Durability Performance Assessment of Transparent Pavement Concrete

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ABSTRACT

This study investigates the possibility of Plastic Optical Fiber (POF)-based transparent concrete as a sustainable alternative for pavement applications. Different POF spacings were performed (0, 5, 10, 15, 20 mm) to explore the effect of durability on water permeability. Rapid Chlorine Penetration Test (RCPT), Ultrasonic Pulse Velocity (UPV), and microstructure analysis were conducted. The results indicated that smaller POF spacings resulted in higher water permeability due to reduced compaction at the interface between POF and concrete. Similarly, RCPT showed higher chloride attacks in samples with smaller POF spacing, while the UPV analysis demonstrated that compaction and strength increased over time. The microstructure analysis exhibited that the presence of pores at the fiber-matrix interface, and the smooth surface of POF reduced bonding, leading to increased crack propagation. Among the tested samples, 1.5 mm diameter POF demonstrated the most optimal balance between strength and durability, making it a promising material for transparent concrete applications.

Keywords-transparent concrete; light-transmitting concrete; Plastic Optical Fiber (POF); pavement materials; durability; mechanical properties

I. INTRODUCTION

In recent years, the production of transparent concrete worldwide has gained attention, being utilized in aesthetical view, interior design, subway illumination, speed bump, roadway lane markings, and traffic control [1, 2]. Concrete is one of the most common construction materials, with a significant environmental footprint, producing 5-9% CO_2 emissions [3]. Its durability is affected by either external or internal factors. Specifically, concrete can be exposed to physical attacks (temperature, humidity, and weather fluctuations), chemical attacks (aggressive substances, like acids, sulphates, chlorides) mechanical stresses (loads, impacts, and vibrations), and biological attacks (microorganisms, algae, or plant growth) [4-8]. Among the most important factors, the water-cement ratio (w/c) affects the porosity and permeability of concrete, with respect to inter-pore connectivity. The presence of such interconnected capillary pores increases the rate at which water and external ingredients penetrate the concrete. Several studies have investigated the mechanical properties of concrete. Authors in [9] indicated that an increase in the POF content in concrete, led to a reduction of compressive and flexural strength. Authors in [10] revealed that the addition of 0-5% POF resulted in 10-20% lower compressive strength, while light transmittance increased by 20-23% with 5% POF content. Authors in [11] demonstrated that concrete cubes with 1% POF inclusion cause a marginal reduction in compressive strength, whereas light transmission increased effectively. Additionally, authors in [12] conducted experiments with optical fibers at the center of concrete cubes in concrete ratios of 0%, 0.09%, 0.87%, 1.05%, and 1.75% by volume. The results showed a 30-39% compressive strength reduction and a 0.34-1.37% light transmission increase. Authors in [13, 14] concluded that the performance of light transmission of self-compacting transparent concrete increased with rising POF content, compressive strength also increased with increasing POF volume ratios, while light transmittance exhibited a direct quadratic relationship with POF volume ratios. Based on the above observations, it is evident that there is a significant gap regarding the long-term durability of POF-based transparent concrete. This study aims to fill this gap.

II. MATERIALS AND METHODS

A. Materials

In this study, the basic materials utilized to manufacture transparent concrete include cement, fine aggregate, coarse aggregate (under 10 mm), tap water, and POF as light transmitting material [15]. Different types of POF can be used, such as polymethyl methacrylate (PMMA) [16, 17] and Glass

Optical Fiber (GOF). In this research PMMA core material with diameter of 1 mm was embedded in concrete to transfer the light from one end to the other. Cement of 43 grade conforming to IS: 8112-1989 was used, with a previous study having determined its specific gravity, soundness, and consistency [18]. Specifically, these tests were conducted, resulting in a specific gravity of 3.09, a soundness of 0.85, and initial and final setting times of 85 minutes and 460 minutes, respectively. The standard consistency of cement was detected to be 27.4%. Locally available coarse aggregate of size not more than 10 mm and fine aggregate sieved with 4.75 mm IS sieve were used, with their properties being presented in Table I. In another study, authors incorporated glass powder to develop transparent concrete [19].

TABLE I. PROPERTIES OF FINE AND COARSE AGGREGATES USED

Properties	Fine aggregate (sand)	Coarse aggregate
Specific gravity	2.68	2.62
Bulk unit weight (kg/m^3)	1740	1690
Fineness modulus	2.40	4.45
Maximum nominal size	≤ 4.75 mm	≤ 10 mm

B. Methodology

The durability of POF-based transparent concrete was analyzed through water permeability, UPV, and RCPT, while for microscopic properties, Scanning Electron Microscopy (SEM) and Energy Dispersive Spectroscopy (EDS) were conducted. For the flexural strength test, a POF of diameter 1 mm was embedded in a wooden mold with different spacing. A wooden mold of size 500 mm x 100 mm x 100 mm was prepared. POF was inserted transversely within the beam so that maximum light can be passed. Three samples for each spacing were cast. The spacing of each sample is detailed in Table II.

TABLE II. POF SPACING IN TEST SAMPLES

C-sample	Sample 2	Sample 3	Sample 4	Sample 5
No POF	5 mm spacing	10 mm spacing	15 mm spacing	20 mm spacing

As the center-to-center distance between POF is small in the mold and there is a problem arising in obtaining good homogeneity and compaction of mixture due to less spacing in optical fibers, coarse aggregates of size not greater than 10mm are used. Figure 1(a) illustrates the formwork prepared utilizing drilled plywood and Figure 1(b) depicts the embedded POF in wooden sheet.

III. RESULTS AND DISCUSSION

A. Water Permeability

The water permeability test on transparent concrete with and without spacings was carried out using 150 mm cube specimens in a civil laboratory, following DIN 1048 Part 5 standards, as shown in Figure 2. The average maximum depth of water penetration from the three samples was taken as the test result. The result indicated that there is more water penetration in the 5 mm POF spacing due to less compaction and a weaker interfacial zone between POF and concrete. This is attributed to the increased surface area of POF in concrete. The test results are presented in Figures 3 and 4.

(a)

(b)

Fig. 1. (a) Formwork using drilled plywood, (b) embedded POF in wood mold.

Fig. 2. Concrete permeability test assembly.

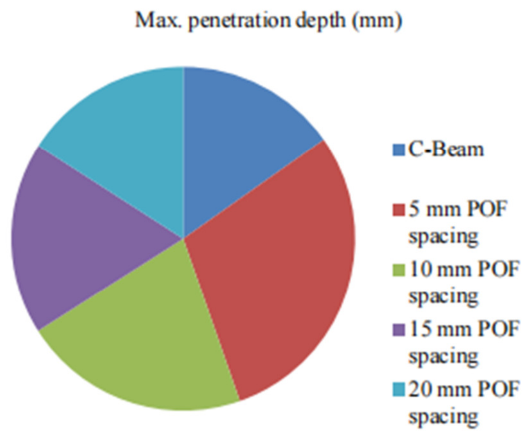

Fig. 3. Concrete permeability depth of each sample.

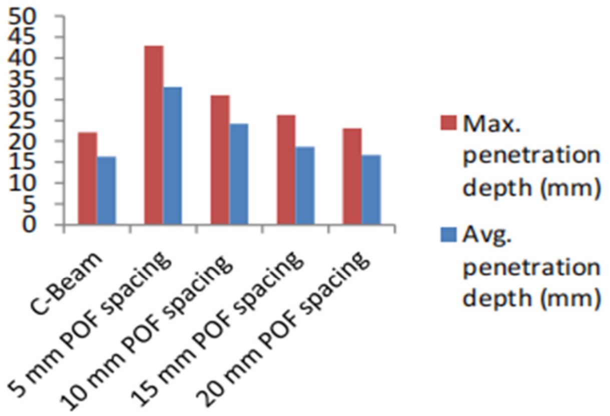

Fig. 4. Comparative study of average and maximum permeability depth of water in different concrete sample.

B. Rapid Chlorine Penetration Test

The RCPT test was performed as per ASTM C 1202-2019 standard. The molds were cylindrical with a diameter of 10 cm and a depth of 5 cm. The test cell was assembled with a 0.3 N NaOH solution on the anode side (+) and a 3% NaCl solution on the cathode side (-). The set up was then subjected to a 60-volt potential for 6 hours. The displayed reading was recorded at 30-minute intervals, and the total charge (C) passed through each sample was calculated and compared. The findings presented in Figure 5 demonstrated that 0.5 mm and 10 mm POF spacing are more vulnerable to chloride penetration because the charge passed through samples appeared to be more than 4000 C.

C. Ultrasonic Pulse Velocity

The UPV of concrete cubes (15 x 15 x 15 cm) in this research was measured according to ASTM C597, as shown in Figure 6, for time intervals of 7, 21, and 28 days. The procedure contains the measurement of time or velocity required for an ultrasonic pulse to travel through a concrete length. The UPV of all mixes remained approximately steady, despite the increase in POF's volume fraction. Figure 7 and Table III present the results, revealing that after 14 days of curing, all samples exceeded 4 km/s, indicating that the concrete exhibits excellent quality.

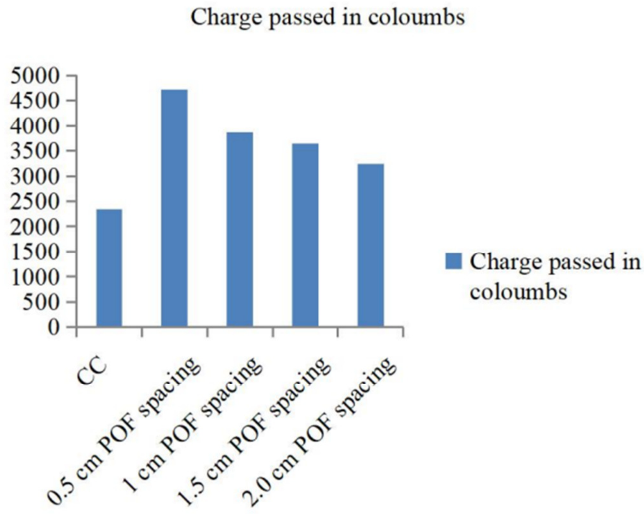

Fig. 5. Concrete permeability test assembly.

D. Scanning Electron Microscopy Study of Plastic Optical Fiber and Transparent Concrete

The SEM analysis was operated to investigate the morphology of both POF and transparent concrete matrix. The SEM images of POF, illustrated in Figures 8 and 9, revealed a transparent buffer coating with visible scratches on its surface. The fiber structure consists of an innermost core, surrounded by a cladding layer that enhances light transmission efficiency. Similarly, the SEM test of concrete, depicted in Figures 10 and 11, showed that a variety of pore exist on the interface between the POF and concrete matrix.

Fig. 6. Ultrasonic test assembly.

TABLE III. UPV OF CONCRETE CUBE.

POF spacing	7-D velocity (km/sec)	21-D velocity (km/sec)	28-D velocity (km/sec)
C- Sample	41.85	42.25	42.53
0.5 mm	36.2	36.4	36.8
1 mm	37.45	37.87	38.25
1.5 mm	38.6	39.2	39.4
2 mm	36.23	36.91	37.31

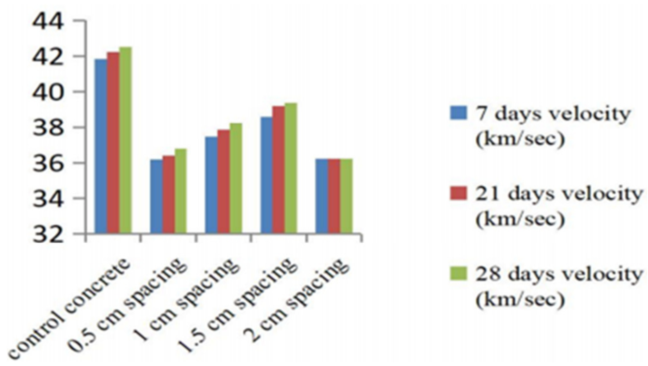

Fig. 7. UPV of different samples.

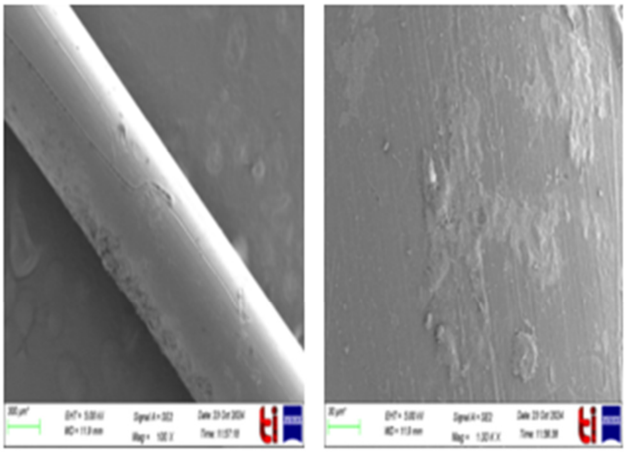

Fig. 8. SEM image of POF exhibiting smooth surface.

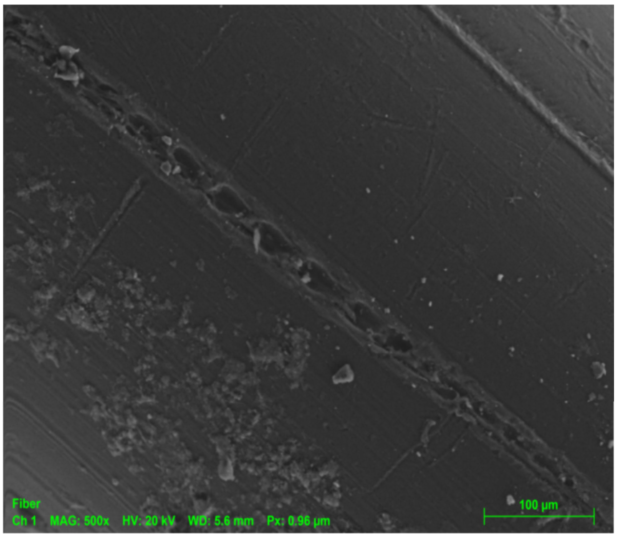

Fig. 9. SEM image of buffer coating of POF.

E. Novelty and Contribution

Conventional construction of roads, buildings, and other applications are often non-sustainable. It is obvious that transparent concrete is a great alternative in saving electricity and money, while it is stronger than glass and possesses almost the same characteristic strength as normal concrete. Despite its high cost, its high performance properties and high utility rate make it a potential material. Additionally, green buildings could get an easy accreditation under daylight saving initiatives with the use of transparent concrete.

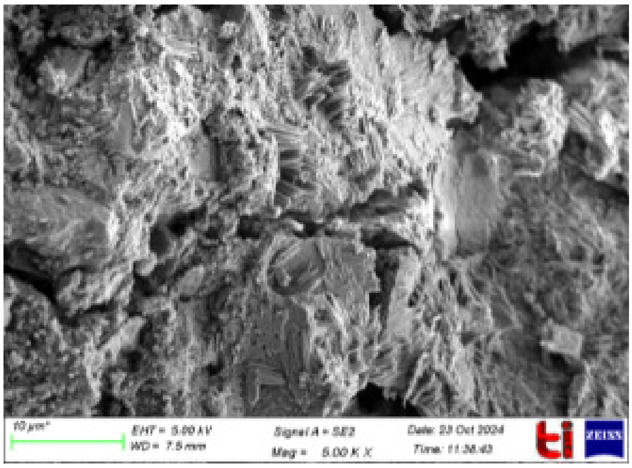

Fig. 10. Microspores in concrete showing rough surface in SEM image.

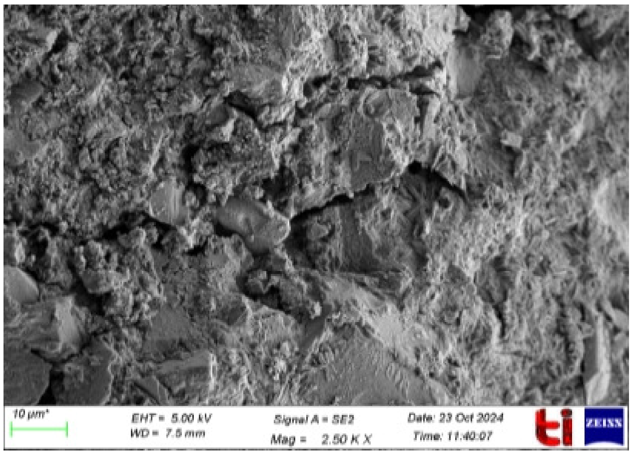

Fig. 11. SEM image of concrete showing pores in the fiber matrix interface.

IV. CONCLUSION

Conventional construction materials, such as virgin aggregates and high carbon footprint cements contribute to pollution and global warming. Thus, it is crucial to develop alternative materials that are eco-friendly and of high performance. This study examined the possibility of using Plastic Optical Fiber (POF)-based transparent concrete in pavements, with different spacings (0, 5, 10, 15, 20 mm) and evaluating its durability. Different methods were used including water permeability, Ultrasonic Pulse Velocity (UPV), Rapid Chlorine Penetration Test (RCPT), Scanning Electron Microscopy (SEM), and Energy Dispersive Spectroscopy (EDS). The results revealed that more voids are created as the spacing of POF in concrete decreases. The 5 mm and 10 mm POF spacing exhibited more water permeability because concrete is less compacted at the boundary between POF and concrete. The RCPT tests confirmed that the samples with smaller POF spacing showed higher chloride attacks.

Additionally, the UPV results indicated that the compaction of transparent concrete increases with age due to the formation of CSH gel, which increases with curing time period. Hence, overall compressive strength and durability increases with time. The microstructure analysis of POF and concrete revealed infinitesimal pores in the fiber-matrix interface. The highly smoothened surface of POF caused weak bonding between concrete and POF, further leading to crack propagation. Among the different material types, 1.5 mm diameter POF was the optimal for both strength and durability in transparent concrete applications.

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