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Investigation of selected properties of porous asphalt using recycled concrete aggregates and fly ash

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KEYWORDS

Urban flooding
Permeable pavement system (PPS)
Porous asphalt (PA)
Natural aggregate (NA)
Recycled concrete aggregate (RCA)

ABSTRACT

The increasing frequency of urban flooding highlights the urgent need for effective surface drainage solutions, among which the Permeable Pavement System is considered a promising approach. Porous asphalt (PA) is commonly employed as the surface layer in such systems due to its high permeability. This study evaluates the impact of replacing natural aggregates (NA) with recycled concrete aggregates (RCA) in PA mixtures and examines how this substitution influences key mechanical and hydraulic properties of the material. A series of PA samples were fabricated and divided into two groups: one group incorporating RCA, and the other employing NA as the control. The investigated properties include bulk density, permeability coefficient, Marshall stability, indirect tensile strength, Cantabro loss, and resistance to clogging. The results indicate that PA mixtures incorporating RCA exhibit lower bulk density, Marshall stability, indirect tensile strength, and Cantabro resistance, with reductions of 11%, 14%, 5%, and 38.5%, respectively, compared with the NA samples. Conversely, the permeability coefficient of the RCA mixtures increases by approximately 9%. Despite the decrease in several mechanical indicators, all evaluated properties satisfy the technical requirements specified in TCVN 13048. Overall, the findings confirm the feasibility of using RCA in PA mixtures, offering benefits in reducing construction waste while enhancing surface drainage performance in urban infrastructure.

1. Introduction

Amid accelerating urbanization and the escalating impacts of climate change, urban areas are increasingly exposed to a range of critical hydrological and environmental challenges, including localized surface flooding, deterioration of stormwater runoff quality, urban heat-island intensification, and broader environmental degradation. Traditional asphalt pavement systems, with their dense gradation and inherently low permeability, have proven insufficient to accommodate current stormwater management requirements, particularly in high-density built environments where impervious surfaces dominate. As a result, permeable pavement systems featuring highly porous surface layers such as pervious concrete porous asphalt (PA) have gained significant attention as a technically viable pavement solution capable of improving surface hydraulic conductivity, enhancing stormwater infiltration, reducing flood susceptibility, and promoting safer driving conditions during high-intensity rainfall events [1],[2],[3].

In parallel with these challenges, the increasing demand for construction materials to support transportation infrastructure has placed significant pressure on natural resources, particularly mineral aggregates. To address this issue, numerous previous studies have investigated the properties of recycled concrete aggregates (RCA) and demonstrated that RCA exhibits mechanical and physical characteristics suitable for use as aggregates in pavement construction [4],[5],[6],[7],[8],[9]. Besides, in Vietnam, tens of millions of tons of fly ash (FA) and slag are generated annually, most of which remain underutilized, leading to substantial land occupation, dust pollution, and potential risks associated with heavy metal leaching. The failure to effectively recycle and repurpose these materials not only results in resource wastage but also increases disposal costs and contributes negatively to environmental quality. Numerous previous studies have explored the reuse of FA in various road construction activities, such as its application as embankment fill material [10],[11], soil stabilization for soft ground improvement [12],[13] substitution of fine particles in base and subbase layers [14], and incorporation in concrete production [15]. Notably, several studies have indicated that FA can fully replace mineral filler in the manufacture of asphalt mixtures, including dense-graded asphalt concrete and porous asphalt [8],[16], [17],[18]. These studies have confirmed that FA is an effective mineral filler capable of enhancing binder viscosity, reducing draindown, and improving the moisture resistance of porous asphalt mixtures. Khowshnaw (2019) found that replacing limestone filler with 6 % FA significantly enhanced stability, durability, and permeability in porous asphalt mixtures [16]. Pradoto (2019) showed that finely ground FA further improved stability and reduced permeability compared to unmilled fly ash, while all mixtures satisfied Indonesian porous asphalt standards [17]. In addition,

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recent work by Elmagarhe (2024) demonstrated that porous asphalt mixtures using blended granite–RCA aggregates exhibited notable gains in tensile strength, stiffness, moisture resistance, and raveling resistance, particularly with PG 67–22 binder [19].

However, the simultaneous utilization of FA and RCA in the production of porous asphalt mixtures remains limited in Vietnam. Comprehensive studies are lacking, and there is a scarcity of relevant standards, technical guidelines, and experimental data adapted to the specific material conditions in the country. Therefore, investigating the use of FA in combination with recycled materials for the production of porous asphalt mixtures is imperative from both scientific and practical perspectives. This research not only contributes to addressing environmental challenges and promoting a circular economy but also opens new avenues for the application of sustainable materials in modern transportation infrastructure. The findings are expected to provide a critical basis for the optimal mixture design, facilitate the widespread adoption of permeable pavement technology, and support strategies for developing green and sustainable infrastructure in Vietnam.

2. Materials and Experimental Methods

In this study, materials were prepared to produce PA12.5 samples, a type of PA commonly used as the surface layer in permeable pavement systems. The prepared PA12.5 samples were classified into two types: (1) PA12.5 using RCA, designated as 100RCA, and (2) PA12.5 using NA, serving as the control samples, designated as 100NA.

2.1. Materials

The coarse and fine NA were crushed stone (carbonatic) sourced from the Bac Ha quarry, Thanh Nghi - Thanh Liem, Ha Nam. The coarse and fine RCA aggregates were prepared by crushing waste concrete collected from the Thanh Tri landfill, followed by laboratory sieving. The particle size distribution curve is presented in Figure 1, and the physical and mechanical properties of the aggregates are summarized in Table 1.The gradation selected for samples preparation is indicated by the solid red line in Figure 1. The aggregate blend fully complies with the limits specified in TCVN 13048 [20]. In this mixture, coarse aggregates (retained on the 4.75 mm sieve) accounted for 75 % of the total mass, fine aggregates (particle size 0.075–4.75 mm) accounted for 20 %, and filler (fly ash) accounted for 5 %. It can be observed from Table 1 that the physical and mechanical properties of the NA meet the requirements specified in TCVN 13048 [20], whereas several properties of the RCA, such as Los Angeles abrasion (LA) and water absorption, do not satisfy the specified criteria.

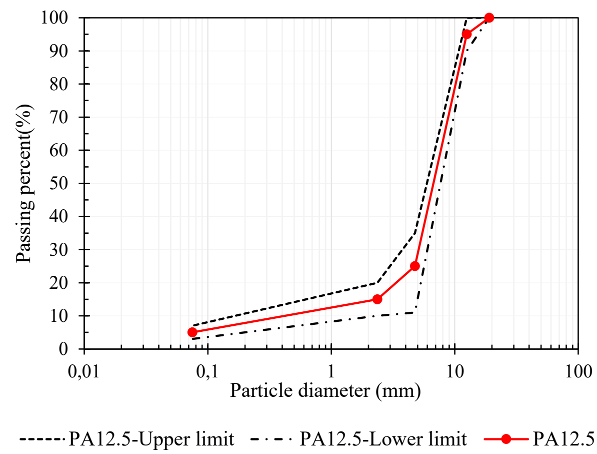

Figure 1. Particle size distribution of material mixtures used for PA12.5 samples.

The filler used for preparation of samples is Fly ash (FA). FA was sourced from the Quang Ninh Thermal Power Plant, Ha Long City, Quang Ninh, which employs pulverized coal combustion technology. The FA contains less than 10 % CaO and is classified as Class F according to TCVN 10302 [21]. Its particle size distribution and physical properties are presented in Table 2, with all measured parameters meeting the requirements specified in TCVN 13048 [20].

The asphalt binder used in this study was Polymer-Modified Bitumen (PMB III), supplied from the production and quality-controlled facilities at the Asphalt Depot of Petrolimex Petrochemical Joint Stock Company. Its physical and mechanical properties are summarized in Table 3.

Table 1. Physical and mechanical properties of aggregates.

Property	Unit	Measured values		TCVN 13048:2020	Test Method
		NA	RCA		
Specific gravity (G_s)	g/cm^3	2.62	2.57	≥2.45	AASHTO T85
Elongation and Flakiness index	%	6.22	6.00	≤ 10	TCVN 7572-13
Los Angeles abrasion (LA)	%	20.5	31.6	≤ 25	TCVN 7572-12
Water absorption	%	0.66	5.2	≤ 3	AASHTO T85
Dust, clay, and silt content	%	0.71	-	≤ 2	TCVN 7572-8
Bitumen adhesion ability	-	Grade 4	-	≥ 4	TCVN 7504

Table 2. Physical and mechanical properties of FA.

Parameter	Unit	Measured values	TCVN 13048	Test Method
Particle size distribution (percentage passing) 0.600 mm 0.300 mm 0.075 mm	%	 100 100 88	 100 95 - 100 70 - 100	AASHTO T37
Moisture content	%	0.42	≤ 1.0	AASHTO T255
Plasticity index	%	-	≤ 4.0	TCVN 4197
Specific gravity	g/cm^3	2.24	-	AASHTO T85

Table 3. Laboratory test properties of PMB III asphalt binder.

No.	Property	Unit	Test Result	Technical Requirement	Test Standard
1	Penetration at 25°C, 0.1 mm, 5 second	0.1 mm	49.7	40 ÷ 70	TCVN 7497
2	Flash Point (Cleveland Open Cup)	°C	273	Min 230	TCVN 7495
3	Softening Point (R&B method)	°C	94.3	Min 80	TCVN 7498
4	Loss on heating at 163°C for 5 hours	%	0.008	Max 0.6	TCVN7499
5	Penetration of residue, % of original	%	91.28	Min 65	TCVN 7495
6	Solubility in Trichloroethylene	%	99.70	Min 99	TCVN 7500
7	Specific Gravity	g/cm^3	1.028	1.00 – 1.05	TCVN 7501
8	Coating criteria (Boiling method)	Grade	5	Min Grade 4	TCVN 7504
9	Storage Stability for 48 hours at 163°C, Difference of Softening Point	°C	2.0	Max 3,0	TCVN 11195
10	Dynamic Viscosity at 135°C (spindle 21, 18.6 s^{-1}, Brookfield Viscometer)	cm	1.431	Max 3	TCVN 11196
11	Elastic Recovery at 25°C, 10cm elongation	%	92.0	Min 70	TCVN 11194

2.2. Experimental Methods

The PA12.5 samples prepared in this study were divided into two groups: (i) PA12.5 using RCA, designated as 100RCA, and (ii) PA12.5 using NA as control samples, designated as 100NA. The mixture gradations were designed according to the gradation curve shown in Figure 1. A total of 24 PA12.5 samples were fabricated, evenly distributed between the two experimental groups. Specimen preparation followed the Marshall compaction procedure in accordance with TCVN 8860-1 [22].The mixtures were prepared with a 5 % asphalt binder content and compacted at 160 °C using 50 blows per side for each specimen. After fabrication, the samples were evaluated for basic properties, including bulk density, voids in the mineral aggregate (VMA), interconnected voids, and permeability coefficient. Marshall stability (at 60 °C), indirect tensile strength (at 30 °C), and Cantabro particle loss tests were conducted on separate sample sets, each consisting of three samples. The experimental procedure is illustrated in Figure 2.

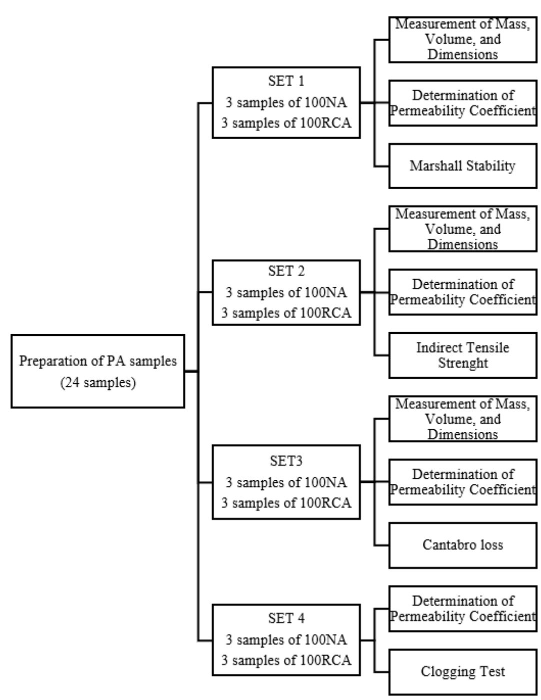

Figure 2. Experimental procedures for PA samples.

3. Experimental Results and Discussion

3.1. Bulk Density

Figure 3 illustrates the differences in bulk density measurements among the PA samples. For the 100RCA samples, the bulk density was 1.879 g/cm³, lower than that of the 100NA samples (2.084 g/cm³). This reduction is consistent with the characteristics of RCA, which inherently has a lower specific gravity and a porous surface, as recycled concrete fragments often contain voids within the cement matrix [23], [24]. Nevertheless, the decrease in bulk density did not excessively compromise the mechanical strength, indicating that the open-graded structure of 100RCA still provides the necessary stability.

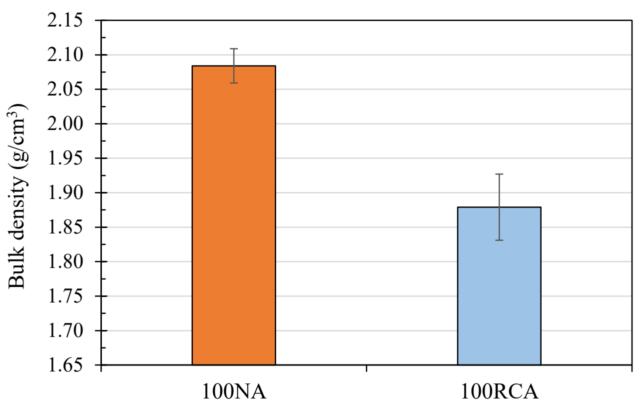

Figure 3. Bulk density of the PA samples.

3.2. Air Void Content

Figures 4 and 5 present the results of voids in the mineral aggregate (VMA) and interconnected voids for the 100NA and 100RCA samples. The experimental results indicate a significant difference between the two aggregate types. The mixture composed entirely of 100NA samples exhibited an average VMA of 12.08 %, whereas the samples using 100RCA reached a VMA of 20.72 %. This discrepancy reflects the inherent characteristics of RCA, which is derived from demolished concrete blocks containing numerous internal voids and typically exhibits more angular shapes and rougher surfaces compared to NA [6]. These features reduce the packing efficiency during compaction, resulting in a higher void content within the mixtures.

In addition to VMA, the interconnected void content of PA is the critical parameter determining its actual drainage capacity, as only voids that are continuously connected throughout the mixture can allow water to infiltrate. The results indicate that the 100RCA mixture exhibited an interconnected void content of 12.45 %, significantly higher than the 10.09 % observed for the 100NA mixture. Although the increase is not as pronounced as that of VMA, this improvement is highly meaningful because interconnected voids directly form the "water-conducting channels" within the material. This demonstrates that replacing NA with RCA not only increases the total void content but also enhances the functional void network.

In summary, the use of 100% RCA enables PA to achieve a higher and more interconnected void system, which is a key factor in enhancing surface water drainage. This indicates that RCA is not only a sustainable alternative to NA but can also directly improve the functional performance of PA under real-world conditions.

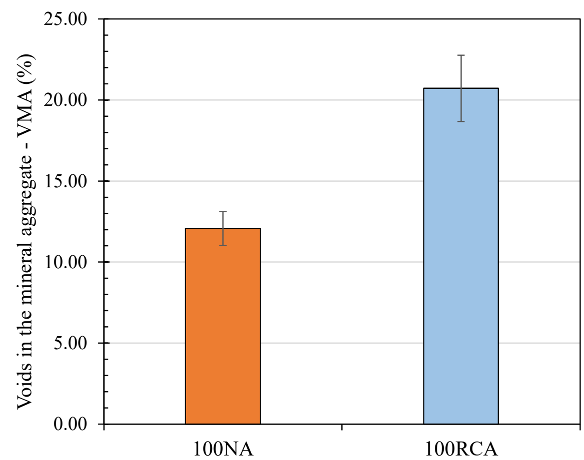

Figure 4. Voids in the mineral aggregate of the PA samples.

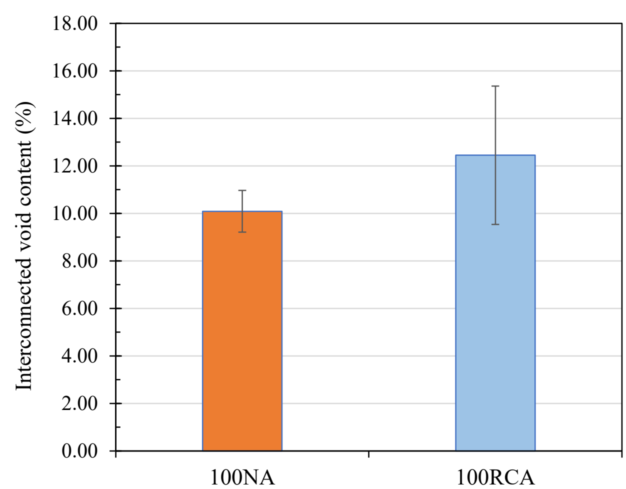

Figure 5. Interconnected void content of the PA samples.

3.3. Permeability Coefficient

The permeability test results shown in Figure 6 indicate that the 100RCA samples achieved an initial permeability coefficient of 0.115 cm/s, higher than the 0.105 cm/s observed for the 100NA samples. The rough surface texture and high water absorption of RCA contribute to the formation of larger voids and irregular but better-connected water channels compared to the NA mixture. These void networks create a more efficient water-conducting system, increasing the overall permeability. Additionally, the lower density of RCA (reflected in its reduced bulk density) indicates a more "open" aggregate skeleton, which reduces resistance to water flow through the mixture. Therefore, the use of RCA not only meets technical requirements for void structure but also significantly enhances water drainage performance.

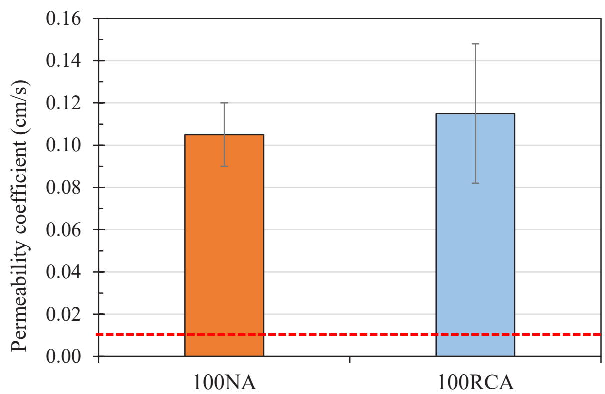

Figure 6. Laboratory-measured permeability coefficient of the PA samples. The dashed line represents the minimum value specified in TCVN 13048.

3.4. Marshall Stability

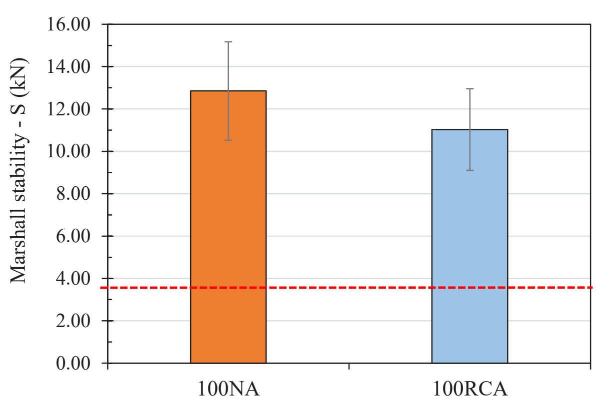

Figure 7. Marshall stability of the PA samples. The dashed line represents the minimum value specified in TCVN 13048.

The Marshall stability of the 100RCA and 100NA samples is presented in Figure 7. The results indicate that the mixture with NA achieved a stability of 12.85 kN, approximately 1.17 times higher than that of the RCA mixture, which was 11.03 kN. Although the Marshall stability of 100RCA tends to decrease compared to 100NA, the reduction is minor and still well above the minimum requirement of 3.5 kN for PA according to TCVN 13048. The decrease in Marshall stability with RCA can be attributed to material characteristics, as RCA have lower particle strength due to prior demolition and contain numerous micro-cracks [14]. This property results in a less stable aggregate skeleton under compressive loading. Nevertheless, the analysis confirms that the reduction in Marshall stability caused by using RCA remains within permissible limits and does not compromise the practical applicability of PA.

3.5. Indirect Tensile Strength (ITS)

The results of the indirect tensile strength (ITS) tests are presented in Figure 8. The PA mixture using 100NA achieved an average ITS of 0.56 MPa, while the 100RCA mixture reached 0.53 MPa. This minor difference indicates that replacing 100 % NA with RA does not significantly reduce the indirect tensile performance of PA. The slight variation can be attributed to the characteristics of RCA, which exhibits lower particle strength and contains numerous microvoids, reducing the load-transfer capacity within the aggregate skeleton. Nevertheless, the small reduction suggests that the weakening effect of RCA is partially compensated by mechanical interlocking and increased asphalt coating on the aggregate surfaces.

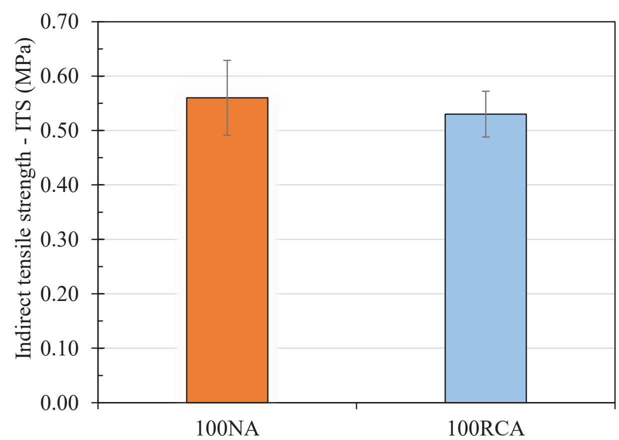

Figure 8. Indirect tensile strength of the PA samples.

3.6. Cantabro loss

Figure 9 presents the Cantabro loss results for the 100RCA and 100NA samples. The findings indicate that all PA mixtures exhibit Cantabro loss values within the allowable limits specified in TCVN 13048. The 100NA sample shows an average mass loss of 14.22 %, whereas the 100RCA sample demonstrates a significantly lower value of only 8.75 %. This substantial reduction reflects the superior raveling resistance of the mixture incorporating RCA, despite the inherently lower mechanical strength and higher porosity of RCA compared with NA. Notably, the RCA even exhibits a Los Angeles abrasion (LA) value exceeding the limit prescribed in TCVN 13048 (see Table 1). These results suggest that the asphalt–aggregate bonding in the 100RCA sample is highly effective and may even outperform that of mixtures produced with natural aggregates.

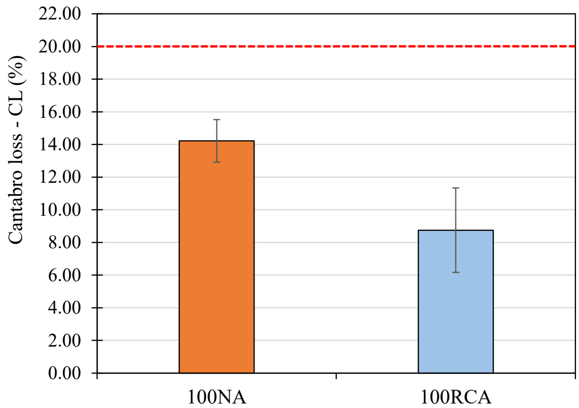

Figure 9. Cantabro loss of the PA mixtures. The dashed line indicates the maximum allowable limit specified in TCVN 13048.

3.7. Clogging Test

The clogging characteristics of PA mixtures incorporating NA and RCA are presented in Figure 10. The results indicate that the permeability coefficients of both mixtures decreased as the amount of clogging material increased. However, a clear divergence between the two mixtures was observed in the early stage of the clogging process. At 50 g of applied sediment, the 100RCA samples maintained a permeability coefficient of 0.023 cm/s, which is higher than that of the 100NA samples (0.020 cm/s). This finding suggests that the larger and more interconnected void structure of the 100RCA mixture provides better resistance to clogging during the initial phase, when sediments primarily occupy surface voids and the largest pore channels. This behavior can be attributed to the rough surface texture, abundant micro-pores, and angular shape of the recycled aggregates, which collectively contribute to a more open and interconnected void network compared with NA.

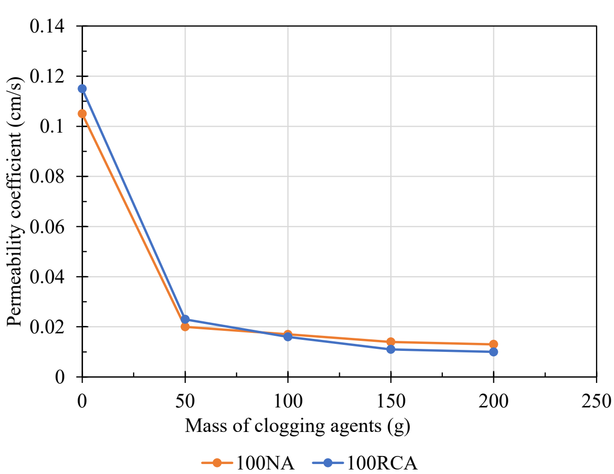

Figure 10. Clogging behavior of the applied agents on the PA mixtures.

4. Conclusions

This study evaluates the feasibility of using recycled concrete aggregate (RCA) as a full replacement for natural aggregate (NA) in the production of porous asphalt (PA). PA 12.5 mixtures were prepared using aggregates, fly ash as filler, and PMB III binder, and divided into two groups for comparison: mixtures incorporating natural aggregates (100NA) and those incorporating recycled concrete aggregates (100RCA). The results indicate that the 100RCA mixtures fully satisfy the technical requirements specified in TCVN 13048, confirming the feasibility of substituting NA with RCA in PA production. The use of RCA not only enables the recycling and reuse of concrete waste but also contributes to reducing the exploitation of natural resources, particularly construction aggregates. Furthermore, PA incorporating RCA demonstrates improved drainage capability, thereby helping to mitigate surface water accumulation and reduce the risk of urban flooding – an increasingly critical issue for developing countries such as Vietnam.

Acknowledgements

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