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Sustainable Pavement Concrete Utilizing Waste Plastic and Quarry Dust: Strength and Permeability Evaluation

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Abstract:
Due to the increased need for environmentally friendly building materials brought on by rapid urbanization, porous concrete which is renowned for its capacity to control rainwater and infiltrate water was developed. The purpose of this study was to improve conventional porous concrete, which frequently lacks mechanical strength, by adding quarry dust and waste plastic. After testing a number of combinations, mix PC2 (4% waste plastic and 10% quarry dust) performed better than the others. Along with better split tensile (2.12 MPa) and flexural (2.88 MPa) strengths, it attained a compressive strength of 18.6 MPa, a 14.8% increase above traditional porous concrete. Additionally, the adjusted mix showed adequate permeability (8.2 mm/s), strong abrasion resistance, and effective drainage, making it appropriate for a range of sustainable applications. By using recycled resources, this method not only enhances the performance of concrete but also encourages environmentally friendly building.

1. Introduction

For socioeconomic growth, pavements are essential parts of the transportation infrastructure. They offer smooth, long-lasting surfaces and enable effective load transfer. However, because they are dense and impermeable, traditional pavements worsen environmental problems including surface runoff and urban flooding, especially in places that are quickly urbanizing. Demand for environmentally friendly paving materials that strike a balance between structural integrity and sustainability has surged as a result [1-4].

Because of its great permeability, porous concrete has become a viable environmentally acceptable substitute. The load-bearing capacity of porous concrete, in contrast to standard concrete, which depends on a compact structure for strength, is primarily derived from the interaction between coarse aggregates, creating interconnecting spaces that let water drainage. Usually between 15% and 30%, this empty content helps recharge groundwater and reduces urban flooding [6,12].

(a) Urban Flooding (b) Surface Runoff (c) Heat Island Effect

Figure 1 Pavement challenges in urban settings

Conventional concrete and porous concrete have quite different structural characteristics. Porous concrete relies on stone-to-stone contact and has lower compressive strengths (5 MPa to 20 MPa), making it appropriate for uses like parking lots and pedestrian pathways, whereas the latter is strengthened by a dense cement paste matrix [14-17].

Figure 2 Pervious concrete

Another important advantage of porous concrete pavements is their hydraulic efficiency, which makes rainwater management easier [18]. By allowing water to seep into the underlying soil, the permeable surface greatly lowers runoff and improves water quality by removing impurities. Because of this, porous concrete is perfect for a number of uses, such as bike lanes, walkways, and urban drainage systems, all of which promote user safety and environmental preservation [19-21].

Due to the substantial use of natural resources and the production of building waste, typical pavement construction still faces sustainability issues. Recycling and sustainability are encouraged by methods that add waste materials to concrete, such as shredded plastic and quarry dust. Although plastic garbage helps lessen its influence on the environment, it must be balanced to prevent impairing performance. In a similar vein, adding quarry dust to porous concrete increases its durability and strength without significantly altering its permeability [22,27].

Notwithstanding its benefits, porous concrete has drawbacks that may affect its long-term durability, including reduced strength, clogging susceptibility, and constrained design requirements. For it to be widely used in pavement applications, these problems must be resolved by material optimization and thorough testing, especially in particular contexts like India where the combined usage of plastic and quarry dust is still understudied. All things considered, encouraging developments in porous concrete technology is crucial to creating efficient and long-lasting paving solutions [28-30].

The work of Tennis et al. (2004), who emphasized the drainage capacity and significance of porous concrete in stormwater management, has greatly improved the field of porous concrete research. They observed that porous concrete had compressive strengths between 5 and 20 MPa and permeability levels sufficient for rapid water infiltration. Nevertheless, it was found that the lack of fines considerably decreased strength, restricting its use to low-load pavements [15].

Neville (2011) went into greater detail about the variables that affect the strength of porous concrete, highlighting the significance of aggregate interlock and paste thickness over paste volume. The requirement for ideal mix proportions is highlighted by the fact that although too much paste might decrease permeability, too little paste can cause raveling [11].

According to research by Yang and Jiang (2003), aggregate size also has a significant impact on performance. They discovered that whereas single-sized coarse aggregates improve permeability, their larger voids reduce strength. Smaller aggregates, on the other hand, typically increase strength but decrease permeability, indicating the need for careful balancing [16]. According to Chandrappa and Biligiri's (2016) analysis of the pore structure, drainage effectiveness depends on pore continuity and tortuosity, and interconnected porosity is essential for permeability [20].

The eco-friendly benefits of using waste materials into porous concrete are gaining popularity. According to research by Saikia and de Brito (2012), adding plastic aggregates improves ductility and impact resistance while generally lowering density and compressive strength, making them appropriate for non-structural applications [13]. Ismail and Al-Hashmi (2008) demonstrated that while higher replacements have a detrimental impact on compressive strength due to poor adhesion, lower levels of plastic replacement produce sufficient strength with environmental benefits [8].

Other research looked at quarry dust as an alternative to fine aggregates; Ilangovana et al. (2008) found that the angular roughness of the dust improved particle packing and bonding, which increased compressive strength. Though little study has been done on its application in porous concrete, some experts contend that tiny amounts can improve paste cohesion and reduce raveling without having a major effect on permeability [7].

There are still few studies on the combined use of waste materials in porous concrete, most of which concentrate on single-material solutions. The strength-permeability conundrum may be solved by the combination of waste plastic, which encourages sustainability, and quarry dust, which increases strength. However, thorough experimental data in this area, especially under pavement conditions, are absent. Last but not least, appeals for additional empirical research to create thorough models for waste-based porous concrete have been spurred by the documented negative association between permeability and compressive strength.

For sustainable pavement solutions, the project intends to assess the performance of porous concrete that incorporates waste plastic and quarry dust. The specific objectives include: creating mixtures with partial substitutions of quarry dust and waste plastic; examining the effects of waste plastic addition on the mechanical and permeability properties; analyzing the impact of quarry dust on matrix densification and strength; determining the optimal substitution percentages for balanced strength and permeability; assessing compressive strength under various curing times; exploring split tensile strength and crack resistance; evaluating flexural strength under bending loads; testing resistance to surface wear from vehicular traffic; measuring permeability for groundwater recharge and rainwater infiltration; scrutinizing long-term drainage performance and clogging resistance; determining porosity and water absorption characteristics; comparing modified and traditional porous concrete; investigating relationships among strength, permeability, and porosity; promoting the sustainable use of materials; mitigating environmental pollution from waste disposal; and developing eco-friendly porous concrete for sustainable urban infrastructure.

2. Materials & Methods

2.1 Materials

This chapter describes the extensive materials and experimental approach used to evaluate porous concrete's performance for pavement applications, with a focus on waste plastic and quarry dust. The goal was to assess how these waste elements affected the mechanical and hydraulic characteristics of porous concrete. To guarantee accuracy and repeatability of results, all materials were chosen, processed, and tested in compliance with Indian Standards.

In accordance with IS 12269:2013 requirements, Ordinary Portland Cement (OPC) 53 grade was utilized. Because of its early strength, it was selected for porous concrete pavements with low paste content. As shown in the accompanying tabulated data, essential physical properties were examined. Based on IS 383:2016, crushed angular coarse aggregates with diameters ranging from 10 to 20 mm were chosen. To make sure the aggregates were pure and free of impurities, characteristics including specific gravity and water absorption were evaluated.

Coarse aggregate was partially substituted with discarded polyethylene-based plastic from bags and packaging. It was found to be lightweight and hydrophobic, improving environmental sustainability, after being thoroughly cleaned and shredded into 4–10 mm particles. A 4.75 mm sieve was used to filter the quarry dust, which came from stone crushing machines and used as a filler in the porous concrete. While controlled levels avoided obstructing pore connection, its presence was intended to enhance paste-aggregate bonding. Concrete was mixed and cured using potable water that complied with IS 456:2000 criteria, guaranteeing the absence of hazardous materials that could impede hydration.

Table 1 Properties of Materials Used

S.No	Material	Property	Value
1	**Cement**	Type	OPC 53 Grade
		Specific Gravity	3.15
		Standard Consistency	31%
		Initial Setting Time	35 min
		Final Setting Time	580 min
		Fineness	5%
2	**Coarse Aggregate**	Aggregate Size	10–20 mm
		Specific Gravity	2.72
		Water Absorption	1.2%
		Aggregate Crushing Value	18%
		Impact Value	16%
		Shape	Angular

3	**Waste Plastic**	Type	Recycled Plastic Waste
		Specific Gravity	0.92
		Water Absorption	Negligible
		Shape	Irregular/Crushed
		Size Range	5–10 mm
4	**Quarry Dust**	Color	Grey
		Specific Gravity	2.60
		Fineness Modulus	2.85
		Water Absorption	1.5%
		Particle Size	Fine Powder
5	**Water**	Type	Potable Water
		pH Value	6.5–7.5
		Requirement	Clean and Impurity Free

To improve workability without raising the water-to-cement ratio and help preserve the porous structure, a superplasticizer based on polycarboxylate ether was used.

2.2 Proportioning Mix

Trial mixes varied the amounts of plastic waste and quarry dust substitutes while maintaining the same cement content and water-to-cement ratio. Maintaining sufficient permeability and mechanical strength for pavement applications was the aim. A baseline for comparison analysis was created by a control mix that contained no waste items.

Table 2 Mix Proportion Details

Mix ID	Waste Plastic (% by vol. of CA)	Quarry Dust (% by wt. of cement)	Water-Cement Ratio
PC0	0	0	0.30
PC1	2	5	0.30
PC2	4	10	0.30
PC3	6	15	0.30
PC4	8	10	0.30

2.3 Testing and Preparation of Specimens

To guarantee even material distribution, controlled mixing methods were used in a lab to prepare concrete specimens. Compressive strength, split tensile strength, flexural strength, abrasion resistance, permeability, clogging resistance, and water absorption evaluations were among the tests carried out in accordance with established standards.

Specimens were covered to conserve moisture after casting, and the curing process was observed for seven, fourteen, and twenty-eight days. Low slump readings, which reflect the particle content of porous concrete, were suggestive of its workability. Preventing segregation during placement was the main emphasis of evaluations.

Table 3 Quantity of Materials per Cubic Meter of Concrete

Material	**Quantity**
Cement	350 kg
Coarse Aggregate	1200 kg
Waste Plastic	As per mix
Quarry Dust	As per mix
Water	105 liters
Superplasticizer	0.8–1.0% of cement

Table 4 Details of Test Specimens

S.No	Test Conducted	Specimen Type & Size	Standard Followed
1	Compressive Strength Test	Cube (150 × 150 × 150 mm)	IS 516
2	Split Tensile Strength Test	Cylinder (150 mm diameter × 300 mm height)	IS 5816
3	Flexural Strength Test	Beam (100 × 100 × 700 mm)	IS 516
4	Abrasion Resistance Test	Cube/Disc Specimen	ASTM C944
5	Permeability Test	Cylinder (100 mm × 200 mm)	ACI 522R
6	Clogging Resistance Test	Pavement Slab Specimen	ASTM C1701
7	Water Absorption & Porosity Test	Cube Specimen	ASTM C642

The study focused on different ratios of waste plastic and quarry dust could maximize the durability and mechanical strength of porous concrete. In the end, the experiments offered advise on the optimal mix proportions for sustainable pavement applications utilizing these waste materials by providing important insights into performance under real-world settings.

Figure 3 Casting of specimens

Following the recommendations outlined in IS 1199 and related standards, a variety of inspections of both fresh and hardened porous concrete are described in depth in this section. Workability, mechanical strength, durability, permeability, and overall performance of porous concrete mixtures incorporating waste plastic and quarry dust were the objectives of the evaluations.

2.4 Fresh Concrete Examination

The workability of the porous concrete, which usually shows very little droop because of its low particle content, was assessed using the slump test and visual inspections. In order to guarantee efficient placement without segregation, this evaluation was essential.

2.5 Hardened Concrete Tests

Several tests were carried out after curing to ascertain how porous concrete reacted to actual loads and environmental circumstances. The following crucial tests were carried out:

2.5.1 The Compressive Strength Test

The test assessed the concrete's resistance to axial loads using cubic specimens (150 mm). Specimens were evaluated in compliance with IS 516 after seven, fourteen, and twenty-eight days of curing; the average strength was determined from three samples to evaluate the impact of waste plastic and quarry dust.

Figure 4 Compressive strength testing

2.5.2 Split tensile test

This test assessed the tensile characteristics and crack resistance of porous concrete using cylindrical specimens of 150 mm by 300 mm. In accordance with IS 5816 guidelines, the load was applied diametrically until a vertical split occurred.

Figure 5 Split tensile specimen testing

2.5.3 Flexural Strength Test

After curing for 28 days, beam specimens (100 mm x 100 mm x 700 mm) were tested under two-point loading to determine bending resistance owing to wheel loads. The flexural strength was computed using the modulus of rupture.

Figure 6 Flexural strength test

2.5.4 The Abrasion Resistance Test

This test assessed how well porous concrete resists wear from vehicle movement to ensure durability. The percentage of weight loss following abrasion cycles, measured in accordance with ASTM C944, demonstrated the material's resistance to wear.

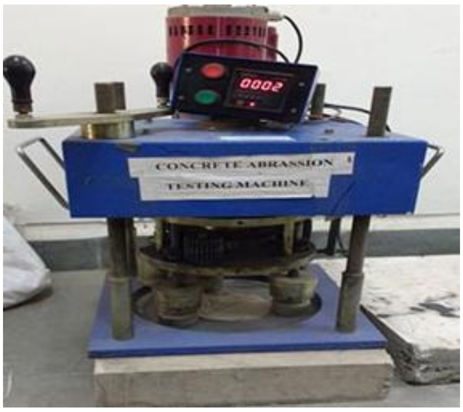

Figure 7 Abrasion testing

2.5.5 The Permeability Test

Using constant head permeability equipment in accordance with ACI 522R rules, this test evaluated water infiltration capacity, a crucial functional feature that demonstrated the efficacy of stormwater management.

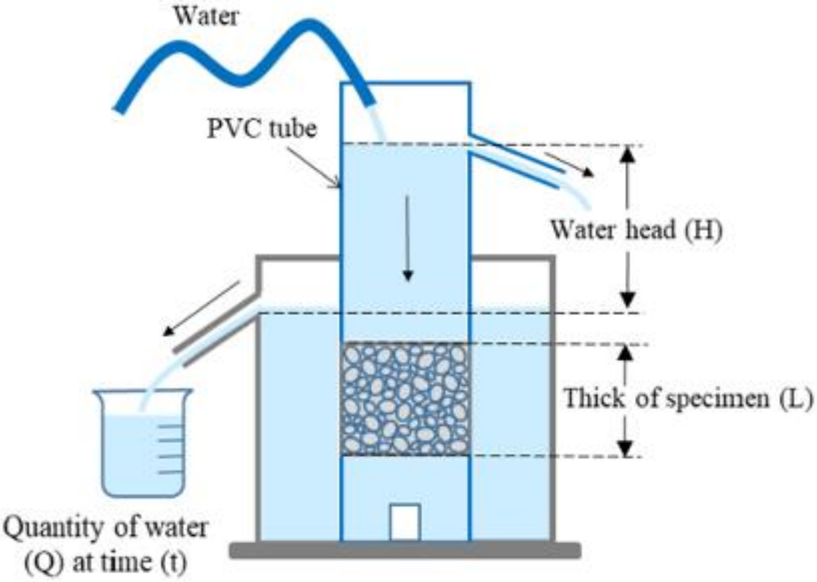

Figure 8 Permeability test procedure.

2.5.6 Clogging Resistance

This test simulated clogged situations with fine particles to assess the long-term drainage effectiveness of porous concrete under realistic circumstances. After a blockage, the reduction in drainage efficiency was measured.

2.5.7 The test for porosity and water absorption

Tests were conducted to identify the void structure in the concrete using ASTM C642 techniques. In order to calculate water absorption and porosity, dry weights were taken both before and after the specimens were submerged in water. This experiment demonstrated the connection between mechanical strength, permeability, and porosity.

Figure 9 Porosity and Water Absorption Test

By combining mechanical strength and permeability to satisfy environmental requirements, these exacting experimental techniques sought to identify the ideal mix proportion for sustainable pavement applications. Overall, the performance assessments shed light on the crucial traits and real-world uses of porous concrete, guaranteeing its efficient implementation in paving and associated infrastructure.

3. Results & Discussion

The experimental results on porous concrete mixes containing waste plastic and quarry dust are presented in this chapter, along with an assessment of their mechanical and permeability properties for pavement applications. After 28 days, compressive strength testing showed that the control mix (PC0) had a strength of 16.2 MPa. This strength increased with the addition of waste materials, reaching a peak of 18.6 MPa in mix PC2 (4% waste plastic and 10% quarry dust), indicating a 14.8% increase because of improved hydration and bond strength. Strength in mixes PC3 and PC4 was adversely influenced by excessively high quantities of waste plastic.

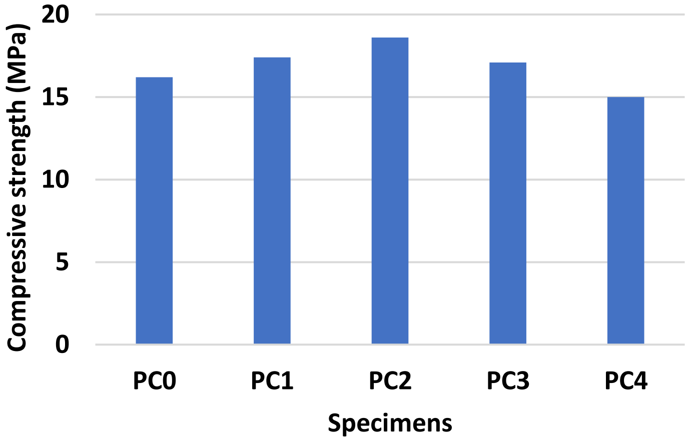

Figure 10 Compressive strength test results

Due to better bonding made possible by quarry dust, the optimized mix PC2 demonstrated a split tensile strength of 2.12 MPa, which is 14.6% higher than the control. However, in higher combinations like PC4, too much plastic resulted in poor bonding and decreased tensile strength.

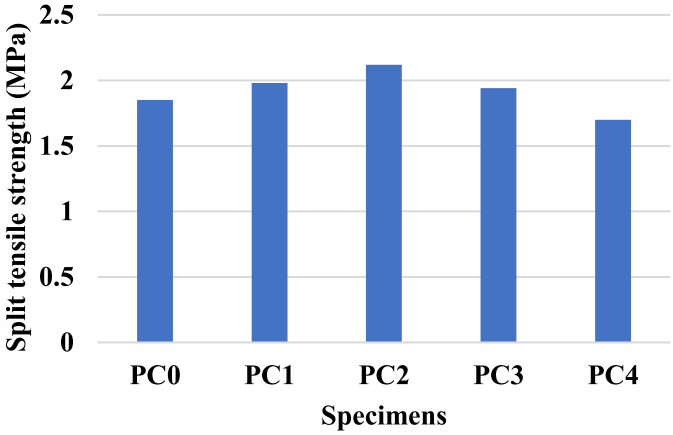

Figure 11 Split tensile test results

According to studies on abrasion resistance, mix PC2 had an abrasion loss of 6.8%, which was enhanced by quarry dust, while mix PC4 did poorly at 9.1% abrasion loss because of its high plastic content.

Table 5 Abrasion properties of samples

Mix ID	Abrasion Loss (%)	Surface Durability Rating
PC0	8.2	Moderate
PC1	7.5	Good
PC2	6.8	Excellent
PC3	7.9	Good
PC4	9.1	Poor

All mixes satisfied drainage criteria, according to permeability testing, with mix PC4 having the maximum permeability at 9.6 mm/s. Although it increases permeability, excessive usage of waste plastic may compromise strength.

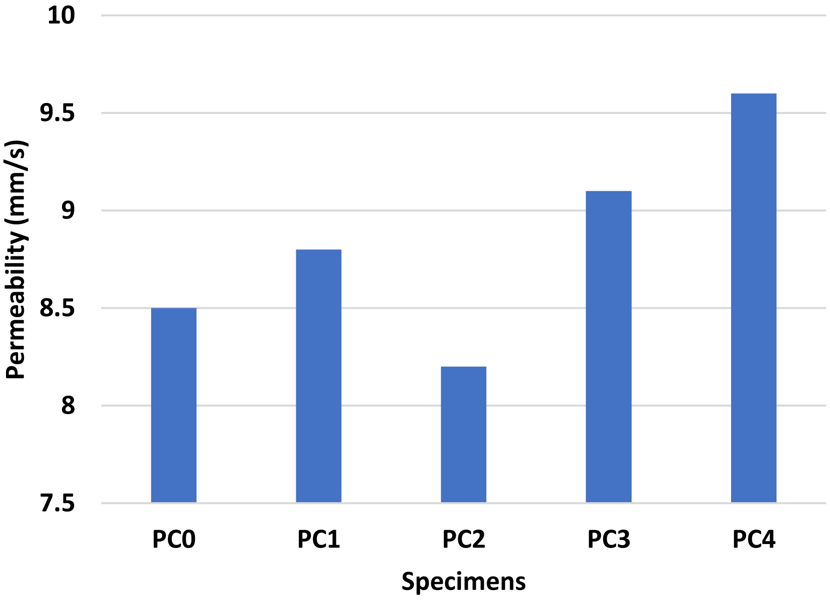

Figure 12 Permeability results

PC4 was most prone to clogging, while mix PC2 retained better infiltration capability, according to clogging resistance measurements. Increased plastic content improved both water absorption and porosity, according to tests, but it might have a detrimental effect on compressive strength.

Table 6 Clogging Resistance of porous concrete slab

Mix ID	Initial Infiltration Rate (mm/s)	Final Infiltration Rate After Clogging (mm/s)	Reduction (%)
PC0	8.5	6.9	18
PC1	8.8	7.4	16
PC2	8.2	7.1	14
PC3	9.1	7.4	19
PC4	9.6	7.4	23

Table 7 Water absorption & porosity outcomes

Mix ID	Water Absorption (%)	Porosity (%)
PC0	5.8	18.5
PC1	6.1	19.2
PC2	6.4	20.1
PC3	6.9	21.4
PC4	7.5	22.8

Finally, mix PC2's flexural strength increased by 17.5% to 2.88 MPa, demonstrating the advantages of carefully mixing additives for peak performance. Overall, the study emphasizes how crucial it is to control waste material inclusion levels in order to improve the longevity and effectiveness of porous concrete pavements.

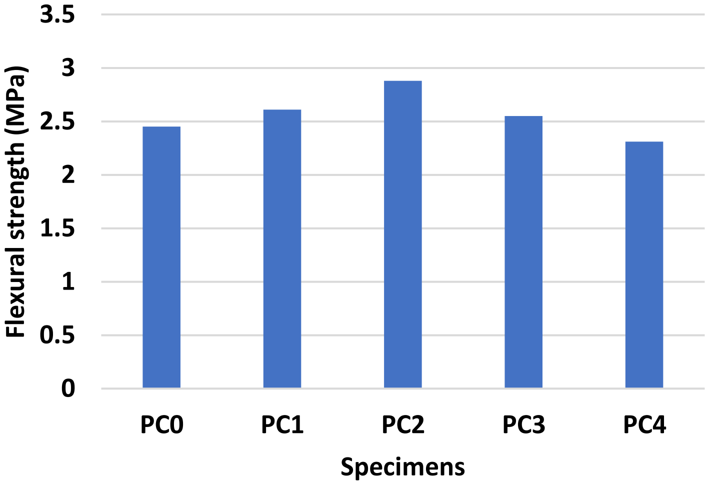

Figure 13 Flexural strength results

4. Conclusions

Regarding its potential for sustainable pavement applications, the experimental study on porous concrete incorporating waste plastic and quarry dust reveals numerous important discoveries. Incorporating waste plastic and quarry dust results in a material that maintains structural performance while supporting proper drainage. In particular, the study emphasizes that:

1. Because quarry dust is a fine filler, it improves the matrix's compactness, the link between the aggregate and paste, and the particles packing qualities.
2. Waste plastic helps the porous concrete become more ductile, resistant to cracks, and capable of redistributing stress.
3. With a maximum compressive strength of 18.6 MPa, which is roughly 14.8% higher than conventional porous concrete mixes, the optimized mix designated PC2 which is composed of 10% quarry dust and 4% waste plastic—performed better than the other combinations tested.
4. The split tensile strength increased significantly as a result of improved interfacial bonding and higher matrix cohesion, reaching a performance of 2.12 MPa, indicating improved tensile performance and fracture resistance under repeated load circumstances.

5. The optimized mix's flexural strength also improved significantly, reaching a maximum measured strength of 2.88 MPa, or a 17.5% improvement over the control mix.
6. The investigation discovered that the adjusted concrete's abrasion resistance greatly increased, improving the pavement's durability. The mix showed only 6.8% abrasion loss. This demonstrates improved serviceability and lower maintenance requirements.
7. Due to a larger waste plastic content that resulted in better-connected void structures within the matrix, all porous concrete mixes showed sufficient permeability for rainwater infiltration and drainage.
8. An important discovery was that the improved mix successfully optimized the trade-off between strength and permeability. Consistent void distribution and excellent long-term infiltration performance were maintained by the improved porous concrete.
9. Because too much waste plastic can negatively impact bonding qualities and cause instability in pore structure, a controlled approach to porosity was shown to be crucial for achieving a balance between mechanical strength and hydraulic performance.
10. The study backs up the idea that the best replacement ratios are required to provide long-lasting and structurally sound pavements, which can reduce stormwater runoff, enhance groundwater recharge, and lessen urban flooding.
11. By lowering landfill trash and preserving natural aggregates, the use of leftover plastic and quarry dust also contributes to the advancement of sustainable building techniques.

Lastly, a number of uses, including parking spaces, bike lanes, low-traffic roads, drainage systems, landscaping, and sustainable urban development, are thought to benefit from the suggested porous concrete. The results show that waste-based porous concrete has a bright future in producing environmentally friendly pavements with improved functional and environmental advantages.

5. Future recommendations

Even though the results of the current study on waste-modified porous concrete are encouraging, more investigation is necessary to fully realize its potential. Important suggestions for additional research include:

- Evaluate long-term performance under challenging circumstances, such as clogging, chemical attacks, freeze-thaw effects, and wet-dry cycles.
- To assess performance under real traffic and environmental exposure, build trial pavement sections using the optimal mix.
- Investigate mechanical or chemical treatments to improve strength by strengthening the bond between plastic particles and cement paste.
- Since pavement slabs are primarily subject to flexural pressures, examine flexural strength and fatigue behavior.
- To ensure long-term maintenance, research clogging mechanisms and cleaning techniques.

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