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Advanced Reclaimed Asphalt Pavement Treatment for Sustainable Pervious Concrete: Optimizing Strength, Hydraulic Performance and Long-Term Durability

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Abstract

The increasing depletion of natural aggregates and escalating construction waste necessitate the implementation of environmentally friendly substitutes in concrete production. This study explores the incorporation of treated Reclaimed Asphalt Pavement (RAP) as an eco-efficient alternative to traditional coarse aggregates in pervious concrete (PC) matrices by evaluating its structural integrity, permeability, durability, and microstructural characteristics. A comprehensive multi-stage treatment process involving solar heating, natural oxidation, and mechanical roughening was employed to enhance aggregate bonding and bitumen reduction. The treatment of RAP was conducted for three treatment durations: 0-month, 12 months, and 24 months. Coarse aggregates were substituted with 0%, 25%, 50%, 75%, and 100% RAP by weight, and all mixtures were cured for 90 days. The investigation focused on evaluating essential functional characteristics, including density, porosity, hydraulic conductivity, compressive and flexural responses, as well as durability under abrasion and chemical exposure to sulphate and chloride environments. Microstructural analysis utilizing Energy Dispersive X-ray Analysis (EDAX) demonstrated a substantial reduction in bitumen content, as evidenced by a declining carbon peak with increased treatment duration. Additionally, Scanning Electron Microscopy (SEM) micrographs revealed fewer voids, increased C-S-H formation, and improved bonding, with minor Interfacial Transition Zone (ITZ) variations across 12-month and 24-month treatments. The findings highlight that extended RAP treatment significantly improves density, reduces porosity, enhances compressive and flexural strength, and lowers permeability. Furthermore, 24-month treated RAP demonstrated superior durability, exhibiting enhanced abrasion and chemical resistance due to improved aggregate cohesion and matrix integration. This study establishes that pervious concrete with more than 50% RAP content, previously considered unviable, is structurally feasible when suitable treatment and gradation techniques are used, thereby advancing sustainable construction materials.

Keywords: Reclaimed Asphalt Pavement (RAP); Pervious Concrete; Compressive Strength; Flexural Strength; Permeability; Durability; Microstructural Analysis.

1. Introduction

The evolution of pavement construction has increasingly focused on mitigating environmental impacts, particularly those associated with conventional flexible pavements. Asphalt pavements, being widely used, have significantly altered hydrological patterns and thermal environments, contributing to urban heat island (UHI) effects and increased stormwater runoff [1]. In addition, asphalt-based flexible pavements are highly susceptible to degradation due to oxidation, aging, and environmental stressors, leading to reduced service life and frequent costly maintenance [2, 3]. Such maintenance requirements often disrupt transportation networks, compromising

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infrastructure sustainability. In response to these challenges, the Ministry of Road Transport and Highways (MORTH) in India has actively promoted the adoption of cement concrete pavements owing to their superior load-bearing capacity, enhanced durability, and reduced maintenance requirements [4, 5]. This transition from flexible pavements to rigid pavement alternatives underscores the government's commitment to developing more sustainable infrastructure solutions. However, cement production presents significant environmental concerns due to substantial, carbon footprint, with emissions from cement production nearing a 1:1 ratio of CO_2 to product weight [6]. The extensive carbon footprint and high energy demands of cement and concrete production continue to pose critical challenges to environmental sustainability [7, 8].

Rapid urbanization further exacerbates these challenges, with paved surfaces occupying approximately 30–45% of urban landscapes [9, 10]. Heavy dependence on impervious pavements contributes to various environmental issues, including waterlogging, flooding, and water pollution resulting from inadequate stormwater management. Additionally, impervious surfaces obstruct natural infiltration processes, hinder evaporation, and disrupt local hydrological cycles. The absorption and gradual release of stored heat into the atmosphere by these surfaces significantly contribute to UHI effects, elevating urban temperatures, increasing cooling energy demand, and degrading air quality [11-13].

The growing awareness of these issues has prompted policymakers and municipalities to explore sustainable infrastructure solutions. Pervious concrete (PC) has emerged as a viable alternative, offering efficient stormwater management by allowing water to infiltrate through its porous structure, thereby reducing surface runoff and mitigating UHI effects. Furthermore, PC promotes groundwater recharge and enhances urban resilience against flooding and pollution. Employing open-graded pavement solutions in urban infrastructure demonstrates a broader commitment to fostering eco-friendly urban environments [14, 15]. PC is increasingly utilized for stormwater management applications, particularly in sidewalks, driveways, and parking lots. Its ability to rapidly absorb and redirect water prevents pooling and enhances safety for pedestrians, cyclists, and motorists. Its porous structure also contributes to its sustainability as an urban infrastructure material [16-19]. Typically, PC exhibits compressive strengths ranging from 2.8 MPa to 28 MPa and water permeability values between 0.135 and 1.21 cm/s (equivalent to 81–730 L/minute/m²) [20]. The pore diameters in PC range from 0.15 to 8 mm, facilitating efficient water infiltration. Its porosity generally ranges from 15% to 35%, significantly enhancing permeability and drainage capacity. The density of PC varies between 1820 kg/m³ and 2100 kg/m³, which is lower than traditional concrete due to its open-graded structure aimed at improving void content and drainage efficiency [13, 21-22].

Rising concerns over the depletion of natural aggregate sources have led regulatory bodies to impose stringent restrictions and quarrying bans aimed at minimizing ecological degradation. In response, the pursuit of environmentally responsible construction alternatives has intensified, particularly within cementitious material systems. Reclaimed Asphalt Pavement (RAP), sourced from milled and rehabilitated asphalt layers, is gaining recognition as a technically feasible and environmentally responsible replacement for virgin aggregates. Its utilization not only diverts asphalt waste from landfills but also conserves finite natural resources, thereby contributing to sustainable construction practices and improved material efficiency [3, 4, 23-28].

Despite its environmental and economic benefits, RAP usage in concrete presents several limitations. The aged bitumen coating that adheres to RAP particles hinders effective bonding with cementitious materials, particularly at the Interfacial Transition Zone (ITZ), resulting in compromised mechanical properties and reduced structural integrity [4, 26, 29]. Chen et al. [30] studied the effect of emulsifier-based surface treatment of RAP on the interfacial behavior and mechanical performance of concrete incorporating RAP aggregates. Their findings revealed that the emulsifier pretreatment significantly improved the bonding interaction between the aged asphalt surface and the surrounding cementitious matrix. Extensive research exists on RAP use in traditional concrete. However, studies examining treated RAP in pervious concrete contexts are notably scarce. Existing enhancement techniques—particularly chemical and mechanical processing—have shown potential to improve the interaction between RAP and cementitious binders. However, these strategies are often constrained by high implementation costs, environmental implications, and variable performance outcomes. Furthermore, the physico-chemical interplay between treated RAP and cement-based matrices in pervious concrete, especially regarding improvements in structural integrity, water permeability, and long-term durability, remains insufficiently investigated.

This study introduces an environmentally sustainable multi-stage treatment methodology for Reclaimed Asphalt Pavement (RAP), combining solar heating, natural oxidation, and Abrasion & Attrition Treatment (AB&AT). The proposed strategy offers a low-impact alternative to conventional RAP processing techniques, aiming to improve interfacial bonding between RAP particles and cementitious matrices. The research is expected to yield valuable insights into improving mechanical strength, hydraulic conductivity, and the long-term durability of pervious concrete. Furthermore, it advances sustainable construction efforts by promoting the use of treated RAP as a viable replacement for traditional coarse aggregates in open-graded concrete systems. The overall methodological framework is shown in Figure 1.

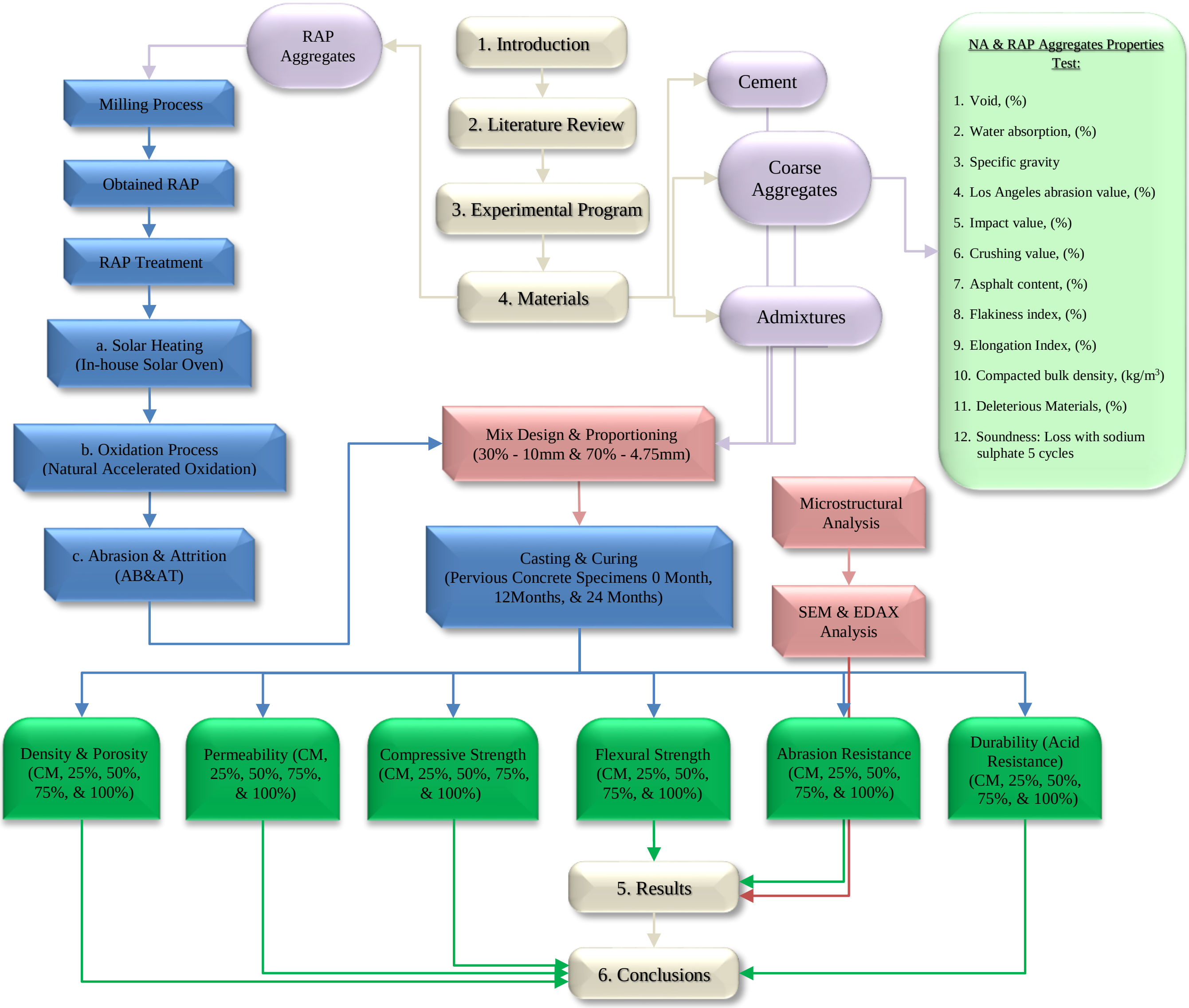


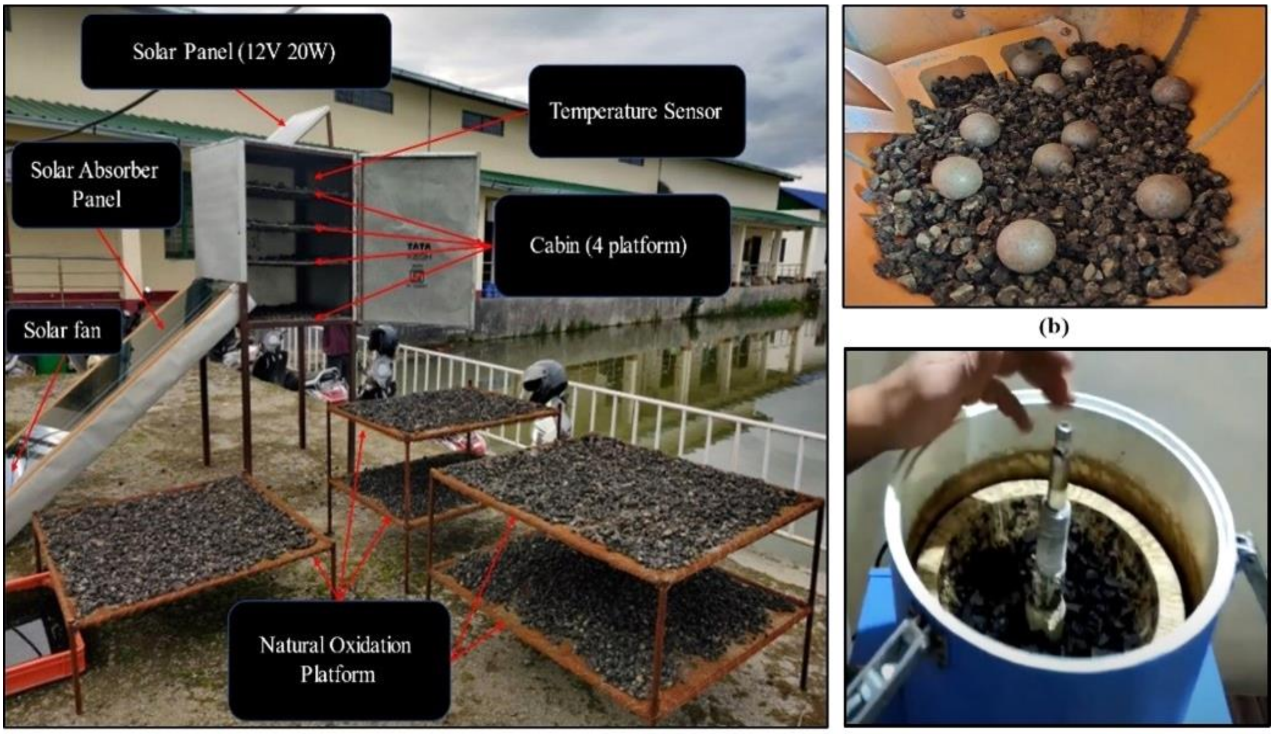
Figure 1. Process flow diagram of the methodology used in this research

2. Composition and Mix Proportioning

2.1. Methods For Treated RAP

The treatment process was designed to improve the interfacial compatibility between RAP particles and the cementitious binder by effectively reducing the residual bitumen coating, as well as dust and agglomerated particles. The proposed method involved several stages: RAP collection and preparation, solar heating, natural accelerated oxidation, and Abrasion & Attrition (AB&AT), applied over treatment durations of 0 months (0M), 12 months (12M), and 24 months (24M). The RAP utilized in this study was retrieved from a local pavement demolition site and manually processed to achieve the required gradation. The pulverized RAP was submerged in water for 24 hours to eliminate dust and contaminants, ensuring the cleanliness of the particles. After cleaning, the RAP aggregates were thoroughly dried before proceeding to the subsequent treatment processes. The first stage of solar heating was carried out using an in-house fabricated solar oven (Figure 2a) to thermally treat the RAP aggregates. The temperature within the solar oven was maintained between 40°C and 70°C, monitored using a temperature sensor. The RAP was evenly spread within the oven to achieve uniform heating. This process aimed to induce thermal softening of the stiff bitumen coating, enhancing its susceptibility to partial oxidation. Following the thermal treatment, the RAP aggregates were transferred to an open environment oxidation platform, where they were spread uniformly to undergo natural accelerated oxidation. This process promoted the gradual oxidation of the softened bitumen over time, enhancing its brittleness and making it easier to remove during the mechanical roughening stage. To maintain particle cleanliness, dust particles were periodically removed using a water jet. The natural oxidation process was essential for improving bitumen removal efficiency by enhancing the stiff bitumen and making it more brittle.

Mechanical surface treatment using Abrasion and Attrition (AB&AT) was employed as the final stage to refine the texture of RAP aggregates. During this process, the RAP aggregates were subjected to abrasion within a rotating drum containing abrasive charge, enhancing the abrasive action to remove loose bitumen particles effectively. This mechanical treatment facilitated the exposure of the underlying aggregate surface and improved its texture, promoting better adhesion with the cementitious matrix (Figure 2b). The 12-month process involved two treatment cycles, each consisting of thermal treatment followed by oxidation exposure, repeated every quarter. After each cycle, the RAP aggregates were mechanically treated to effectively remove the oxidized bitumen coating and improve surface characteristics. The 24-month process extended over eight quarters, completing four full cycles of alternating thermal and oxidation processes. After completing the treatment processes, the treated RAP was sieved to ensure it met the required gradation for incorporation into PC mixes and stored in a controlled environment until further testing and mixing. A comparison of RAP samples after 0, 12, and 24 months of treatment is shown in Figure 3.



(a) (c)

Figure 2. (a) The Solar oven for heating the RAP (b) Abrasion and Attrition (AB&AT) (c) Bitumen Extraction Test of RAP

(a) (b) (c)

Figure 3. RAP Samples after (a) 0, (b) 12, and (c) 24 Months of Treatment

The mineralogical characteristics of RAP critically influence its applicability as a replacement for natural aggregates, necessitating a detailed evaluation of elemental shifts across different treatment durations. Table 1 presents the X-ray Fluorescence (XRF) results for Natural Aggregate (NA) and RAP samples subjected to 0, 12, and 24 months of treatment. The analysis aimed to quantify chemical modifications associated with the progressive removal of bituminous residues, thereby enhancing aggregate purity and improving compatibility with pervious concrete systems.

Table 1. Chemical Composition of NA, 0M RAP, 12M RAP, and 24M RAP (XRF Analysis)

Name of Oxides	Oxides	Natural Aggregate (NA)	0 Month (Untreated RAP)	12 Months RAP	24 Months RAP
		Weight (%)			
Silicon Dioxide	SiO_2	74.2	62.7	69.7	73.0
Aluminum Oxide	Al_2O_3	12.0	15.8	13.1	12.8
Ferric Oxide	Fe_2O_3	5.20	5.92	6.07	5.57
Calcium Oxide (Lime)	CaO	2.86	7.19	1.72	0.475
Potassium Oxide	K_2O	2.15	2.18	2.18	1.96
Magnesium Oxide	MgO	1.50	2.63	1.89	1.87
Titanium Dioxide	TiO_2	1.05	0.984	0.956	0.888
Sulphate Trioxide	SO_3	0.214	1.85	3.44	2.69
Chlorine	Cl	0.0685	0.123	0.255	0.0749

The XRF analysis reveals pronounced chemical transformations in the RAP samples across different treatment durations, indicating successful bitumen removal and exposure of underlying aggregates. The progressive increase in Silicon Dioxide (SiO_2) content from 62.7% (0M) to 73.0% (24M) signifies effective stripping of bituminous layers, thereby enhancing aggregate purity. A substantial reduction in Calcium Oxide (CaO) content, from 7.19% at RAP treated for 0month (0M) to 0.475% for 24 months (24M) RAP, suggests the decomposition or oxidation of calcium-bearing compounds, likely present as residues from asphalt binder interactions. This transformation highlights the efficiency of the applied treatment process in breaking down these compounds and enhancing aggregate reactivity. Furthermore, a gradual decrease in Aluminum Oxide (Al_2O_3) and Ferric Oxide (Fe_2O_3) content supports the notion of enhanced aggregate purity, suggesting that the treatment process effectively eliminates impurities associated with the bituminous phase. The observed increase in Sulphate Trioxide (SO_3) content from 1.85% (0M) to 3.44% for RAP treated for 12 months (12M) followed by a decrease to 2.69% (24M) suggests that sulphate-containing compounds initially oxidize during treatment but gradually degrade or dissipate under extended exposure.

2.2. Aggregates

In this study, both RAP and natural aggregates (NA) were used with gradations of 12.5-10 mm and 6.3-4.75 mm. NA was sourced from a crushing unit in New Keithelmanbi, Imphal West, Manipur, whereas RAP was collected via full-depth reclamation using an uncontrolled milling method from the Imphal-Moreh National Highway (NH 102) construction site. The RAP aggregates were treated for 0, 12, and 24 months. The material characteristics of NA and RAP, measured in line with the IS 2386 standards [31-33], are shown in Table 2.

2.3. Cement

OPC of 43 grades, meeting the specifications of BIS-IS 8112:43 [34], was used in this study. The cement was evaluated for critical properties including fineness, setting times, consistency, and specific gravity, as per the relevant Indian standard codes [35-36]. The tests resulted in 3.10% fineness, 33% consistency, 3.13 specific gravity and 65 min and 280 min initial and final setting time respectively. X-ray Fluorescence (XRF) was employed to assess the cement's oxide composition. The results indicated that CaO (59.7%) was the predominant compound, followed by SiO_2 (20.0%), Al_2O_3(8.51%), SO_3(3.18%), Fe_2O_3(3.07%), and MgO (2.26%).

2.4. Mix Proportion

Figure 4 presents the gradation profiles for both natural aggregates and treated RAP. The control mix (CM) was prepared using a combined fraction ratio of 0.3:0.7, corresponding to aggregate sizes of 12.5–10 mm and 6.3–4.75 mm, respectively. Detailed gradation specifications for all mix variants are provided in Table 3. To achieve uniform compaction, fresh concrete was placed in two sequential lifts and consolidated using a standard 2.5 kg Proctor hammer with 25 blows per layer.

Table 2. Assessment of NA and RAP Aggregates Properties with testing standards

Aggregate Characteristic	NA		RAP 0 Month		RAP 12 Months		RAP 24 Months		Testing Standard
	10 mm	4.75 mm	10 mm	4.75 mm	10 mm	4.75 mm	10 mm	4.75 mm	
Void, (%)	36.41	33.72	38.43	34.24	36.73	31.67	36.05	29.35	ASTM C1688 [33]
Water absorption, (%)	0.96	0.81	1.69	0.8547	1.05	0.72	0.79	0.69	ASTM C127 [34]
Specific gravity	2.638	2.504	2.478	2.313	2.499	2.379	2.552	2.49	IS 2386-4 [30]
Los Angeles abrasion value, (%)	15.06	14.35	19.34	16.84	17.81	15.11	16.43	14.99	IS 2386 (Part 4) [30]
Impact value, (%)	17.754	-	12.07	-	10.678	-	8.85	-	IS 2386-4 [30]
Crushing value, (%)	14	15.6	18.21	17.3	17.89	16.24	17.15	16.11	IS 2386-4 [30]
Asphalt content, (%)	-	-	2.8	3.2	2.14	2.9	1.95	2.85	ASTM D2172 [35]
Flakiness index, %	8.245	-	10.65	-	11.72	-	10.996	-	IS:2386(Part I) [31]
Elongation index, %	15.5718	-	11.45	-	6.79	-	8.593	-	IS:2386(Part 1) [31]
Compacted bulk density, kg/m^3	1674.09	1581.16	1522.6	1563.97	1579.56	1574.63	1603.5	1580.6	IS:2386(Part 1) [31]
Deleterious Materials, %	0.85	0.98	1.01	1.14	0.65	0.82	0.45	0.5	IS:2386(Part III) [32]
Soundness: Loss with sodium sulphate 5 cycles	5.11	5.75	8.57	6.14	6.33	5.73	6.52	6.05	IS:2386(Part V) [36]

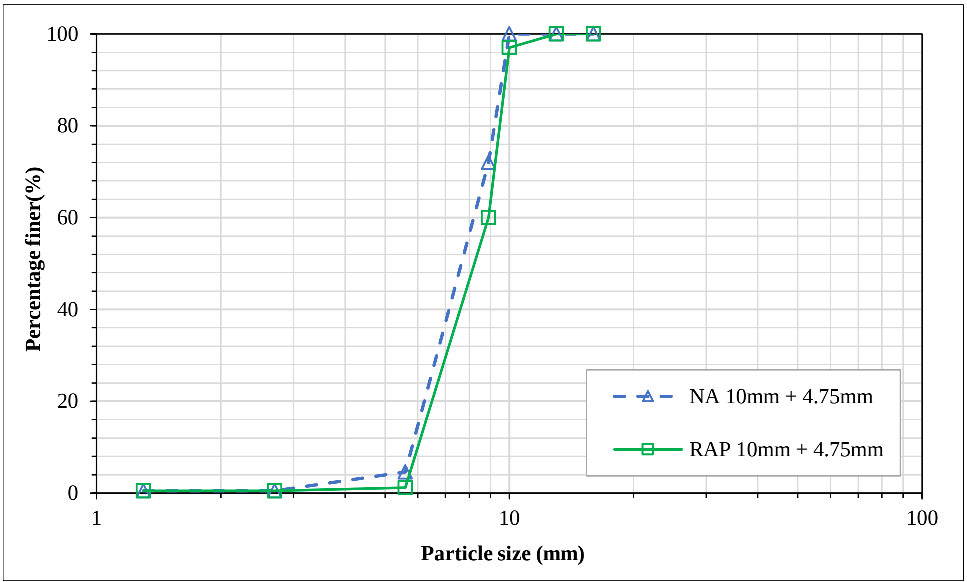


Figure 4. Grain sieve analysis of Natural Aggregate and RAP

Table 3. Proportion of the NA and RAP aggregates

Composition (%)	W/C ratio	C/A ratio	Superplasticizer (% by weight of cement)	NA Kg/m^3 10-12.5 mm	NA Kg/m^3 4.75-6.3 mm	RAP Kg/m^3 10-12.5 mm	RAP Kg/m^3 4.75-6.3 mm	Cement (kg/m^3)	Water (kg/m^3)
Control Mix	0.36	1:4	0.3	470.184	1097.10	0	0	391.82	137.137
25 RAP	0.36	1:4	0.3	386.14	772.28	154.456	231.684	386.14	135.149
50 RAP	0.36	1:4	0.3	227.346	530.474	227.346	530.474	378.91	132.6185
75 RAP	0.36	1:4	0.3	149.42	224.13	373.55	747.1	373.55	130.7425
100 RAP	0.36	1:4	0.3	0	0	441.12	1029.28	367.6	128.66

2.5. Test Methodology

Density and porosity were measured on 100 × 200 mm cylinders [37]. Compressive strength tests on 150 mm cubes with gypsum coating [38] was conducted following IS 516-1959 [39]. Flexural strength was tested on 100 × 100 × 500 mm beams using a 4-point bending apparatus [39]. Abrasion resistance was evaluated via the Los Angeles abrasion test

[40] recording Cantabro mass loss after 500 revolutions. Permeability testing adhered to ACI 522R-2010 [20], with the setup shown in Figure 5. Permeability was determined using Darcy's equation, as outlined in Equation 1.

$$K = \left(\frac{La}{tA}\right) Ln \left(\frac{h_1}{h_2}\right) \quad (1)$$

where, K denotes the permeability coefficient (cm/s); A and a represent the cross-sectional areas of the specimen and the standpipe, respectively in cm²; L is the specimen length (cm); and t refers to the elapsed time (s) for water to drop from height h_1 to h_2.

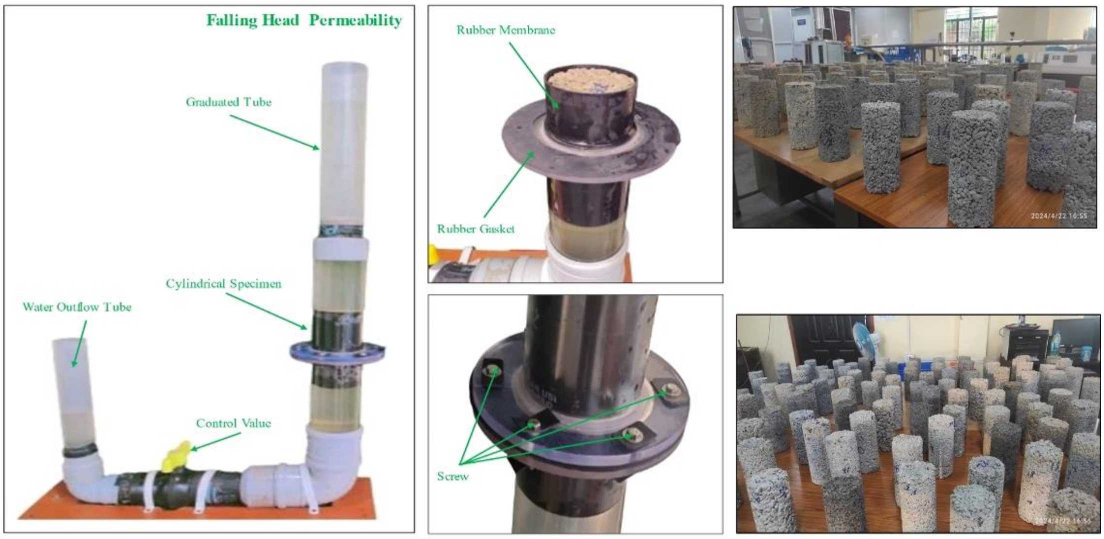


Figure 5. In-House Permeability Test Setup and samples

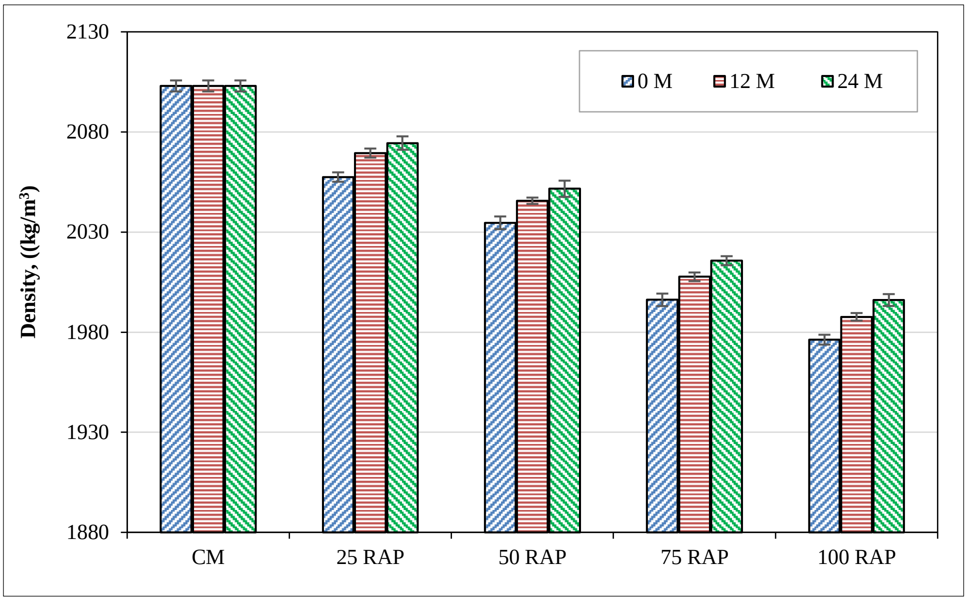
Acid resistance of PC was tested on 100 mm cubes [41] immersed in 2% HCl and H_2SO_4 for 60 days, with solutions refreshed every 15 days. Mass loss and loss in strength were measured after exposure [39].

3. Experimental Results and Interpretations

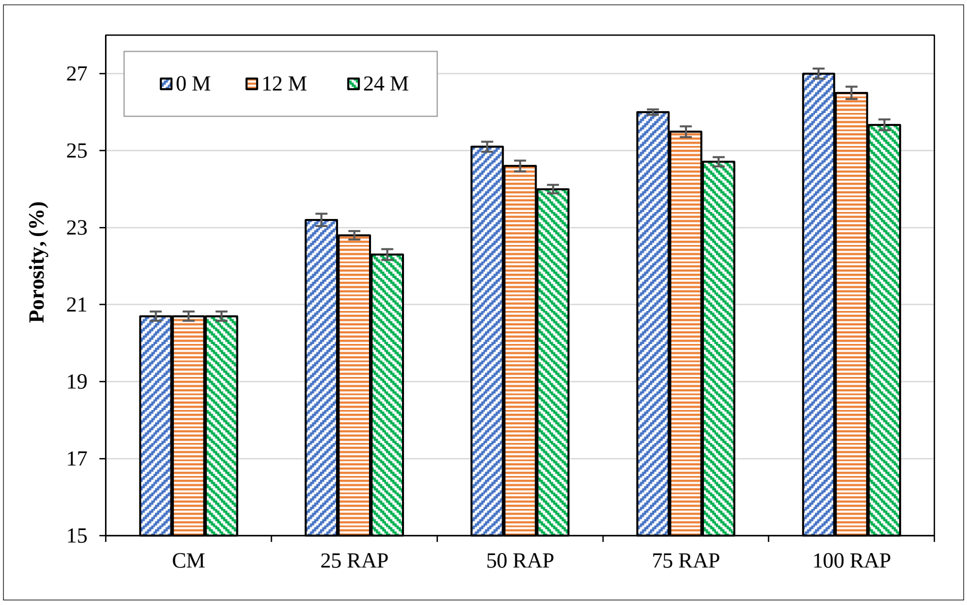
3.1. Density and Porosity

Figures 6(a) and 6(b) show the effect of varying RAP replacement ratios and treatment durations on the density and porosity characteristics of pervious concrete. As RAP content increased from 25% to 100%, a consistent decline in density was observed, with values ranging from approximately 3% to 12% below that of the control mix. This reduction is primarily associated with the inherently lower specific gravity of RAP aggregates relative to virgin stone materials, as outlined in Table 2. Due to their lighter mass and reduced compaction potential, RAP particles tend to form looser mixtures with diminished packing capability. The lowest density values were recorded for untreated RAP (0M), likely due to retained surface dust, oxidized asphalt residues, and agglomerated fines, which interfere with uniform particle packing and interfacial bonding. Additionally, the irregular surface topography and lower weight of RAP aggregates contribute to weak interlocking behavior and suboptimal adhesion with the surrounding cement paste. These deficiencies were most prominent in mixes incorporating untreated RAP. The measured hardened densities across all RAP-treated PC specimens fell within the range of 1900–2100 kg/m³, aligning with ACI 522R-2010 [20] standards and affirming the structural viability of the proposed mixtures. These findings are consistent with those reported in prior research [16, 17, 19].

As shown in Figure 6(b), porosity in pervious concrete mixtures increases progressively with higher Reclaimed Asphalt Pavement (RAP) content, ranging from 0% to 100%. However, prolonged RAP treatment durations contribute to a steady decline in porosity, indicating improved aggregate structure and compaction behavior. PC mixes incorporating untreated RAP, characterized by a noticeable dust layer, stiff asphalt, and agglomerated particles, encounter challenges with RAP-cement matrix adhesion. This weak bond results in the formation of micro-voids, which elevates porosity and reduces concrete density. The higher porosity in RAP-incorporated mixes is also linked to micro-fissures on RAP aggregate surfaces caused by uncontrolled asphalt milling [42]. These micro-fissures, along with the geometry characteristics, influence the density and contribute to the increased porosity in RAP-based mixes. The observed increase in density and corresponding reduction in porosity with longer treatment periods is attributed to the enhanced surface properties of the RAP aggregates achieved through the treatment processes. Over time, these treatments improve the bond between RAP and cementitious materials, facilitating better compaction and densification of the PC mix. This improvement results largely from the removal of stiff bitumen coatings from the RAP, as well as the breakdown of agglomerated particles (Tables 1 and 2). The porosity values observed range from 19.5% to 27.0%, covering all replacement levels and treatment durations (0M to 24M). Notably, these values fall well within the acceptable limit for conventional pervious concrete, which typically exhibits porosity between 15% and 35% [16, 17, 29]. The significant reduction in porosity with increasing treatment duration highlights the effectiveness of the treatment process in enhancing the mechanical integrity and long-term resilience of RAP-modified pervious concrete.



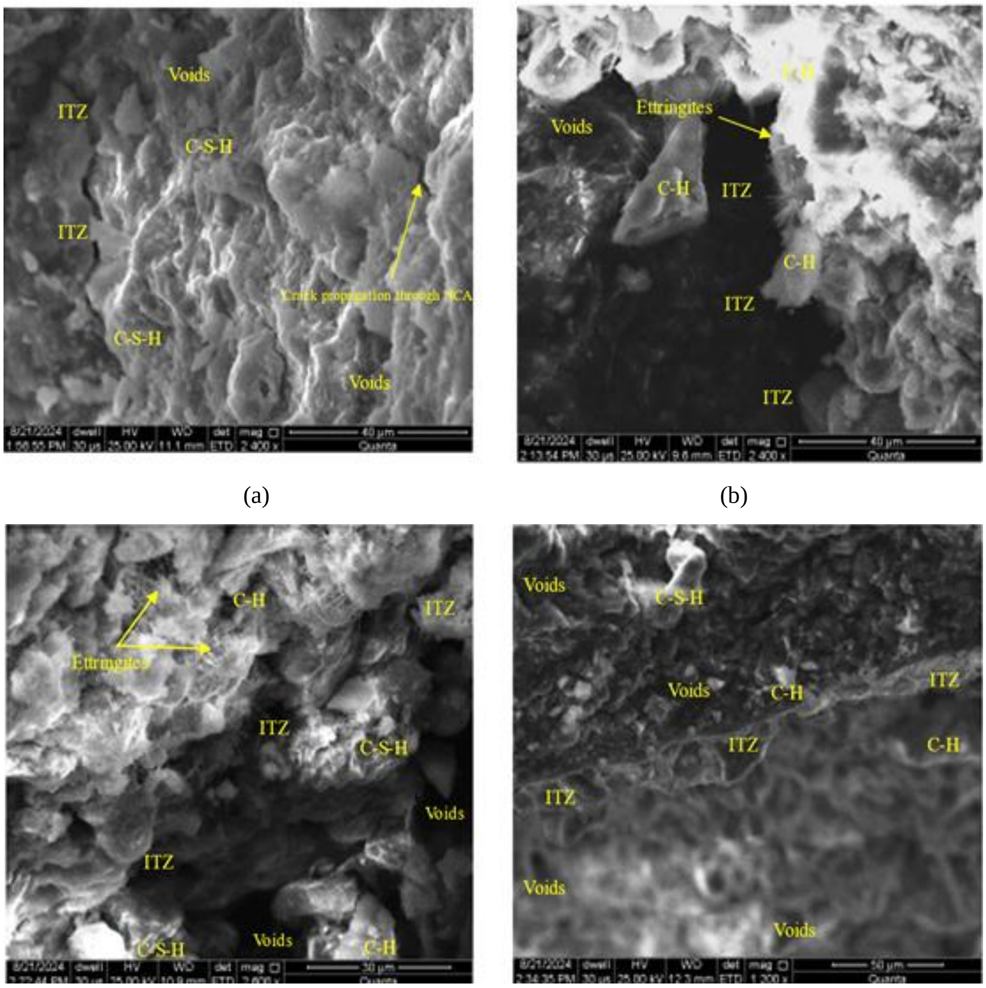
(a)



(b)

Figure 6. (a) Density and (b) Porosity of Pervious Concrete with 0, 12, and 24 Months Treated RAP

The SEM and EDAX analyses, shown in Figures 7 and 8, show various conditions of RAP at various treatment stages. The EDAX spectrum for untreated RAP showed significant peaks for elements like silicon, aluminium, calcium, and magnesium, likely originating from dust and fine particles adhering to the aggregates. The prominent carbon peak, representing the bitumen content, was the highest at 0 months, indicating a substantial asphalt layer. As the treatment progressed, the carbon peak diminished, indicating the reduced presence of bitumen. Insufficient bonding and compaction resulted in more interconnected pores and larger voids, thereby increasing the porosity of the mixes with higher RAP content. This heightened porosity adversely impacts the performance and durability of PC, thereby affecting its permeability, strength, and resistance to environmental factors.



(a) (b) (c) (d)

Figure 7. SEM images of (a) CM, (b) 0, (c) 12 and (d) 24 months treated RAP in Pervious concrete

3.2. Compressive Strength

Figure 12 shows how variations in RAP replacement ratios and treatment durations affect the compressive strength of pervious concrete, showing a progressive reduction in strength with increased RAP content. This reduction is due to weaker inter-particle bonds from the stiff oxidized asphalt layer on RAP particles. SEM analysis, conducted on both the control mix (CM) and 100% RAP specimens treated for 0, 12, and 24 months, highlighted significant variations in the ITZ across the different mixes (Figure 7). In the 0-month RAP specimens, the ITZ demonstrated a greater extent of porosity, with elevated concentrations of CH, reduced C—S—H, and larger void spaces than the control mix and treated specimens. The porous ITZ indicates weak bonding between RAP and cement, reducing compressive strength.

3.3. Permeability

The permeability of PC mixes depends on void connectivity and aggregate bonding, enabling efficient water flow. Figure 10 shows the combined effects of RAP replacement and RAP treatment on PC permeability. The rise in permeability highlights RAP's role in improving water flow in PC mixes through the interconnected voids. The findings showed a marked increase in permeability as the proportion of RAP aggregates elevated. Higher RAP content weakened the aggregate-cement bond, significantly increasing permeability. The permeability trend showcases a clear progressive hierarchy, systematically increasing from the Control Mix (CM) to higher RAP content levels. Regardless of treatment duration, this ascending order remains consistent, signifying that the presence of RAP aggregates directly influences permeability enhancement. However, while the pattern is maintained, the magnitude of permeability is progressively reduced as the treatment duration increases, indicating the efficacy of the treatment process in mitigating excessive permeability. These values remained within the permissible limits established in previous research [16, 17, 43]. Figure 11 shows a strong porosity-permeability correlation in PC mixes ($R^2 = 0.892$).

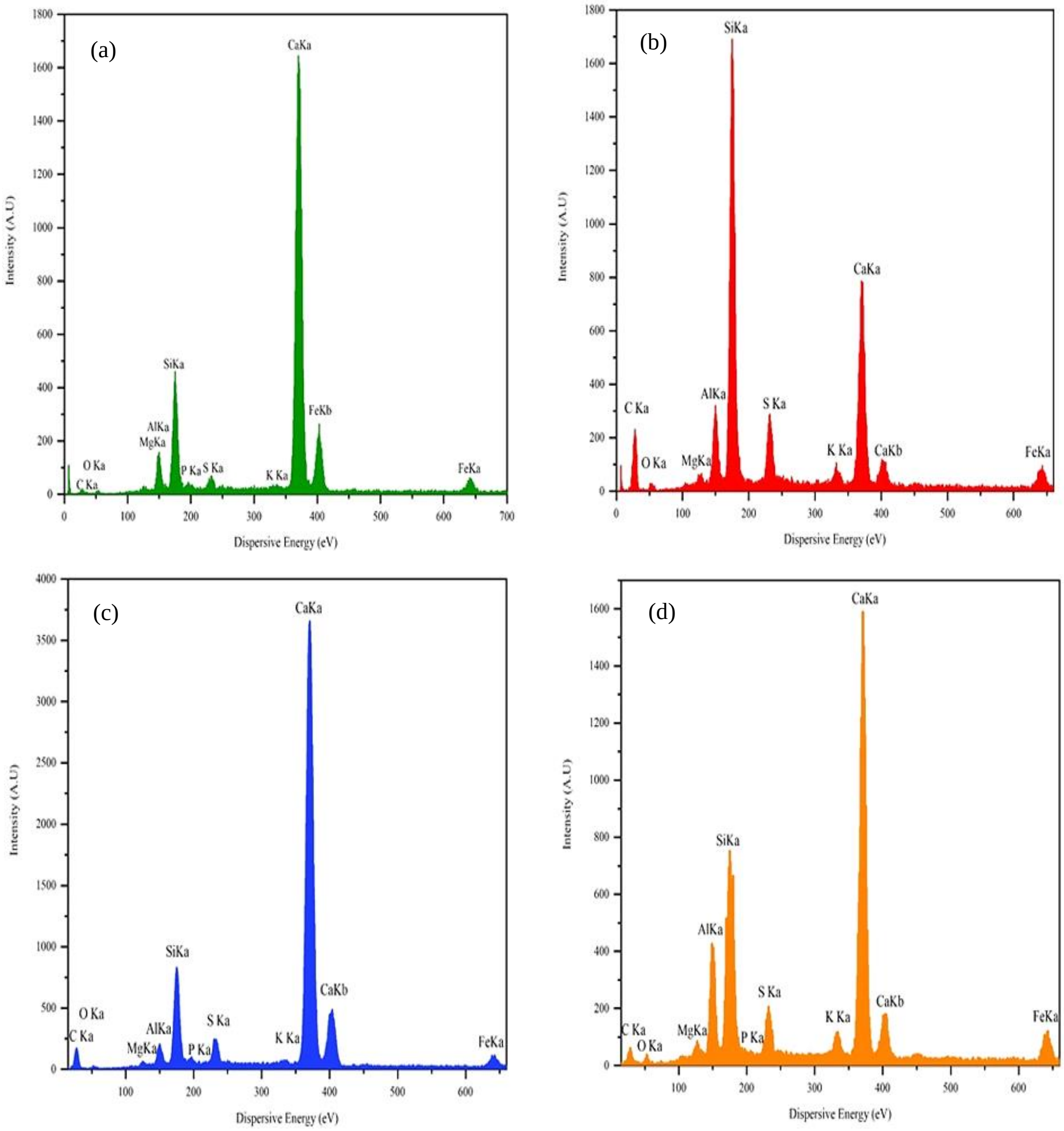


Figure 8. EDAX spectra of (a) CM, (b) 0, (c) 12 and (d) 24 Months treated RAP in Pervious Concrete

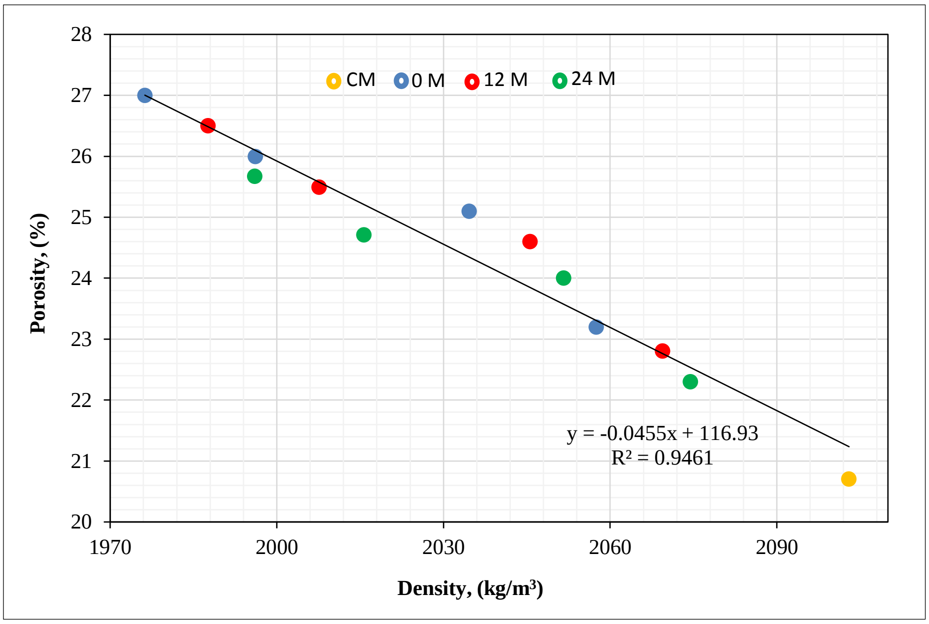


Figure 9. Comparative analysis of porosity and density trends in pervious concrete containing RAP at different treatment durations

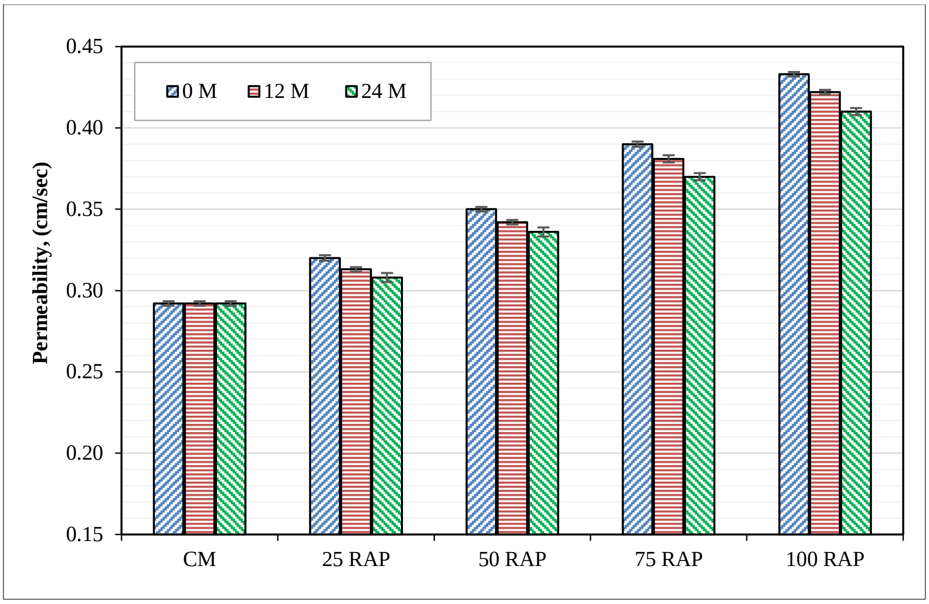


Figure 10. Permeability of Pervious Concrete with 0, 12, and 24 Months Treated RAP

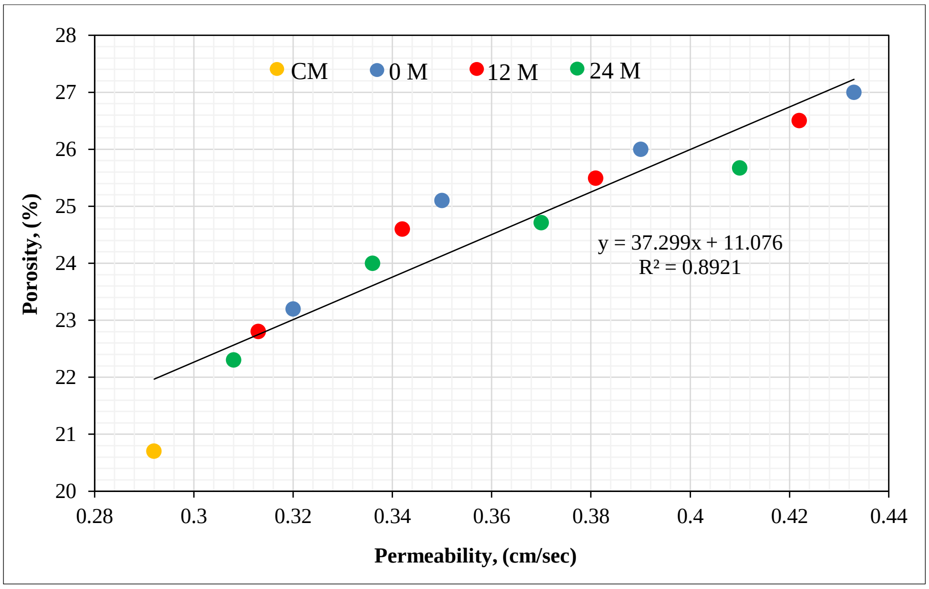


Figure 11. Relationship between porosity and permeability in pervious concrete incorporating RAP treated for 0, 12, and 24 months

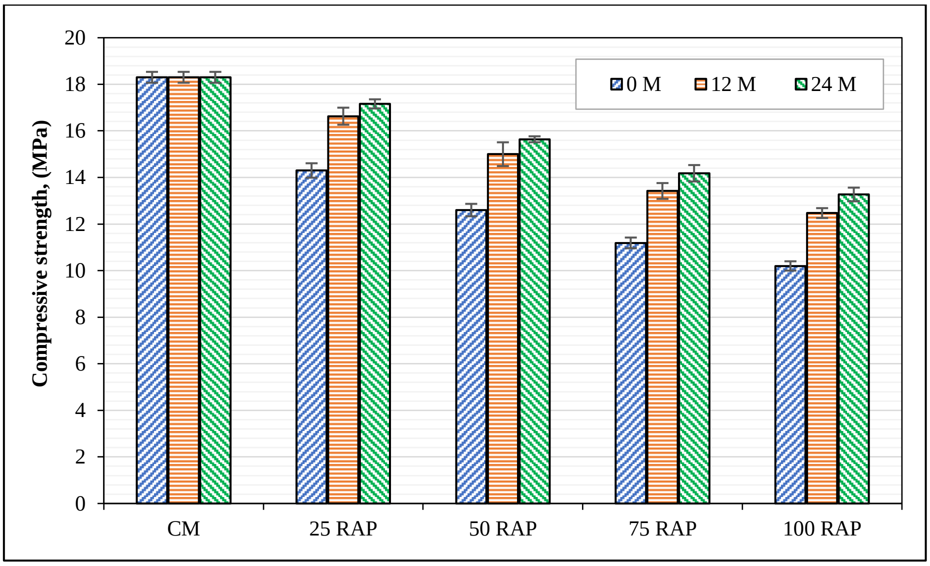


Figure 12. Compressive Strength of Pervious Concrete with 0, 12, and 24 Months Treated RAP

As the treatment duration increased, notable improvements in ITZ quality were observed. SEM micrographs revealed fewer voids and a higher proportion of C─S─H in the specimens treated for 12 and 24 months, indicating enhanced bonding between the RAP and cementitious matrix. While the ITZ in the treated RAP specimens continued to develop, resulting in a denser structure, slight variations in ITZ width were noted between the 12-month and 24-month treated specimens. The treatment mitigated adverse effects, improving RAP compressive strength compared to untreated RAP but remaining below CM. This is due to incomplete asphalt removal during treatment, which hinders optimal bonding with cementitious materials. Additionally, the compressive strength trend shows a consistent improvement across all RAP replacement levels with prolonged treatment durations. Similar improvements are observed at higher RAP replacement levels, indicating that the treatment process effectively enhances aggregate-cement bonding, thereby improving compressive strength. The observed compressive strength values of all mixes were within the acceptable limit for pervious concrete [16, 43, 44].

3.4. Flexural Strength

Flexural test was conducted on the 4-points bending apparatus (Figure 13), the results of which are presented in Figure 14. Flexural strength was observed to decrease with higher RAP content which may be due to RAP's lower specific gravity and weak inter-particle bonding from the rigid asphalt coating.

Figure 13. Flexural Strength of Pervious Concrete with Treated RAP

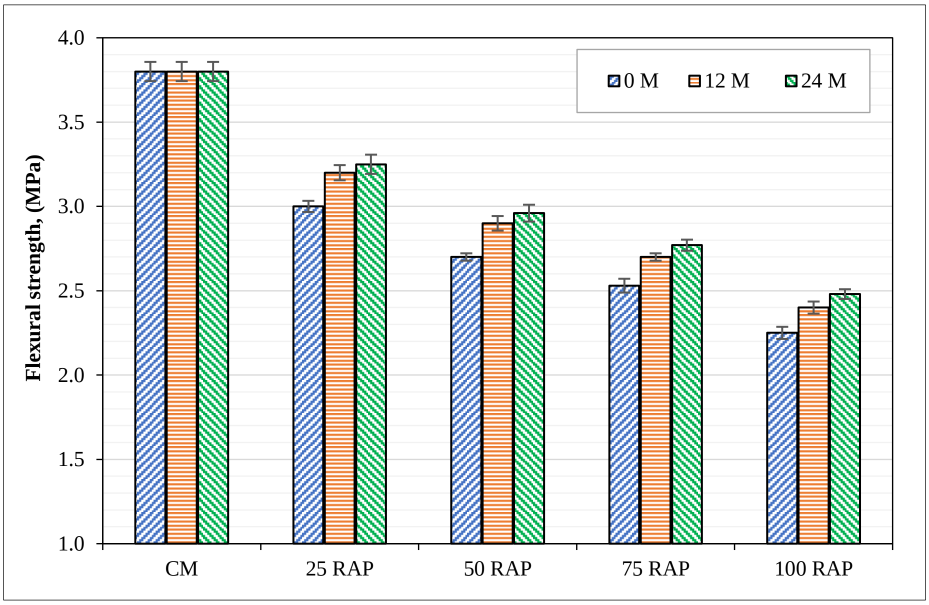


Figure 14. Flexural Strength of Pervious Concrete with 0, 12, and 24 Months Treated RAP

Extended RAP treatment improved PC flexural strength, with 12-month and 24-month treatments increased by 6.8% and 9.5%, respectively. Despite these incremental improvements, all treated RAP mixes maintained flexural strength values within the acceptable limits for pervious concrete, as outlined in previous research [1, 18, 20, 43, 45].

3.5. Cantabro Abrasion Resistance

Cantabro abrasion resistance is a key indicator of concrete durability under traffic-induced stresses and environmental wear [46]. As shown in Figure 15, higher RAP content increases abrasion mass loss stemming from weak interfacial interaction between RAP particles and hydrated cement system, primarily weakened by aged bitumen layers, dust-coated surfaces, and hydrophobic properties. However, RAP incorporation also improves toughness by enhancing stress absorption and redistribution, providing partial resistance against abrasive forces [47, 48].

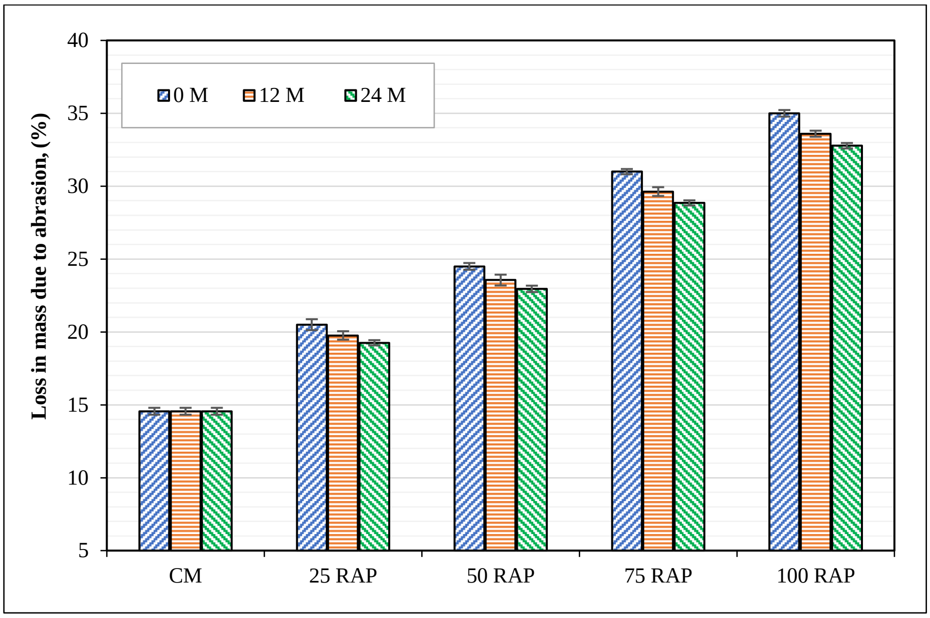


Figure 15. Mass Loss from Abrasion in Pervious Concrete with 0, 12, and 24 Months Treated RAP

The Control Mix (CM) exhibited the lowest mass loss, attributable to its dense matrix and superior aggregate-to-paste bonding, as illustrated in Figure 16. In contrast, untreated RAP specimens showed the highest material degradation under abrasion, primarily resulting from insufficient interfacial adhesion between RAP and the cementitious phase. This led to greater particle detachment and higher surface wear. After 12 months of treatment, the partial removal of surface bitumen improved bond quality to a certain extent, thereby reducing mass loss. However, the 12-month treated mixes still experienced greater mass loss than the CM, indicating that the treatment was only partially effective in overcoming issues related to RAP's agglomerated texture and hydrophobic nature.

A marked enhancement in abrasion performance was recorded after 24 months of treatment, with the mass loss for fully replaced RAP mixes dropping from 34.0% (0 M) to 31.5% (24 M). This improvement is associated with increased bitumen removal, dispersion of clustered particles, and surface roughening of the aggregates, which promoted more effective bonding at the RAP–paste interface. These changes contributed to a more uniform and resilient concrete matrix, thereby reducing surface wear. Overall, the results affirm the role of extended treatment in addressing the limitations of untreated RAP, ultimately enhancing the abrasion resistance and service life of RAP-modified pervious concrete.

(a) (b) (c) (d)

Figure 16. Abraded specimens of (a) CM, (b) 0 Month, (c)12 Months and (d) 24 Month Treated RAP incorporated PC

3.6. Durability Test

Mass loss following exposure to HCL and H_2SO_4

The durability of PC in acidic environments was assessed by measuring the mass loss in different RAP-PC mixes exposed to 2% solutions of HCl and H_2SO_4. As shown in Figure 17(a), the mass loss data revealed the influence of RAP replacement levels and treatment durations. Under HCl exposure, the control mix (CM) exhibited the lowest mass loss of 4.6%, whereas the 100% RAP mix experienced a significantly higher mass loss of 8.8%, nearly double that of the control mix. Similarly, in the H_2SO_4 exposure, CM showed a 5.6% mass loss, while the 100% RAP mix reached 9.9%. However, the treatment of RAP aggregates proved effective in reducing the mass loss over time. For untreated 100% RAP, the mass loss under HCl decreased from 8.8% to 8.0% after 24 months of treatment, and for 50% RAP, it decreased from 6.5% (0M) to 5.8% (24M). A similar trend was observed under H_2SO_4 exposure, with the mass loss for untreated 100% RAP reducing from 9.9% to 9.3% after 24 months of treatment, while 50% RAP decreased from 7.1% to 6.5%. The findings suggest that RAP aggregates in PC performed better in HCl environments compared to H_2SO_4, as evidenced by the mass loss trends in Figures 14(a) and (b). Nevertheless, PC containing RAP exhibited significant outer layer degradation when subjected to sulphate solutions. This accelerated degradation results from the easy ingress of sulphate ions through the pore network, which facilitates calcium leaching and subsequent gypsum precipitation both within the pore structure and on exposed surfaces. The resulting reaction between deposited gypsum and calcium aluminate hydrate led to the formation of ettringite (Figure 18), intensifying surface spalling and compromising structural integrity. Over time, the accumulation of gypsum caused scaling, softening, and a gradual loss of structural strength in concrete [23, 49].

When RAP-modified pervious concrete was exposed to chloride environments, hydrochloric acid (HCl) reacted with the cementitious matrix, promoting the generation of both mobile and precipitated salt species. The more soluble salts were dissolved and flushed out due to the elevated calcium ion concentration within the matrix, while less soluble compounds remained deposited in the damaged regions. In addition to these salts, gel-like phases may also develop. Under continued chloride exposure, further chemical transformations occur, leading to the formation of complex compounds involving iron, aluminium, silicon, and calcium. These reactions accelerate the extraction of calcium hydroxide from the matrix, progressively diminishing structural resilience. As calcium depletion advances, the concrete becomes increasingly vulnerable to degradation, resulting in long-term mechanical weakening.

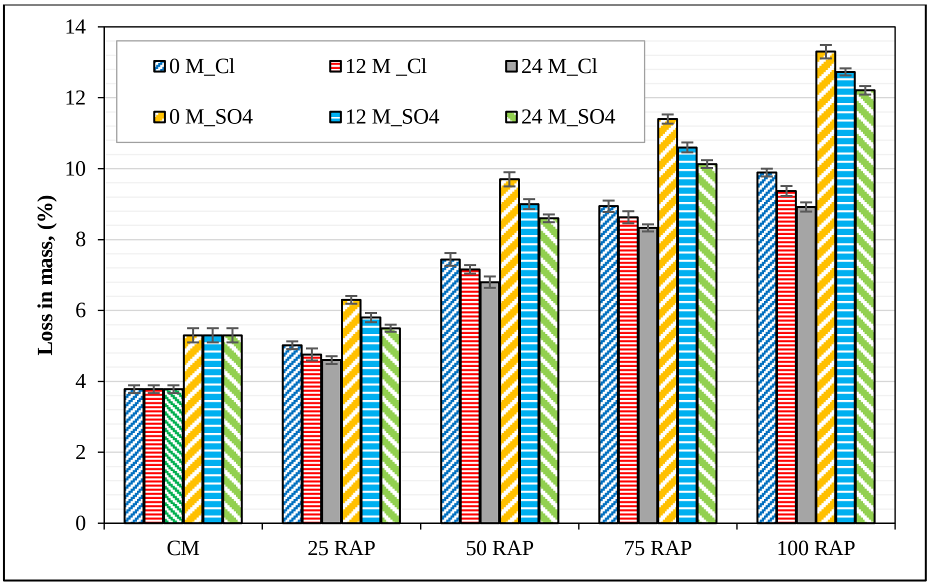
Strength Degradation after Exposure to HCL and H_2SO_4

The CM exhibited minimal strength loss, ranging from 14% to 17%, demonstrating strong chemical resistance. With increasing RAP content, this strength reduction amplified, particularly under sulphate exposure. At 25% RAP, losses peaked at 20%, while 50% RAP experienced losses between 24% and 27%. For 75% RAP, degradation ranged from 28% to 35%, while 100% RAP exhibited the highest losses, reaching 45% under sulphate and 36% under chloride exposure. This trend underscores the increased vulnerability to sulphate attacks as RAP levels increase. RAP treatment significantly reduced the strength loss across all RAP content levels. Untreated RAP showed the most severe loss, with 100% RAP losing 45% under sulphate and 36% under chloride. After 12 months of treatment, these losses reduced to 42% and 34%, respectively. Further improvements were observed after 24 months, with losses decreasing to 40% under sulphate and 32% under chloride for 100% RAP. For 50% RAP, the strength loss reduced from 27% to 24% (sulphate) and from 24% to 22% (chloride) (Figure 17b). RAP treatment, especially for 24 months, proved to be more effective in mitigating strength loss under chloride exposure compared to sulphate. HCl exposure led to calcium hydroxide leaching, which degraded C─S─H and weakened the matrix, although the treatment helped alleviate these effects.

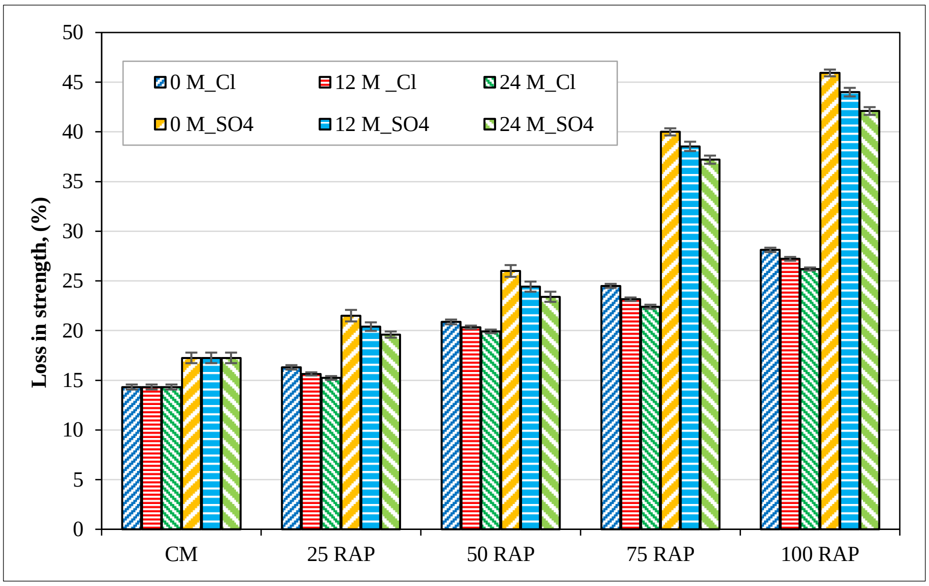
4. Analysis of Concrete Damage

The Control Mix (CM) exhibited well-distributed cracking patterns with minimal propagation, indicating superior bonding between natural aggregates and the cement matrix. The uniform stress transfer across the matrix resulted in enhanced structural integrity and load-bearing capacity. The observed cracks were primarily confined to matrix-aggregate interfaces without extensive propagation, demonstrating the robustness of the CM sample under applied loads (Figure 19a). In contrast, the 0M RAP samples displayed extensive and irregular crack networks characterized by micro-cracks distributed throughout the matrix. The thick coating of cement paste over RAP aggregates further contributed to inadequate load transfer and premature cracking. This poor bonding is reflected in the widespread and uncontrolled crack propagation observed during mechanical testing (Figure 19b).

The 12M RAP samples demonstrated noticeable improvement in crack resistance and mechanical performance. Partial removal of bitumen through the treatment process exposed aggregate surfaces, promoting better adhesion with the cement matrix. This improvement resulted in reduced crack density and more uniform crack propagation, indicating enhanced structural integrity. While minor cracks were still present, their size and frequency were significantly reduced compared to untreated samples (Figure 19c).



(a)



(b)

Figure 17. (a) Mass Loss and (b) Strength Loss after HCl and H_2S_4 Acid Exposure of Pervious Concrete with 0, 12, and 24 Months Treated RAP

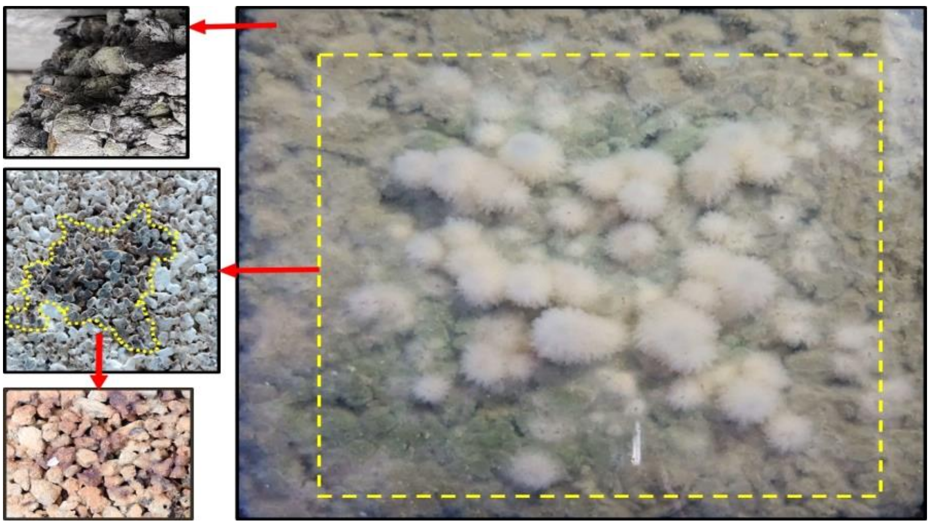


Figure 18. Formation of ettringites on soaking PC in H_2So_4 acid

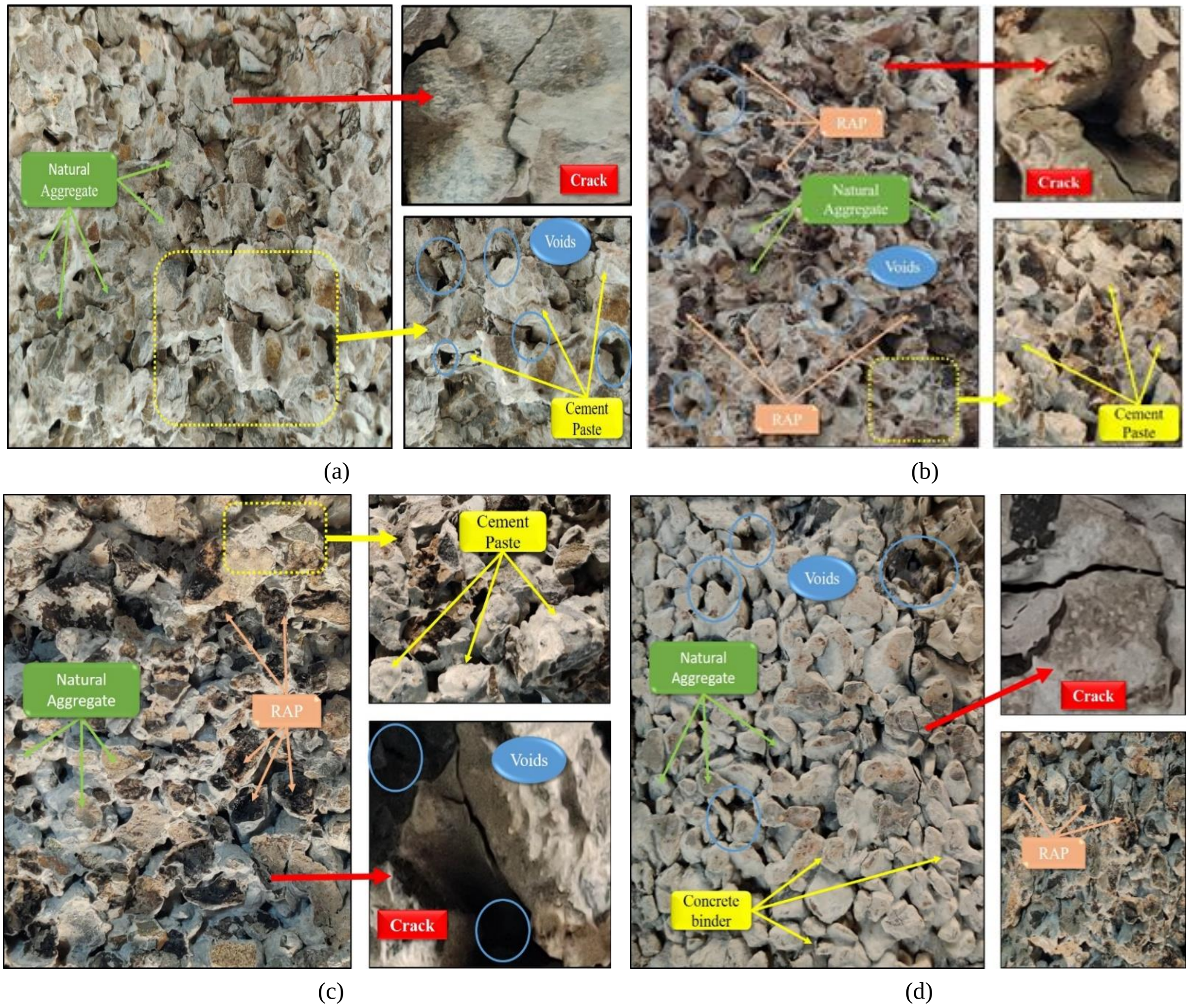


Figure 19. (a) CM, (b) 0 Month, (c) 12 Months and (d) 24 Months pre-treated RAP aggregate concrete

The most refined crack pattern was observed in the 24M RAP samples, where isolated, well-defined cracks were primarily concentrated at matrix-aggregate interfaces. The extended treatment effectively eliminated residual bitumen, promoting superior bonding between RAP aggregates and cement paste. This improved interfacial bond strength resulted in enhanced load-bearing capacity, reduced cracking, and superior structural stability. The roughened aggregate surfaces, coupled with the removal of residual bitumen, contributed to superior interfacial bonding and mechanical performance (Figure 19d). The findings from the XRF and EDAX analysis further support the mechanical observations. The progressive increase in Silicon Dioxide (SiO_2) content from 0M RAP to 24M RAP reflects the effective removal of bituminous layers and the exposure of aggregate surfaces. Additionally, the reduction in Calcium Oxide (CaO) content suggests the decomposition or oxidation of calcium-bearing compounds associated with bituminous residues. These chemical alterations improve the interfacial bonding between RAP aggregates and the binder matrix, contributing to improved load-bearing capacity and overall structural integrity of the concrete. The combined analysis of chemical composition and crack pattern behavior demonstrates the efficacy of the RAP treatment process in enhancing aggregate-matrix bonding. The progressive improvement from 0M RAP to 24M RAP samples indicates that prolonged treatment effectively mitigates the detrimental effects of residual bitumen, promoting superior bonding and mechanical performance. Further quantitative testing is recommended to validate these findings and optimize the RAP treatment process for practical pervious concrete applications.

5. Performance Comparison of Past and Present Research on RAP in Concrete

A comprehensive comparative analysis has been undertaken between the present study and selected prior investigations on RAP-incorporated pervious concrete. As outlined in Table 4, the synthesis captures essential mix design parameters, including RAP replacement percentages, treatment methodologies, water–cement ratios, and the incorporation of mineral admixtures. In addition, the table compiles key performance indicators such as compressive and flexural strength, density, porosity, permeability, chemical and abrasion resistance, and interfacial transition zone (ITZ) behavior, as determined through microstructural characterization.

Figure 20 presents a comparative analysis of compressive strength from previous studies and the current investigation. Among untreated RAP studies, Sahdeo et al. (2020) [50] showed relatively superior performance due to a combination of favorable conditions including 90-day curing, binary gradation (10 mm and 4.75 mm at a 30:70 ratio), high cement content (362.6–409.5 kg/m³) and Proctor compaction. These parameters improved packing density and matrix cohesion, while the low bitumen content (~1.6%) of RAP minimized ITZ disruption, allowing strength values to remain close to treated systems. In contrast, Saboo et al. (2020) [50] implemented only partial conditioning—heating RAP at 80 °C followed by manual fragmentation—which helped disintegrate agglomerates but left the aged asphalt film intact. Although their course G1 gradation outperformed G2 due to lower surface area demands, compressive strength still dropped significantly with increasing RAP content. Bittencourt et al. (2021) [44] recorded the weakest mechanical performance due to high residual bitumen (5.23%), wide particle gradation (2.36–19 mm), limited 28-day curing, and manual steel roller compaction, all of which led to poor densification and a compromised ITZ. Diwate et al. (2024) [51] further emphasized the limitations of RAP under minimal treatment conditions. Despite maintaining a consistent w/c ratio of 0.32 and standard compaction, the smooth surface of RAP hindered bonding, leading to a steep decline in compressive strength at higher RAP levels. In contrast, RAP's porous, rough surface texture supported stronger interaction with the cement paste, enhancing the strength at lower RAP levels.

Table 4. Comparative Summary of Previous and Present Research on RAP-Integrated Pervious Concrete (2020- 2025)

Performance Parameter	Saboo et al. (2020) [50]	Sahdeo et al. (2020) [43]	Bittencourt et al. (2021) [44]	Diwate et al. (2024) [51]	Present Studies
Concrete Type	Pervious Paver Blocks (PPB)	Pervious Concrete	Pervious Concrete	Pervious Concrete	Pervious Concrete
RAP Treatment	Oven-heated (30–40min), manually fragmented (wooden hammer)	Untreated, aged (~1 year), stockpiled RAP with dust/asphalt coating	Untreated RAP (as-received, ~5.32% bitumen content)	Untreated RAP milled from highway	Solar Heating + Oxidation + AB&AT
RAP % Used	0%, 50%, 100%	0%, 25%, 50%, 75%, 100%	10% to 100%	30%, 60%, 90%	0–100%
Mineral Admixtures	None	None	None	None	None
Density / Porosity	G2 denser; Porosity 20–33%	↓ Density (1,860–2,030 kg/m³); ↑ Porosity (up to +6.5%)	↓ Density (up to −13%) ↑ Porosity (21.8%–25.3%)	↓ Density with RAP ↑ Porosity (25–35%)	↑ Density, ↓ Porosity
Permeability	Functional (not explicit)	↑ with RAP; 0.222–0.315 cm/s	High permeability (up to 10.54×10^{-3} m/s)	Not explicitly quantified but porosity-based	↓ Permeability
Strength (Comp/Flex)	2–8 MPa; best at 50% RAP	↓ Comp. (up to -44%); ↓ Flexural (up to -32%)	↓ Strength with ↑ RAP: −71% compressive, −46% flexural; Optimum at 20%	↑ at 30% RAP (~7.5 MPa at 7-day); ↓ at 60–90%	↑ Strength up to +20%
Durability	Lowest Cantabro loss at 50% RAP	↑ Mass loss under acid/sulfate (9.5–12.1%); ↓ strength up to -43.8%	Infiltration loss up to 86% after clogging cycles	↑ Abrasion Resistance (↓ Cantabro Loss at 60%)	Excellent acid/abrasion resistance
Microstructure / ITZ	Weak ITZ reduced strength	Wider ITZ; ↑ CH, ↓ C-S-H, ↑ Voids; weak bond due to stiff asphalt	No SEM/EDAX; Weak ITZ due to asphalt film	Weak ITZ due to aged bitumen; observed asphalt film	Clean, cohesive ITZ (SEM/EDAX)
Sustainability	Factory-compatible, resource-saving	High reuse potential; recommend ≤50% RAP for durability balance	Advocates RAP pre-treatment for improved performance	↓ Cost/Strength at 30% RAP; ↑ GHG and TEE beyond 60%	Energy-efficient RAP processing

Note: ↑ Increase ↓ Decrease, Green House Gas (GHG), Total Embodied Energy (TEE).

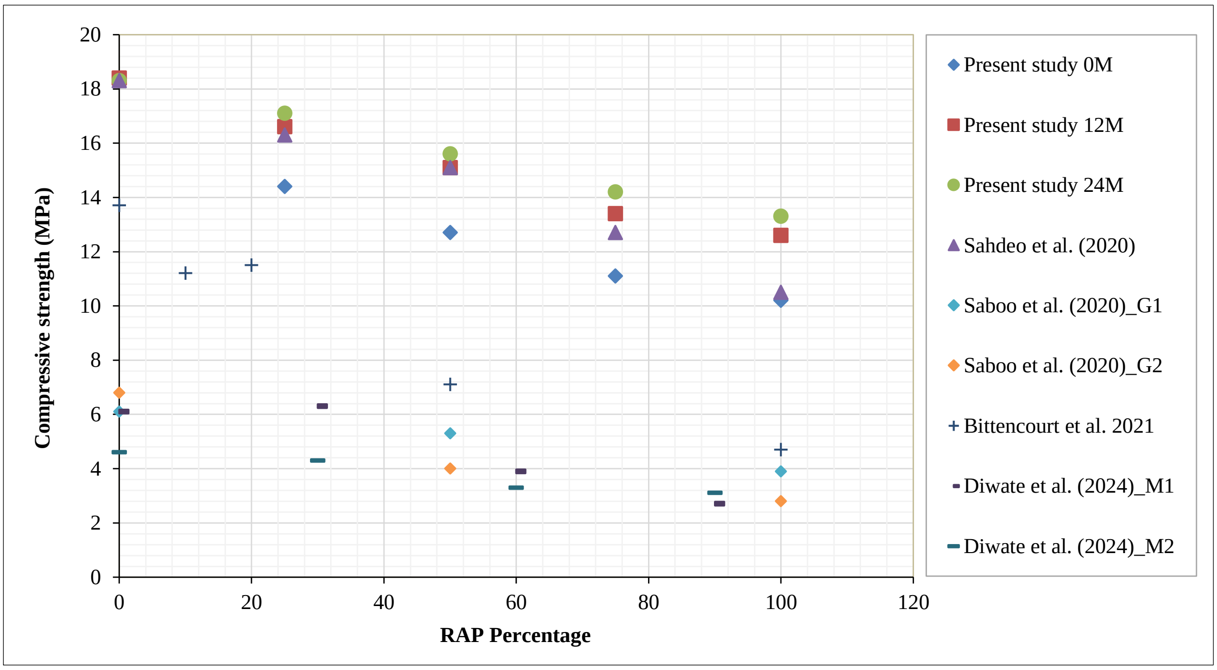


Figure 20. Comparative Summary of Previous and Present Research on RAP-Integrated Pervious Concrete (2020- 2025)

6. Conclusions

This investigation assessed the effect of varying RAP treatment periods (0, 12, and 24 months) on the structural resilience, fluid permeability characteristics, and extended durability of pervious concrete. The findings reveal that longer treatment durations led to marked improvements across critical performance metrics of the modified PC mixtures:

- ***Density and Porosity***: Pervious concrete incorporating untreated RAP (0-month) exhibited reduced density and elevated porosity, largely due to inadequate interfacial bonding and residual contaminants. Progressive treatment, particularly over 24 months, significantly improved particle adhesion and cleanliness, leading to increased density and reduced pore volume.

- ***Permeability*****:** At 0 months, RAP-PC demonstrated high permeability, attributed to weak aggregate cohesion and enlarged void structures. Treatments at 12 and 24 months enhanced aggregate interlock, reduced void continuity, and thereby lowered permeability, contributing to improved hydraulic resistance.

- ***Compressive and Flexural Strength*****:** Mechanical strength parameters improved progressively with treatment duration. While untreated RAP weakened the Interfacial Transition Zone (ITZ), resulting in strength degradation, the 24-month treatment notably enhanced compressive and flexural strength through improved matrix consolidation and aggregate-paste interaction.

- ***Abrasion Resistance*****:** High mass loss was observed in untreated RAP samples due to insufficient adhesion at the aggregate interface. Enhanced bonding and effective removal of surface bitumen following 12- and 24-month treatments significantly improved abrasion resistance, reflected in lower material loss under mechanical wear.

- ***Durability in Acidic Environments*****:** Untreated RAP-PC exposed to aggressive sulphate and chloride environments suffered marked deterioration, primarily driven by gypsum and ettringite formation. Extended treatments—especially at 24 months—minimized mass and strength loss, evidencing superior resistance to chemical attack and improved long-term durability.

- ***Microstructural and Chemical Purity (XRF and EDAX)*****:** SEM imaging revealed denser microstructures and improved matrix uniformity in treated specimens. EDAX results indicated a gradual reduction in residual carbon across treatment durations, signifying the progressive removal of asphaltic content. Concurrently, XRF analysis showed increasing silicon content and reduced calcium oxide presence, highlighting effective mineral purification and enhanced chemical compatibility with the binder phase.

The findings confirm that RAP aggregates treated for 24 months exhibit substantial enhancements in mechanical strength, fluid transport regulation, and resistance to environmental degradation in pervious concrete systems. The optimized treatment protocol improves interfacial bonding, structural integrity, and chemical stability, establishing treated RAP as a technically effective and environmentally responsible replacement for conventional aggregates in pavement applications.

7. Declarations

7.1. Author Contributions

Conceptualization, G.T. and K.R.D.; methodology, G.T. and K.R.D.; validation, G.T. and K.R.D.; investigation, K.R.D.; resources, G.T. and K.R.D.; writing—original draft preparation, G.T.; writing—review and editing, G.T. and K.R.D. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

Data sharing is not applicable to this article.

7.3. Funding

The authors received no financial support for the research, authorship, and/or publication of this article.

7.4. Conflicts of Interest

The authors declare no conflict of interest.

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