Performance Evaluation of Glass Fiber-Reinforced Pervious Concrete for Urban Infrastructure

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Abstract*— Pervious concrete (PC) is increasingly recognized as a sustainable pavement material due to its ability to reduce stormwater runoff and improve groundwater recharge. However, its widespread application is limited by relatively low strength and poor durability. This study investigates the combined use of alkali-resistant glass fibers (ARGF) and silica fume (SF) to improve the mechanical performance of PC while maintaining its permeability. ARGF, with high zirconia content for alkali resistance, was incorporated to enhance crack resistance and tensile properties, while SF, a highly reactive pozzolanic material, was added to refine pore structure and strengthen the cementitious matrix. Experimental testing included compressive strength, split tensile strength, porosity, and permeability assessments at curing ages of 14 and 28 days. Results indicated that incorporating 1.5% ARGF by cement weight yielded a 52% increase in split tensile strength compared to the control at 28 days. The addition of SF further improved matrix density and strength without compromising PC's open-cell structure. Observations of failure planes revealed that cracks propagated through the cement paste rather than aggregates. These findings demonstrate that the combination of ARGF and SF enhances both the durability and tensile performance of PC, enabling its broader application beyond light-load pavements. The study provides a practical approach for producing high-performance pervious concrete with improved mechanical properties, contributing to sustainable pavement design and long-term urban infrastructure resilience.

Keywords : Pervious Concrete, Alkali Resistance Glass Fiber

I. INTRODUCTION

Rapid urbanization and the growth of built infrastructure have changed natural landscapes reducing the soil cover and vegetation while increasing impermeable surfaces. This urbanization and increased impervious areas lead to environmental problems such as increased pollutants build up, urban heat island effects, increased surface runoff and flash floods, disturbing the natural hydrological cycle. As runoff flows across urban pavements, it mobilizes contaminants such as hydrocarbons, and suspended solids, resulting in environmental degradation, surface water pollution, and groundwater contamination [1,2].

In Sri Lanka, increasing urban development has taken over paddy fields, marshlands, and natural drainage paths. This has led to repeated flash floods in several areas [3,4]. While hydrological systems and drainage factors are included in development planning, sustainable stormwater management (SSWM) solutions have not received enough attention [5,6,7]. Therefore, it is timely important to develop alternative, sustainable stormwater management practices that go beyond traditional centralized drainage systems [8].

Pervious concrete (PC), also known as permeable concrete or, or no-fines concrete, is a typical high-porosity concrete used in concrete paving applications [9,10]. Its high porosity allows water to pass through it therby reducing surface runoff and improving groundwater recharge [11]. However, its open pore structure lowers mechanical performance, making PC unsuitable for busy areas and limiting its broader use in urban construction. There are also no standardized mix designs and construction methods, which further limits its application. It is important to improve its structural properties while maintaining required permeability. Fiber reinforcement could be a possible solution, with alkali-resistant glass fibers enhancing tensile strength, crack resistance, and durability. By optimizing the mix design, it is possible to develop a pervious concrete material that could be utilized in a wider range of infrastructure, including pavements and walkways, while also boosting stormwater infiltration and reducing noise.

This study investigates the physical & mechanical properties of pervious concrete mixes incorporating alkali-resistant glass fibers. The research evaluates porosity, permeability, compressive strength and split tensile strength across multiple mix proportions, comparing their performance with the conventional PC. The aim is to identify an optimized mix that enhances PC's mechanical performance without compromising its environmental benefits, thereby offering a practical, sustainable solution for stormwater management.

II. LITERATURE REVIEW

Permeable pavements are gaining attention due to its wider range of advantages in stormwater management [12]. The open cell structure in PC allows precipitation runoff to permeate the pavement and seep into the underlying soils contributing to the preservation of the pavement's surface and surrounding environment [13]. Water can be filtered, purified, and biodegradable oils can be captured by the permeable concrete pavement system [14].

According to Barrett et al. [15], PC has low bulk density, low heat conductivity, negligible capillary phenomena (average pore diameter greater than 1 mm), almost no slump, no segregation, and low shrinkage compared to conventional concrete. Pervious concrete's capacity to mitigate tire-pavement noise is advantageous, as noise reduction is crucial for urban quality of life [16]. Its high porosity enables effective absorption of road noise, contributing to a safer and more comfortable driving environment [17].

Regardless the above advantages, widespread applications of PC are still limited due to some issues. Low strength and poor durability are PC's main drawbacks, particularly when it comes to freeze-thaw resistance in seasonal frozen locations [18]. Due to its low compressive strength and inconsistent mechanical performance qualities, PC is currently primarily utilized in urban development for the construction of walkways, parking spaces, and light-load pavements rather than as a material for road pavement [19,20]. Researches identified that the porous structure of PC (15–30% porosity) leads in inferior mechanical characteristics compared to ordinary concrete [20].

Many researches are being carried out in reinforcing PC with fiber to enhance its performance. Two crucial properties of fiber-reinforced concrete are its ability to bridge cracks and to restrict shrinkage. The plastic shrinkage test results performed by [21] Rahmani et al. (2012) revealed that the maximum and average crack width for Glass Fiber Reinforced Concrete (GCRF) were equal to 1.12 mm and 0.37 mm, which were 57% and 50% less than conventional concrete, respectively. According to Barluenga and Hernandez-Olivares [22], depending on the type of fiber, adding 0.6 to 0.9 kg/m^3 of GF to regular concrete decreased crack area by about 60–70%.

GF offers some unique advantages over other materials due to its thickness, weight, and strength. With such a broad variety of characteristics, the material can fulfill project and design goals in several industrial applications. GF is a durable, light-weight, and a significantly strong material. According to Kumar S. & Lee H.P. [13], raw ingredients are significantly less expensive and the material is generally less brittle.

Glass fiber that has had zirconium oxide (ZrO_2) added to it to assist it withstand alkalinity attack is known as alkali-resistant glass fiber (ARGF). Given that the atmosphere in concrete is highly alkaline, this is a crucial component of these fibers. ARGF is specifically made to have a high degree of resistance against alkali attack from cement (usually pH 12.9) and good durability, according to the International Glass Fiber Association Practical Design Guide [23]. The distinctive component of ARGF, specifically its zirconia content, is resistant to this aggressive alkaline boundary. A minimum of 16% zirconia concentration was suggested for sufficient alkali resistance based on the investigations. Additionally, 16% zirconia content in glass fiber, referring to it as ARGF [24].

Gao et al., [25] examined the mechanical properties, surface characteristics, and bulk performance of ARGF under various environmental exposures. They concluded that there was a considerable surface defect dependence on the fiber's strength at failure. According to Arabi et al., [26], ARGF with a 12 mm length and a 2% replacement level produced superior flexural strength outcomes. The maximum compressive strength was found to be at 1.2% of the ARGF content as reported by Hiles et al., [27]. Desai et al., [28] investigated the behavior of high-performance concrete (HPC) reinforced with ARGF and lean concrete at various lengths. In comparison to other lengths, it was revealed that the HPC with a 12 mm long fiber had a higher compressive strength. Fibers give concrete its toughness in the early stages and help to increase the strength of the material later on in life.

Producing silicon metal or ferrosilicon alloys yields silica fume (SF) as a byproduct. Concrete is one of the best applications for SF. Its physical and chemical characteristics make it an extremely reactive pozzolan. Silica fume-infused concrete can be extremely strong and long-lasting. SF, which has a high SiO_2 content and is a waste product of industrial silicon manufacturing, has long been valued as a superior supplemental cementitious material [29]. SFs have the ability to fill in the spaces between cement particles and boost the density and strength of the cement binder because of their small particle size and large specific surface area. The PC's split tensile strength and compressive strength are improved by the addition of silica fume to the mixtures [30]. The microaggregate effect of SF can enhance the cement paste's microscopic pore structure, boosting the concrete's strength [31].

III. MATERIALS & METHODOLOGY

A. *Materials & Sample Preparation*

The materials used in this study were Cement, silica fume, fine aggregates, coarse aggregates, superplasticizers, water, and different proportions of alkali-resistant glass fibers (ARGF). High-performance blended hydraulic cement (INSEE rapid flow plus cement) of 42.5N that complied with SLS 1247:2015 was utilized, and it was produced locally. The specific gravity is 2.9, and the fineness is 420 m^2/kg. This high-performance cement consists of ground-granulated blast furnace slag (GGBFS) and fly ash variants.

Fine aggregates used in this study was locally available natural river sand compiling to SLS 1397. Sand, which was passed through 5 mm sieve, was used for the study. The bulk density of sand was 1507 kg/m^3. Natural crushed stone passing through 20 mm sieve, was used as coarse aggregates. The density of metal was 1586 kg/m^3. The sample of coarse aggregate and fine aggregates were washed with water to ensure it had no silt content.

The specific gravity of the silica fume used in concrete mix was 2.75. Alkali-resistant glass fiber was utilized in this experiment. The purpose of using glass fibers with an 860 ºC melting point was to increase the mechanical strength of concrete. The specification of alkali-resistant glass fiber is given in Table I.

A mix design comprising cement, coarse aggregate, fine aggregate, silica fume, superplasticizers, ARGF and water was established based on the previous literature which have demonstrated reasonable results for mechanical strength such as compressive strength, split tensile strength, porosity and permeability. Six specimens were prepared for each test for 14 and 28 days, respectively. Four different mix designs were examined in the study: one control specimen and three other mixes containing 1%, 1.5%, and 2% of ARGFs (by weight of cement). M25-grade concrete without fiber glass was used for the control sample.

Silica fume was incorporated at 5% of the cement weight, fine aggregate at 10% of the concrete weight, and superplasticizer at 0.2% of the cement weight, with a water-to-cement ratio of 0.28. Moisture corrections were followed to account for the moisture in river sand. The digital moisture tester was used to determine the moisture content and the correction factor for moisture content. Superplasticizer (Sika 2055) was used in the first trial batch, and it has improved workability for a water-to-cement ratio (W/C) ratio of 0.28. However, superplasticizer was not used in sample as it has made fibers less stiff and the W/C ratio was increased to 0.31 from 0.28 for the mixture without superplasticizers. The proportions of the mix with corrected weight of water and sand are given in Table II. A concrete mixer was used to mix the components after they had been weighed according to the intended mix proportion. Prior to mixing the fiber-reinforced PC, the aggregates were first processed into the required saturated surface dry condition.

TABLE I Specification of the Alkali resistant glass fiber

Description	Unit	Standard	Test Value
Diameter	μm	15 ± 2.3	15.7
Length	mm	10 - 50	10 & 50
Moisture Content	%	≤ 0.2	0
Combustible matter content	%	1.9 ± 0.3	1.83
Elastic Modulus	GPa	71.7 - 80.0	72
Specific gravity	-	2.6 - 2.8	2.7
ZrO_2	%	16.8 ± 0.5/0.3	16.57
TiO_2	%	5.5 ± 0.5	5.45
Volume weight	g/cm^3	2.5 - 2.7	2.68
Tensile strength	MPa	1200 - 4800	1700
Resistance temperature	^{0}C	700 - 900	860

TABLE II Mix proportions of the pervious concrete

Material	Weight (kg)
Cement	360
Coarse aggregates	1189.5
Fine aggregates	168.69 (Corrected) 166.11 (Designed)
Potable water	109.03 (Corrected) 111.6 (Designed)
ARGF by weight of cement 1.0% 1.5% 2.0%	 3.6 5.4 7.2
Silica fume	18

During the mixing process, the aggregates and fiber glass were mixed evenly, and then 20% of the water was added and mixed again. Then cement and silica fume were added and mixed. Finally, a balanced quantity of water was added and well mixed. 0.15 m × 0.15 m × 0.15 m cubic samples were used in permeability test and compressive strength test. Cylindrical specimens of 0.09 m (diameter) × 0.3 m (height) and 0.15 m (diameter) × 0.3 m (height) were used in porosity test and split tensile test respectively. Cylinders were cast in three equal layers. The pervious concrete specimens were demolded after one day and cured in room temperature and placed in a laboratory curing tank for 14 days and 28 days until they were taken out the day before the mechanical test or the physical test.

A. Testing of physical properties

The average value (potential strength, since the same batch) was adopted for each of the mechanical properties test results (axial compression test, split tensile strength test) and mean value was adopted for physical property test (permeability test, porosity test, and density test).

The concrete's workability was evaluated using the visual inspection method recommended by the National Ready-Mix Concrete Association (NRMCA) [9], which is used to evaluate the workability of pervious concrete. The procedure is called the balling or hand-squeezing method. A PC sample was held in the hand, squeezed, and released. The paste was sufficient if the aggregate particles stuck to the hand's vertical surface. If, all of the aggregate slides off the hand and the hand becomes dry, the combination may be deemed excessively dry and if aggregate slides off the hand and there is still moist paste slurry on the hand, the mixture can be deemed extremely wet [9,32]. Density of the samples were determined a per the BS 1881[33].

ASTM C1754 [34] was followed in determining the porosity of each specimen. Prior to performing the porosity test, the specimen's dry mass (M_d) was measured, and the dimensions were measured in order to determine the volume (V). The specimen is then immersed in water for an hour, following which the mass submerged is measured (M_w). Based on the Archimedes' principle, porosity (P) was computed using the density of water (ρ_w), as indicated by Equation (1)

$$P = [1-(M_d-M_w)/ (\rho_w V)] \times 100 \qquad (1)$$

Three cubes were used to characterize the porosity of each mixture at 14 and 28 days of age. The average results for the three tested cubes were taken as porosity.

Permeability of the pervious concrete specimens was evaluated in the laboratory using a modified falling head method. Cylindrical specimens were cast within 450 mm-long uPVC molds, allocating 300 mm for the concrete sample and 150 mm as a water reservoir. The uPVC molds prevented lateral water loss during testing. Each mixture was tested using four replicate specimens, and the average permeability value was reported. During testing, each specimen was submerged in a water pond. The stopwatch was started upon releasing the water and stopped when the reservoir was fully drained. The discharge volume and elapsed time were recorded, and permeability was calculated using Equation 2.

$$k = (A_1 \times l/A_2 \times t) \times \log(h_2/h_1) \qquad (2)$$

Where, k - water permeability (mm/s)

h_1 - initial water head (mm)

h_2 - final water head (mm)

l - length of specimen (mm)

A_1- cross sectional area of specimen (mm^2)

A_2- cross sectional area of tube (mm^2)

t - time (s)

B. *Testing of mechanical properties*

Compressive strength of pervious concrete was determined using BSEN 12390-3-2009 (British Standard Institution, 2009) [35], which is defined for conventional concrete since standard procedure is not established for pervious concrete. The test was conducted on cubic specimens having standard dimensions of 150 mm × 150 mm × 150 mm. The compressive strength of each mixture at 14 and 28 days of age was measured using three cubes. Loading rate of 1.2 kN/s was applied without shock, and it grew steadily from there. Compressive strength was determined by taking the maximum values obtained from the three cubes that were tested.

It is not usually expected that PC will withstand direct tension because of its poor tensile strength and brittle nature. However, as it is a type of tension failure, it is imperative to know the load at which the concrete parts may fracture, so the PC's tensile strength must be ascertained. BSEN 12390-3-2009 [35], which is defined for conventional concrete, was utilized to evaluate the split tensile strength of pervious concrete because there was a lack of information regarding a specific method or standard defined for testing pervious concrete.

The calculated stress rate was 0.04 MPa/s, corresponding to a loading rate of 2.82 kN/s. However, the loading rate specified in the standard was reduced to 1.2 kN/s to account for the lower strength of pervious concrete compared to conventional Portland cement concrete and to ensure a steady, shock-free loading process over an adequate test duration. The maximum results from three tested cylinders of 150 mm diameter and 300 mm height for each mix on 14 and 28 days were calculated. The split tensile strength was calculated using the Equation (3)

$$f_{ct} = (2 \times F) / \pi \times L \times d \qquad (3)$$

Where,

f_{ct} - Tensile splitting strength (MPa or N/mm^2)

F - Maximum load (N)

L - Length of the line of contact of specimen (mm)

d - Diameter if the cylindrical specimen (mm)

IV. RESULTS & DISCUSSION

A. *Workability*

It was found that the concrete's workability reduced as the amount of silica fume increased by visual inspection of PC mixes. Because silica fume has a higher surface area than cement, it is less workable than cement. More water was needed to be added to the mixture to get the ball. The mixer blade was encircled by long (50 mm) fibers that gathered into clusters as shown in Fig. 1 and achieving a uniform distribution was challenging. Short fibers (10 mm) were adhered to the surface of the mixer. It spread smoothly and was combined with ease, without clumping.

B. *Density*

The density of the samples was checked at room temperature and in oven-dried condition. As shown in Fig. 2, the density is lower for oven-dried samples than for samples at room temperature making evident that pores are present in the sample. By comparing the control sample (GF 0.0%), the density of GF 1.0% is lower. It gradually increased when GF increased. However, pores in fiber reinforced samples were lower than in the control sample. Significant difference of density was not observed within samples with varying fiber content. The densities of tested samples are within the range of 16.02–22.84kN/m^3 as presented in previous literature [36]. The addition of glass fibers to concrete strengthens the link between binder matrix, making the concrete denser and less porous, according to the results of the microscopy images as shown in Fig. 3.

Figure 1. The mixer blade was encircled by long (50 mm) fibers that gathered into clusters

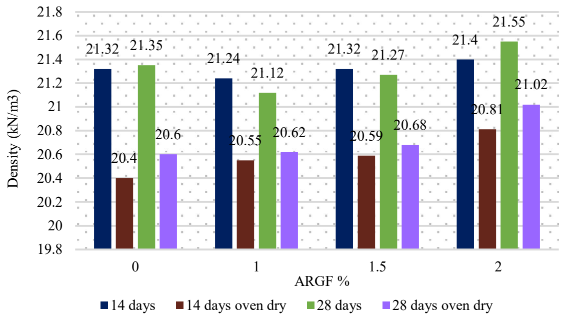

Figure 2. Variation of the Density with ARGF%

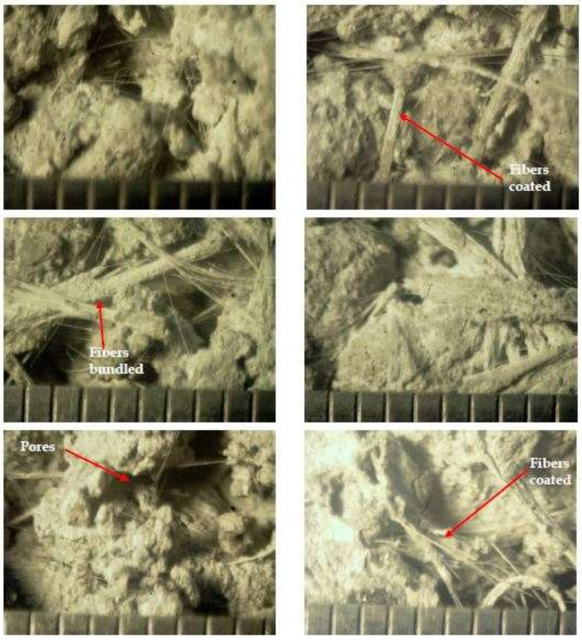

Figure 3. Microscopy images (1×8) of ARGF-PC

C. Porosity

Results on porosity measurements show that porosity has decreased with the increase of fiber content (Fig. 4). However, it is within the required range (15%-35%) recommended by the 522R, 2010. Average pore sizes are within the 2–8 mm range. Distribution of pores are not uniform which may have resulted from poor workability, extremely dry mixture, challenges in manual casting etc.

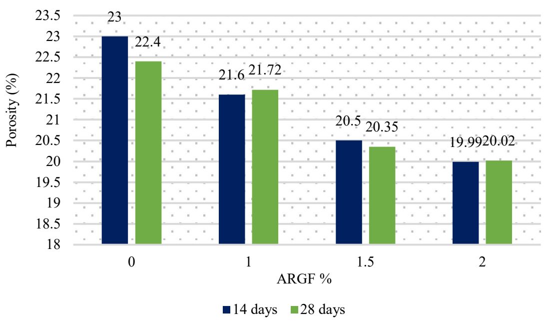

Figure 4. Variation of the Porosity with ARGF%

D. Permeability

As shown in Fig. 5, the permeability of the PC decreases when the fibers increase. However, it is within the range (1.4 mm/s – 12.2 mm/s) recommended in the code ACI 522R, 2010 [37]. The permeability decreases as fiber is added. Nonetheless, it was discovered that the permeability fell within the ACI 522R, 2010 [36] recommended limit. As the number of fibers increases, the number of open spaces decreases, and the permeability of the resulting materials decreases as well.

E. Compressive Strength

The results of the compressive strength test on 150 mm × 150 mm × 150 mm size concrete cubes with varying doses are shown in Fig. 6. All PC specimens reinforced with ARGF resulted in higher compressive strengths than the control specimen. Results indicate that the addition of glass fiber has increased compressive strength to a certain extent. However, after GF 1.5%, the strength is not further increased and is reduced. The lowest compressive strength was found within the range given in the code (2.8 to 28 MPa) 522R, 2010 [37]. 28-day strength of 1.5% GF specimen, 31.5 MPa is greater than the recommended value given in the code.

The results indicate that, in terms of compressive strength, concrete containing 1.5% glass fiber performed significantly better than all other specimens. The experimental investigation revealed that the excess content of ARGF reduces strength due to the poor bond between cement and ARGF. Since fibers mix with cement paste and bridge to each other, excess fibers may not be bonded and create weak joints in their spaces, given their low strength. The positive response of compressive strength is because of the pozzolanic reaction of SiO_2 in silica fume with $Ca(OH)_2$ in cement, which produces additional cementitious compounds. It has also been reported that compressive strength considerably improves with silica fume [38]. The extra binder formed by the silica fume reaction with existing lime $Ca(OH)_2$ permits silica fume concrete to increase strength over time.

Furthermore, the positive effect on compressive strength is due to the confinement of fiber reinforcement in the concrete sample. Compression produces an expansion laterally and, with it, tensile stresses are developed laterally. The tension is resisted by the glass fibers in the concrete therefore, compression is increased.

F. Split Tensile Strength

As shown in Fig. 7, the specimen with 1.5% glass fibers (GF1.5%) achieved the highest compressive strength at both 14 and 28 days, recording values of 3.47 MPa and 3.44 MPa, respectively.

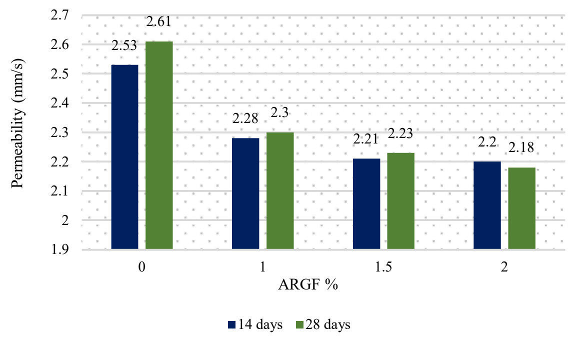

Figure 5. Variation of the Permeability with ARGF%

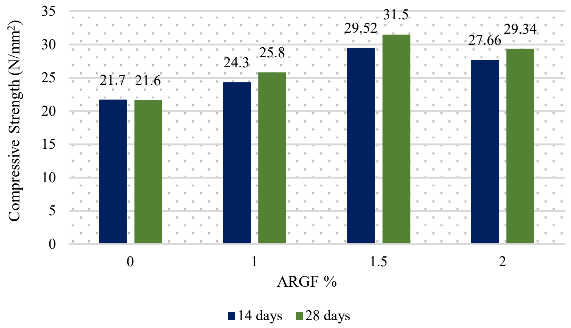

Figure 6. Variation of the Compressive strength with ARGF%

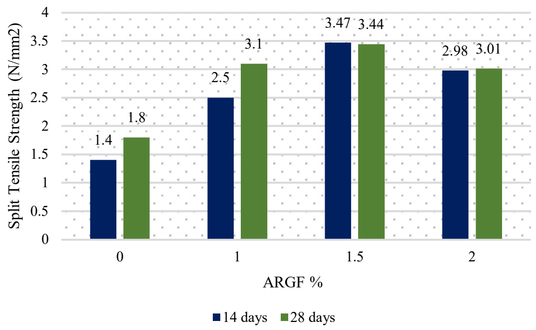

Figure 7. Variation of the Split Tensile Strength with ARGF%

The lower fiber content in GF1.0% resulted in only a slight strength improvement, while GF2.0% exhibited reduced strength compared to GF1.5%, despite having a higher fiber content. This fact is due to poor bonding, caused by the addition of more fiber content. Excess fibers create weak joints, which reduce the aggregate and paste volume, and compaction will not happen. However, increasing GF content up to 2.0% enhances the tensile strength of PC more than the control specimen.

A comparative analysis was performed using the 14-day and 28-day split tensile strength of the control specimens as reference. As illustrated in Fig. 7, the mix containing 1.5% glass fibers (by cement weight) exhibited a 52% increase in split tensile strength at 28 days compared to the control specimen. This suggests that incorporating 1.5% glass fibers is optimal for enhancing the tensile performance of pervious concrete. Failure plane observations indicated that cracking predominantly propagated through the cement paste rather than through the aggregates. Split tensile test results show that the addition of glass fibers has effectively reinforced the binder matrix.

V. CONCLUSION

This study investigated the effect of alkali-resistant glass fibers on the physical and mechanical properties of pervious concrete. Adding glass fibers has reduced workability, porosity, and permeability, while also improving compressive and split tensile strengths. The results for density and porosity showed that fiber reinforcement slightly lowered the void content, and permeability stayed within ACI and local guidelines. In terms of mechanical performance, 1.5% ARGF by cement weight gave the best performance, reaching the highest compressive strength of 31.5 MPa at 28 days and a 52% rise in split tensile strength compared to the 0% ARGF. Excess fiber content (2.0%) has caused reduction in strength due to poor bonding and weak joints. The study shows that adding the optimum amount of fiber improves the structural performance of PC while maintaining its environmental benefits. This offers a practical solution for sustainable stormwater management in urban areas.

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