



**Nesreen Elawadly\*<sup>1</sup>**

1 : Civil Engineering Department, Higher Institute of Engineering and Technology in New Damietta, Damietta, Egypt

\*Corresponding author:

<https://orcid.org/0000-0002-6111-1295>,

[nesreenelawadly@gmail.com](mailto:nesreenelawadly@gmail.com)

**Samah A. Sanad <sup>2</sup>**

2 : Raw Building Materials and Processing Technology Research Institute, Housing and Building National Research Center (HBRC), Cairo, Egypt.

[Samah.sanad@hbrc.edu.eg](mailto:Samah.sanad@hbrc.edu.eg)

**Keywords**

Porous concrete, Silica Sand, Glass Fiber, SEM, Water filtration, waste rain water

## **Development of Enhanced Porous Concrete for Water Treatment Applications: A Study on Mechanical, Water Filtration, and Microstructure Properties**

### **ABSTRACT**

Porous concrete has emerged as a sustainable material for storm-water management and water treatment, particularly in controlling road surface runoff and treating wastewater. This study investigates the development of mechanical properties of specialized porous concrete mixes to enhance their performance in water treatment applications. The novel mix comprises cement, coarse aggregates (10, 20 mm), and 10% Silica-Sand by total aggregate weight. Fiberglass chopper is also examined as an enhancing material. The aim is to develop high strength porous concrete for road purpose to save the rain water to underground water.

Mechanical properties, water filtration and scan electron microscopy (SEM) were comprehensively assessed for each mix to evaluate their suitability for water treatment, with a focus on filtering and managing wastewater and rain runoff on road surfaces. Results demonstrate that the inclusion of these materials significantly impacts the mechanical and durability characteristics of the concrete. This study highlights the potential of engineered porous concrete as a sustainable and efficient technology for addressing water treatment challenges.

## **Introduction**

Porous concrete is a sustainable concrete that allows rainwater to infiltrate through its interconnected pores, reducing runoff and supporting groundwater recharge. Previous studies focused on improving its strength and durability while maintaining permeability, aiming to enhance its performance in pavement applications. A previous study investigated using low-fines sand in roller-compacted concrete pavement. Results showed that it slightly increased workability time and porosity but had minimal negative impact on compressive, tensile, and flexural strengths. It was concluded that the material, despite lacking standard fines content, is a viable aggregate for concrete.[1] This study enhanced No-Fine Concrete (NFC) using coir fiber and nano-graphene oxides. Results showed significant strength improvements up to 67% in compression and 35% in tension, while maintaining high permeability suitable for drainage applications. Microstructural analysis confirmed enhanced hydration products.[2] Other study investigated porous concrete containing mineral adsorbents (zeolite, pumice, perlite, LECA) for municipal wastewater pretreatment. Results showed PC effectively reduced pollutants, with average removals of 40% TSS, 48% BOD, and 30.5% COD, while zeolite demonstrated the best overall performance.[3] This study developed low-fines self-consolidating concrete using rice husk ash (RHA) as a cement substitute. Results showed that 20% RHA replacement optimizes strength and durability, making it suitable for eco-friendly rigid pavement construction.[4] Other



study evaluated low-fines self-consolidating concrete with fly ash. Results showed that 20% fly ash replacement optimized compressive strength, ultrasonic pulse velocity, and electrical resistivity, indicating high-quality, durable concrete suitable for pavement construction.[5] This study investigated porous concrete using only coarse aggregates without fines or additives. Results showed direct correlations between density and strength, and porosity and permeability, while porosity and strength were inversely related. Optimizing water-cement ratio and aggregate type achieved balanced strength 12 MPa and high permeability.[6] This study produced porous concrete using recycled porous concrete aggregate and scoria powder. Scoria improved long-term strength and reduced permeability after 120 days, demonstrating its viability as a sustainable cement substitute[7] This study evaluated the clogging of porous asphalt containing recycled concrete aggregate (RCA). Results showed that 20% RCA and  $\geq 15\%$  porosity maintained permeability above minimum standards. A combined water-vacuum cleaning method effectively restored up to 89% of permeability[8]. This study found that using porous titanium slag as a concrete aggregate enhances strength by improving the interfacial bond and promoting trans-aggregate fracture. It also reduces carbon emissions and costs, with optimal performance at 19% surface porosity and 0.5 mm pore depth [9]. Other study explored using porous diatomite in 3D printed lightweight concrete. Results showed 5% diatomite optimized strength, while 30% improved printability and reduced density. Diatomite enhanced thermal insulation and reduced costs and carbon emissions, demonstrating its viability for sustainable construction.[10] Other study develops high-strength permeable concrete by optimizing mix design and aggregate sphericity for tunnel drainage systems, enhancing urban rainwater management and supporting "sponge city" construction.[11] A study analyzes ecological porous concrete, finding an average compressive strength of 8.76 MPa, 25–30% porosity, and fractal dimensions of 1.2–1.8. It establishes a linear relationship between porosity and fractal dimension, linking microstructural complexity to macroscopic properties.[12]

### Materials

The cement used in the study was Portland cement with a grade of 42.5 MPa, produced by the Al-Askari Cement Factory, Egypt. Compressive strength test of cement mortar was done in accordance of ASTM C 109[13]. The Initial and final setting time tests were conducted in accordance with standard ASTM C191 [14] using the Vicat apparatus. The results of these tests are shown in Table 1.

**Table 1. Portland Cement Characteristic**

|                                        |      |
|----------------------------------------|------|
| Initial Setting Time [mm]              | 60   |
| Final Setting Time [mm]                | 180  |
| Specific surface [cm <sup>2</sup> /gm] | 3000 |
| Compressive Strength [MPa]             | 42   |

As previously mentioned, the main in the aggregate was on coarse aggregate from crushed dolomite, and 10% of fine aggregate from silica sand with a particle size of 0.075 mm to 1.18 mm according to data sheet of the producer. Absorption and bulk density tests were conducted for the used aggregates according to ASTM C 128 [15], and the results are presented in Table 2. Additionally, the particle size distribution test was carried out for both type of the coarse



aggregate according to ASTM C 136 [16]. The N.M.S for (Coarse Agg.20) was 20 mm and the N.M.S for ( Coarse Agg. Zero) was 10 mm

**Table 2. Coarse Aggregate Properties**

|                  | Absorption % | Bulk Density [kg/m <sup>3</sup> ] |
|------------------|--------------|-----------------------------------|
| Coarse Agg. 20   | 1.6%         | 1620                              |
| Coarse Agg. Zero | 2%           | 1450                              |

Super plasticizer PVF man was used in all the concrete mixes to reduce water content and improve compressive strength. It was classified as high-range water-reducing admixtures (superplasticizers- Type F) in accordance with ASTM C494[17]. In the second mix glass fiber was used. It was used as (chopped- glass fiber). It was produced by China, with dimensions of 0.01 mm Diameter and 12 mm length according to the producer datasheet.

## Experimental Methodology

### Mix Design and Proportion

The main target of the study is to develop a porous concrete mix with a moderate compressive strength exceeding 20 [MPa] to achieve the required practical purposes. Scientific research has no real value if it cannot be effectively applied and utilized. Several trial mixes were designed to reach this target, and the compressive strength was tested after seven days of casting, but the results did not meet expectations.

After several trial mixes, it was decided to use a combination of coarse aggregate consisting of one part of small-sized coarse aggregate and two parts of medium-sized coarse aggregate.

The purpose was to strengthen the internal structure of the concrete while keeping voids that act as filters or channels for water permeability. Later, after more trials, it was found useful to add 10% of total aggregate weight silica sand to improve the concrete's structure and to reach a higher compressive strength suitable for use in side-walk along roads, allowing rainwater drainage and it's retention in the soil as groundwater.

Rather high cement content was also used to support the target strength, together with super-plasticizers to ensure that water can penetrate all cement particles for complete hydration.

It was not easy to confirm the mix design without several laboratory experiments on trial mixes, because the main goal of this research is to achieve an ideal mix that combines both strength and permeability.

Two concrete mixes were finally selected. The first one was the basic mix described previously, while in the second mix, glass fiber chopper was added at a rate of 800 [gm] per the cubic meter. The mix design proportions are shown in Table 3. Casting and specimens preparing was done in the laboratory of The Higher Institute of Engineering and Technology in New Damietta.

**Table 3. Mix Design Proportion**

| MIX     | Cement [kg] | Coarse Agg 20[kg] | Coarse Agg. zero[kg] | Slica Sand [kg] | Water [lit] | Super Plasticizer[lit] | Glass Fiber[kg] |
|---------|-------------|-------------------|----------------------|-----------------|-------------|------------------------|-----------------|
| Prev. A | 425         | 1275              | 435                  | 170             | 157.25      | 2.9                    | 0               |
| Prev. B | 425         | 1275              | 435                  | 170             | 157.25      | 2.9                    | 0.8             |

### Absorption and Density

The bulk density, water absorption, and void ratio of the porous concrete samples were measured to evaluate the physical characteristics of the developed mix. The test was conducted according to ASTM C642[18]Two cylindrical specimens with a diameter of 100 mm and a height of 50 mm



were used for the tests. Each specimen was first oven-dried at  $105 \pm 5^\circ\text{C}$  until a constant mass was achieved. The dry mass was recorded. Then, the samples were fully submerged in water for 24 hours to ensure complete saturation of the open pores. After saturation, the specimens were removed from the water, their surfaces were gently dried with a damp cloth to reach the saturated surface dry condition (SSD), and the corresponding mass was recorded. The apparent volume of each specimen was calculated based on its measured dimensions. The bulk density was determined. Water absorption was calculated as the percentage increase in mass from the dry to SSD condition. The total open void ratio was then estimated from the absorbed water volume relative to the total specimen volume. This method allows the assessment of how much of the concrete structure is available for water passage and retention. . Figure1 shows the appearance of the porous concrete.



**Figure 1. Porous Concrete Appearance**

### **Mechanical properties**

Verification of the mechanical properties is a main objective of this study. Therefore, the mechanical properties were examined by preparing standard samples of 150 mm concrete cubes, as well as concrete beams of 100 mm × 100 mm × 500 mm. Standard cylindrical specimens were also prepared with a diameter of 150 mm and a height of 300 mm. The compressive strength test was carried out according to standard specification BS EN 12390[19], the flexural strength test was performed according to standard specification ASTM C 78-2[20], and the splitting tensile strength test was also conducted according to ASTM C 496[21]. The tests were conducted in the laboratories of the Faculty of engineering, Delta University, New Mansoura, Egypt.

### **Permeability Test for Pervious Concrete**

A permeability test was conducted on a cylindrical specimen of pervious concrete with a diameter of 100 mm and a thickness of 50 mm. the test was done for both mixes. The procedure was that sample was placed inside a side confined mold, and water was allowed to flow vertically through it. The passage of water was immediate, indicating very high permeability. The water entered from the top and exited from the bottom almost instantly. This result confirms the effectiveness of the pervious concrete in allowing rapid drainage of surface water and supporting groundwater recharge. The procedure is similar in principle to the ASTM C1701 [22]. It is the suggested test for infiltration rate of pervious concrete. Such high permeability is typical and



desirable for pavement applications designed to manage storm-water efficiently. The tests were done in the Housing and Building National Research Center Research, HBRC, Dokki, Egypt

### **Water Filtrations and Quality Assessment**

To evaluate the influence of porous concrete on the quality of storm-water passing through its structure, a water filtration test was conducted. The physicochemical analyses of the tested water samples were carried out at 26°C after according to (APHA, 2023) [23]. The test was conducted for the two porous concrete mixtures, using cylindrical specimens of 100 mm diameter and 50 mm height. The filtered water collected from the outlet was then analyzed for several water quality parameters, including chloride, sulphate, total dissolved solids (TDS), pH, phosphates, ammonia, nitrate, iron (Fe), manganese (Mn), and turbidity. Firstly, the specimens were submerged completely in water for 2 hours to study the effect of prolonged contact with concrete samples then passed through the two concrete samples to be collected for analyses. The obtained results were compared to the permissible limits specified for potable and environmental water standards to assess the potential environmental compatibility of the pervious concrete. This procedure aimed to investigate the filtration capacity and the influence of concrete composition on the quality of infiltrated water. Figure 2 and 3 shows quality assessment test. The tests were done in the National Center for Housing and Building Research, HBRC, Dokki, Egypt



**Figure 2 & 3. Water filtrations and Quality assessment**

### **Microstructural Analysis**

The microstructure of the developed pervious concrete was examined using a Scanning Electron Microscope (SEM) (model xT810 Inspect S/2007 electron microscope) operated at an accelerating voltage of 25 kV at the Housing and Building National Research Center, HBRC, Dokki, Egypt. to better understand the voids appearance, internal morphology and the bonding characteristics between the cement paste and aggregates. SEM images were captured to identify the distribution of pores, the shape and connectivity of voids, and the nature of the interfacial transition zone (ITZ). The observations helped to clarify how the high cement content and the addition of 10% silica sand influenced the compactness of the matrix and the reduction in open pore volume. The SEM analysis also provided insight into the formation of dense hydration products that contribute to higher mechanical strength with a high permeability.

### **Results and Discussions**

#### **Absorption and Density**



The results showed that the designed pervious concrete showed moderate water absorption and quite high bulk density compared with previous mixes in the previous research. The measured water absorption values for the two specimens were 5.5% and 3.8%, while the calculated void ratios were 11.4% and 8.8%, respectively. The corresponding dry bulk densities were approximately 2080 kg/m<sup>3</sup> and 2280 kg/m<sup>3</sup>. These results indicate that the concrete mixture had a denser structure and a lower volume of connected pores than typical porous concrete. The lower void content is mainly attributed to the high cement content (425 kg/m<sup>3</sup>) and the inclusion of 10% silica sand, which effectively filled the spaces between coarse aggregate particles.

In addition, the use of (Coarse Aggregate Zero) with a nominal maximum size of 10 mm produced a tighter packing arrangement and reduced the size of the interconnected pores. As a result, the concrete maintained sufficient permeability for water infiltration while providing a higher compressive strength compared with standard pervious concrete. The absorbed water volume and void ratio confirm that the material allows the passage of rainwater through its structure, enabling infiltration into the subgrade soil. This characteristic supports the recharge of groundwater and minimizes surface runoff, making it environmentally beneficial for pavement edges and sidewalks. The slightly higher bulk density also reflects improved bonding between paste and aggregate, which enhances durability and load-bearing capacity.

Mix Prev. B, which contained 800 g/m<sup>3</sup> of chopped glass fiber, showed lower absorption and void ratio but higher bulk density. The fibers improved particle packing and reduced open pores, leading to a denser, less permeable structure. The combination of high cement paste, fine silica sand, and controlled aggregate grading achieved a balanced performance ensuring permeability for rainwater drainage. Results of tests are shown in Table4.

**Table 4. Absorption and Density results**

| Mix                                    | Prev. A | Prev. B |
|----------------------------------------|---------|---------|
| <b>Absorption %</b>                    | 5.5     | 3.8     |
| <b>Void Ratio %</b>                    | 11.4    | 8.8     |
| <b>Bulk Density [kg/m<sup>3</sup>]</b> | 2080    | 2280    |

The results water sample passed through (Prev. B) shows better results than (Prev. A) as it had indirect relationship with void ratio. As void ratio increases the filtration decrease.

### **Mechanical Properties**

Compressive strength tests were performed for the two porous concrete mixes. At 7 days, strengths were 16.5 MPa and 15.0 MPa, increasing to 26.5 MPa and 24.0 MPa at 28 days. The compressive strength of porous concrete usually ranges between 10 and 20 MPa. The improved strength which done by the study is mainly due to the novel mix design which depend on high cement content (425 kg/m<sup>3</sup>) and the inclusion of 10% silica sand, which reduced voids and improved bonding between paste and aggregate. The use of small size coarse aggregate (Coarse Aggregate Zero) enhanced packing density and strength without blocking permeability. The mix (Prev. A) Achieved slightly higher strength, likely due to better workability than ( Prev. B) which contains fiber glass chopper. Overall, the mixes demonstrated a good balance between mechanical strength and water permeability, making them suitable for sidewalks and roadside drainage applications. The results are shown in Table 5. and Figure 4.



**Table 5. Compressive Strength Test Results**

| Mix     | Compressive strength 7 days [MPa] | Compressive strength 28 days [MPa] |
|---------|-----------------------------------|------------------------------------|
| Prev. A | 16.5                              | 26.5                               |
| Prev. B | 15.0                              | 24.0                               |



**Figure 4. Compressive Strength Evaluations**

The tests were done to evaluate the cracking resistance of the porous concrete mixes. The mix (Prev.A) recorded flexural and tensile strengths of 4.10 MPa and 3.10 MPa, while (Prev.B) reached 3.76 MPa and 2.85 MPa, respectively. Although (Prev. B) contained 800 g of glass fibers, its results were slightly lower than (Prev. A) This may be due to variations in fiber dispersion and bonding within the matrix, which can affect stress transfer efficiency. Both mix showed higher tensile performance compared with usual porous concrete. The high cement content and inclusion of silica sand improved matrix continuity and reduced weak zones. The results confirm that both mixes possess sufficient flexural and tensile strength for use in sidewalks and roadside applications, where moderate load capacity and resistance to cracking are essential. Results are shown in Table 6.

**Table 6. Flexural Strength & Splitting Tensile Strength Tests Results**

| Mix     | Flexural strength [MPa] | Splitting tensile strength [MPa] |
|---------|-------------------------|----------------------------------|
| Prev. A | 4.10                    | 3.10                             |
| Prev. B | 3.76                    | 2.85                             |

### Permeability for Porous Concrete

The permeability test showed that both porous concrete mixes allowed rapid water flow through their structure. When water was poured onto the 100 mm × 50 mm cylindrical specimens, it passed almost rapidly, indicating high permeability and well-connected pore channels. This confirms that the designed mixes successfully achieved the main function of pervious concrete to permit storm-water infiltration and support groundwater recharge. Mix (Prev. A) appeared slightly denser, showing smoother water flow with fewer surface pores, while (Prev. B) maintained similar permeability despite the inclusion of glass fibers. Overall, both mixes



provided efficient drainage performance suitable for sidewalks and roadside pavements exposed to rainwater.

### **Water filtrations and Quality assessment**

After samples submersion of 24 hrs the water test results are shown in Table 7. The (Raw water) is the water before submersion. The name ( W.Prev A) represents the water in which the concrete (Prev. A) Was submerged. While the name ( W.Prev B) represents the water in which the concrete (Prev. B) Was submerged.

**Table 7. Physicochemical analyses of the tested water samples.**

| Parameter                                        | Raw water | W.Prev.A | W.Prev. B | Limits    |
|--------------------------------------------------|-----------|----------|-----------|-----------|
| Chloride (mg/L)                                  | 37        | 49       | 45        | 250       |
| Sulphate (mg/L)                                  | 60        | 80       | 70        | 250       |
| TDS (mg/L)                                       | 210       | 330      | 285       | 100-1000  |
| pH                                               | 7.73      | 7.66     | 7.6       | 6.5 - 8.5 |
| Phosphorous (mg/L)                               | 0.03      | 0.02     | 0.02      | -         |
| Ammonia (mg/L)                                   | Nil       | Nil      | Nil       | 1         |
| Nitrate (mg/L)                                   | Nil       | Nil      | Nil       | 50        |
| Fe (mg/L)                                        | 0.38      | 0.24     | 0.2       | 0.3       |
| Mn (mg/L)                                        | <0.01     | <0.01    | <0.01     | 0.4       |
| Turbidity (NTU)                                  | 9         | 1.9      | 2.1       | 1         |
| Turbidity (NTU)<br>after 24 hrs of sedimentation | -         | 0.7      | 0.9       | 1         |

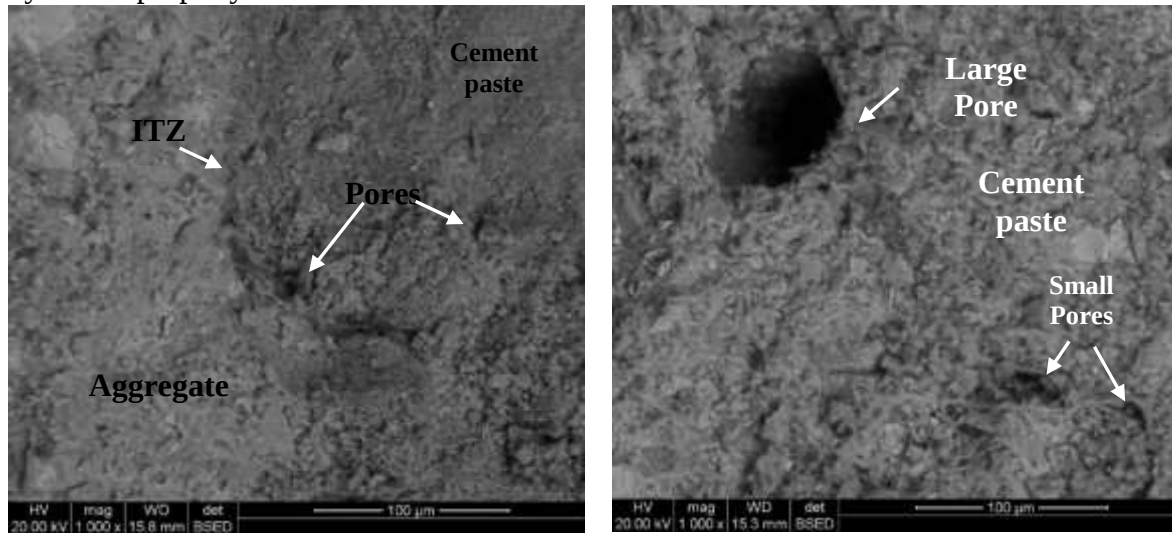
From the previous results, it's noticed that the chlorides, sulphates and Total dissolved salts (TDS) results in samples (W.Prev.A) and (W.Prev.B) water were increased than raw water sample as mentioned in Table 7 due to the presence of salts that found in concrete samples but the results still within the allowance limits. The pH of the samples is not affected and still within the allowance range. Phosphorous is found to be in low concentration of 0.3 mg/L and enhanced to be 0.02 and 0.02 mg/L in samples (W.Prev A) and ( W. Prev B) consequently. Ammonia and Nitrate were lacked in these samples. Moreover, Fe was decreased from 0.38 mg/L to 0.24 and 0.2 mg/L in the samples ( W.Prev A) and ( W.Prev B) consequently. Mn concentration is less than 0.01 in raw water and not affected by concrete samples. The turbidity of the raw water decreased from 40 NTU to 4.79 and 5.98 NTU after passing through concrete samples (W.Prev A) and (W. Prev B) consequently and this is not acceptable within the allowance limits. But after 24 hours of sedimentation for the water samples it's found that the raw water itself dropped to 9 and water samples dropped from 1.9 and 2.1 NTU of sample (W.Prev A) and (W.Prev.B) to be



0.7 and 0.9 NTU consequently to be in compliance with the allowance limits. And these agreed with Guibai and Gregory [24] that proved that turbidity was halved in the first hour, and by day 7 many samples' turbidity dropped to low values (0.3 NTU). All the results of the physicochemical analysis are in compliance with the allowance limits of Decree No. (458/2007) of minister of health and population. The results of water sample passed through Prev. B shows better results than Prev. A as it had indirect relationship with void ratio. As void ratio increases the filtration decrease.

### Microstructure analysis

The SEM photomicrograph for mix (Prev. A) which are shown in Figure 5 clarifies the heterogeneous, multi-phase nature of the studied porous concrete, showing interactions and certain boundaries between the used dense aggregate and the surrounding cement paste, and also the interfacial transition zone (ITZ) at their interface, and the widespread occurrence of small pores throughout the cement matrix. The SEM photomicrograph illustrates the accurate microstructure of the studied porous concrete and showing a solid cement paste matrix interspersed with a different type of voids, including a large pore (macropore) and various much smaller (micropores). Which affect some mechanical properties as strength, durability, and hydraulic property of the studied mix.



**Figure 5. Scan Electron Microscopy SEM of mix ( Prev. A)**

The SEM photomicrograph shown in Figure 6 represent the SEM for the second mix ( Prev.B) which have 800 gm/m<sup>3</sup> glass fiber chopper. It must be notice that as the fiber glass is added in small ratio so it is not obviously seen in SEM. The SEM reveals porous concrete as a multi-phase composite defined by its high degree of porosity as expressed by various sized pores. On the other hand, the presence of small pores reveals the internal porosity of the cement paste which controls the mechanical strength and durability of the studied porous concrete. Moreover, ITZ which considered high porosity zone and represented as a major factor in the overall mechanical performance of the porous concrete. In addition to SEM photomicrograph clearly focused on highly porous cementitious microstructure for studied concrete sample which leads to degree of



porosity that required for high permeability for water drainage and moderate strength for achieved porous concrete requirements.

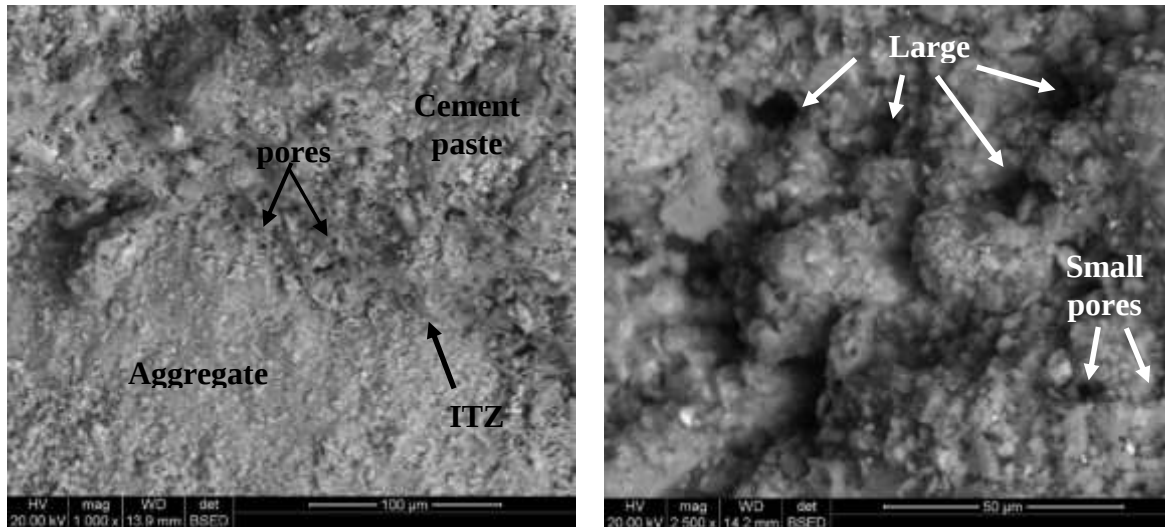


Figure 6. Scan Electron Microscopy SEM of mix ( Prev.B)

## Conclusions

- The developed porous concrete mixes achieved a good balance between strength and permeability, making them suitable for sidewalks and roadside applications that support storm-water infiltration and groundwater recharge.
- The high cement content ( $425 \text{ kg/m}^3$ ) and 10% Silica-Sand addition reduced the pore volume and improved bonding between paste and aggregates, leading to higher bulk density and compressive strength.
- The designed concrete mixes showed good results. Mix (Prev. A) showed slightly higher mechanical strength due to better workability, while Mix (Prev. B), which contained  $800 \text{ g/m}^3$  chopped glass fibers, exhibited lower absorption and void ratio, forming a denser and less permeable structure.
- Both mixes demonstrated adequate tensile and flexural strength for moderate loads, confirming their durability and resistance to cracking under service conditions.
- Permeability tests confirmed rapid water flow through the concrete, ensuring efficient drainage and environmental benefits by reducing surface runoff and enhancing groundwater recharge.
- Water quality tests after filtration and submersion showed all physicochemical parameters within acceptable limits, indicating no harmful leaching or contamination from the concrete.
- SEM analysis revealed a dense cement matrix with interconnected micro-pores, and a clear interfacial transition zone (ITZ) that influences both permeability and strength. The microstructure confirmed the desired balance between open porosity and compactness.



## References

1. Hashemi M, Shafigh P, Abbasi M, Asadi I (2019) The effect of using low fines content sand on the fresh and hardened properties of roller-compacted concrete pavement. *Case Stud Constr Mater* 11:1–11. <https://doi.org/10.1016/j.cscm.2019.e00230>
2. Pateriya AS, Dharavath K, Robert DJ (2021) Enhancing the strength characteristics of No-fine concrete using wastes and nano materials. *Constr Build Mater* 276:122222. <https://doi.org/10.1016/j.conbuildmat.2020.122222>
3. Teymouri E, Mousavi SF, Karami H, et al (2020) Municipal Wastewater pretreatment using porous concrete containing fine-grained mineral adsorbents. *J Water Process Eng* 36:101346. <https://doi.org/10.1016/j.jwpe.2020.101346>
4. Kannur B, Chore HS (2023) Low-fines self-consolidating concrete using rice husk ash for road pavement: An environment-friendly and sustainable approach. *Constr Build Mater* 365:130036. <https://doi.org/10.1016/j.conbuildmat.2022.130036>
5. Kannur B, Sharad Chore H (2023) Ultrasonic pulse velocity and electrical resistance of low-fines self-consolidating concrete for pavements. *Mater Today Proc* 93:1–4. <https://doi.org/10.1016/j.matpr.2023.06.018>
6. Sánchez-Mendieta C, Galán-Díaz JJ, Martínez-Lage I (2024) Relationships between density, porosity, compressive strength and permeability in porous concretes: Optimization of properties through control of the water-cement ratio and aggregate type. *J Build Eng* 97:1–11. <https://doi.org/10.1016/j.jobe.2024.110858>
7. Yavuz D (2025) Effect of scoria powder on the strength and porosity of porous concrete produced with recycled porous concrete aggregate. *Eng Sci Technol an Int J* 69:102141. <https://doi.org/10.1016/j.jestch.2025.102141>
8. Elmagarhe A, Lu Q, Alamri M, Al-Saffar ZH (2025) Evaluation and analysis of the effect of recycled aggregates concrete and sediment size on the clogging behavior of porous asphalt mixtures. *Constr Build Mater* 494:143528. <https://doi.org/10.1016/j.conbuildmat.2025.143528>
9. Zhang J, Wang M, Sun J (2025) Mechanical behavior and fracture mechanisms of high-strength concrete incorporating porous titanium slag aggregate. *J Mater Res Technol* 36:6075–6087. <https://doi.org/10.1016/j.jmrt.2025.04.237>
10. Liu Q, Jiang Q, Zhao H, et al (2025) Porous diatomite promotes lightweight and low-carbon concrete 3D printing: An exploratory study. *J Build Eng* 103:112071. <https://doi.org/10.1016/j.jobe.2025.112071>
11. Zhang H, Li B, Shi J, et al (2024) Framework structure design based on porous permeable concrete material in expressway tunnel drainage system. *Desalin Water Treat* 317:100308. <https://doi.org/10.1016/j.dwt.2024.100308>
12. Ding K, Zeng C (2025) Study on the compressive strength, pore structure characteristics, and fractal dimension of the ecological porous concrete specimens based on ordinary Portland cement. *Constr Build Mater* 483:141795. <https://doi.org/10.1016/j.conbuildmat.2025.141795>
13. ASTM C109/109M (2016) Standard test method for compressive strength of hydraulic cement mortars (Using 2-in. or cube specimens). *Annu B ASTM Stand* 1–10
14. ASTM C191-08 (2009) Standard Test Methods for Time of Setting of Hydraulic Cement by Vicat Needle. *ASTM Int* 04:1–8



15. C128/C128M (2001) Standard Test Method for Density , Relative Density (Specific Gravity), and Absorption. ASTM Int 1–6
16. International A (2009) C 136 - 06 Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. ASTM Int 1–5
17. Shalaby SE, Balakocy NG, EL-Ola SMA, Beliakova MK (2019) Development of pilot scale system for production of nylon-6 fibers grafted with polydimethylaminoethylmethacrylate (PDMAEMA) for the application as ion exchange. Egypt J Chem 62:1713–1723. <https://doi.org/10.21608/EJCHEM.2019.6778.1566>
18. ASTM C 642-13 (2013) Standard Test Method for Density, Absorption, and Voids in Hardened Concrete C642-97. ASTM Int 1–3
19. BS EN 12390-3 (2009) Testing hardened concrete - Part 3: Compressive strength of test specimens. BSI Stand 38:18
20. ASTM (2010) Standard Test Method for Flexural Strength of Concrete ( Using Simple Beam with Third-Point Loading ) 1. Hand C78-02:1–4
21. ASTM C496 (2008) Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens. ASTM Stand B 545-545–3
22. ASTM C1701M (2022) Standard Test Method for Infiltration Rate of In Place Pervious Concrete. Annu B ASTM Stand 04.02:9–11. <https://doi.org/10.1520/C1701>
23. American Public Health Association (APHA)(2023), Standard Methods for the Examination of Water and Wastewater, 24 thed. (Lipps, W.C., Baxter, T.E., Braun-Howland, E.B.,)
24. Guibai, L., & Gregory J (1991) Flocculation and Sedimentation of High-Turbidity Waters. Water Res 25:1137–1143