiltration data graph

5. CONCLUSION

The present study investigated the effect of partially replacing coarse aggregate with waste tyre-rubber crumbs on the compressive strength and infiltration characteristics of pervious geopolymer concrete. The binder consisted of a combination of fly ash (45%), ground granulated blast-furnace slag (GGBS, 30%), rice husk ash (RHA, 15%), and eggshell powder (10%), incorporating

industrial and agricultural waste-derived materials into the geopolymer binder system. Five rubber replacement levels of 0%, 5%, 10%, 15%, and 20% were considered to evaluate the influence of rubber incorporation on the mechanical and hydraulic performance of the developed concrete. The specimens were allowed to rest for 24 hours after casting, followed by oven curing at 70°C for 24 hours and subsequent ambient curing until the respective testing ages of 7 and 28 days.

The compressive strength results indicated that increasing the percentage of rubber crumbs resulted in a decrease in compressive strength. This reduction may be attributed to differences in the mechanical properties of rubber and natural coarse aggregate, as well as differences in the bonding characteristics between rubber particles and the surrounding geopolymer matrix. The 7-day compressive strength reached approximately 80% of the corresponding 28-day strength, indicating substantial early-age strength development following the initial heat-curing treatment. Further strength development occurred during the subsequent ambient-curing period.

In contrast, the infiltration rate increased with increasing rubber-crumbs replacement up to 15%, followed by a slight decrease at 20% replacement. This trend indicates that rubber incorporation influenced the water-flow characteristics of the pervious geopolymer concrete. Changes in aggregate packing and pore connectivity may have contributed to the increased infiltration rate, although further investigation is required to confirm these mechanisms. The opposite trends in compressive strength and infiltration highlight the importance of balancing mechanical performance with water-transmission requirements when selecting an appropriate rubber replacement level.

Overall, the study demonstrates the potential of combining a multi-component binder comprising fly ash, GGBS, RHA, and eggshell powder with waste tyre-rubber crumbs to develop pervious geopolymer concrete using industrial and waste-derived materials. The developed material may be considered for further investigation in ground-improvement applications, including pervious columns in weak soils. However, the present study is limited to laboratory testing of concrete specimens and does not directly establish improvements in soil-bearing capacity or column load-carrying performance. Further research involving porosity, durability, permeability, and soil-column interaction is necessary to determine the optimum mix composition and establish its suitability for practical ground-improvement applications.

5. REFERENCES

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