

Hydraulic Conductivity Response of Waste-Steel Modified Permeable Pavement Systems under Structural Damage

Réponse de la Conductivité Hydraulique des Systèmes de Chaussée Perméable Modifiés par des Déchets d'Acier sous Dommages Structurels

Andres Silva-Balaguera^{1,2}, Luis Ángel Sañudo-Fontaneda², Jose Norambuena-Contreras³

¹GIISAG, Escuela de Ingeniería Civil, Universidad Pedagógica y Tecnológica de Colombia - andres.silva@uptc.edu.co

²Civil, Environmental and Geomatics Engineering Research Group (CEGE), Department of Construction and Manufacturing Engineering, University of Oviedo, sanudoluis@uniovi.es

³Advanced Bituminous Materials Laboratory, Department of Civil Engineering, Faculty of Science and Engineering, Swansea University - j.norambuena@swansea.ac.uk

RÉSUMÉ

Les mélanges asphaltiques drainants (PAM) constituent l'une des principales surfaces utilisées dans les systèmes de chaussées perméables (PPS) et représentent un élément clé des infrastructures vert-bleu (BGI). Les PAM doivent préserver un réseau de vides efficace pour garantir une infiltration adéquate, mais leur performance hydraulique est fortement sensible aux dommages structurels tels que la fissuration. Cette étude évalue les variations de conductivité hydraulique dans des PAM incorporant des poussières de haut fourneau (BFD), un sous-produit de l'industrie sidérurgique, avant et après l'introduction d'une fissure centrale, afin de soutenir de futures applications de guérison par micro-ondes. Des mélanges compactés contenant 0 %, 4 % et 8 % de BFD (M0, M4 et M8) ont été testés afin d'évaluer l'effet de la fissuration sur la connectivité des vides, les chemins d'écoulement et le comportement hydraulique. La conductivité hydraulique (K) a été mesurée à l'aide d'un perméamètre à charge dégressive, permettant la comparaison entre des éprouvettes intactes et d'autres présentant une fissure à mi-hauteur. Les résultats montrent que la fissuration modifie le régime d'écoulement, entraînant une légère augmentation de K dans les mélanges ayant une connectivité des vides plus élevée (M0 et M4) et une augmentation plus marquée des valeurs de K dans le mélange plus dense M8. Les variations hydrauliques sont principalement régies par la structure des vides et la tortuosité, confirmant que la fissuration reconfigure les trajectoires d'écoulement au sein des PAM. Ces résultats mettent en évidence l'interaction entre les dommages structurels et la fonction hydraulique, et établissent une condition de référence pour l'évaluation de la performance de guérison par micro-ondes dans les technologies de chaussées BGI.

ABSTRACT

Porous asphalt mixtures (PAM) are one of the main surfaces used in permeable pavement systems (PPS) and represent a key Blue-Green Infrastructure (BGI). PAM must preserve an efficient void network to ensure adequate infiltration, but their hydraulic performance is highly sensitive to structural damage such as cracking. This study evaluates changes in hydraulic conductivity in PAM incorporating blast furnace dust (BFD), a steel-industry by-product, in both before and after centrally cracked states, supporting future microwave-based healing applications. Compacted mixtures containing 0%, 4% and 8% BFD (M0, M4 and M8) were tested to assess how cracking affects void connectivity, flow paths and hydraulic behaviour. Hydraulic conductivity (K) was measured using a falling-head permeameter, enabling comparison between intact specimens and those with a single mid-height crack. Results show that cracking modifies the drainage regime, with slight increasing K values in mixtures with higher void connectivity (M0 and M4) and a notable increase K-values in the denser M8 mixture. Hydraulic variation was mainly governed by void structure and tortuosity, confirming that cracking reshapes drainage pathways within PAM. These findings highlight the interaction between structural damage and hydraulic function and establish a reference condition for evaluating microwave-healing performance in BGI pavement technologies.

KEYWORDS

Blue-Green Infrastructure, Permeability, Porous Asphalt Mixtures, Stormwater management, Structural performance.

1 INTRODUCTION

Porous asphalt mixtures (PAM) are extensively used as surface layers in permeable pavement systems (PPS), presenting a central component of Sustainable Urban Drainage Systems (SUDS) aka Blue-Green Infrastructure (BGI) [1]. Previous investigations confirm that PPS substantially reduce runoff volumes, attenuate peak flows and improve water quality when their surface and sub-surface layers retain sufficient drainage throughout service life [2,3]. PAM offer a favourable balance between drainage capacity and structural performance when designed with a continuous network of interconnected voids, typically within the 18–25% Air-Void Content (AVC) range [4]. Standardised hydraulic conductivity values (K) for PAM range from 5800×10^{-5} cm/s [5] to 7000×10^{-5} cm/s [6]. This hydraulic functionality becomes highly sensitive to changes in the internal void structure under operational conditions, making K as a critical parameter for the design, monitoring and long-term maintenance of PAM.

The hydraulic response of PAM depends strongly on void connectivity, pore size distribution, and flow-path tortuosity, which collectively regulate infiltration and dissipation of hydraulic energy [4]. Most existing research has examined clogging mechanisms under repeated runoff and sediment loading while treating the mixture as structurally intact [7]. Meso-structural analyses using X-ray CT shows that void topology and effective tortuosity can substantially modify preferential flow paths, generating anisotropic or direction-dependent permeability in PAM [3,4]. The interaction between mechanical damage (specifically cracking for this study) and hydraulic performance remains underexplored, despite mounting evidence that modifications in void topology and effective tortuosity can alter preferential flow paths and significantly affect drainage efficiency in PPS.

Parallel to these hydraulic concerns, thermally induced self-healing has emerged as a strategy to extend the durability of PAM by activating temperature dependent viscoelastic recovery of the bitumen binder [8]. Microwave heating is particularly promising as it delivers rapid, volumetric energy absorption, and enabling efficient crack closure without damaging the porous framework [9]. Studies have demonstrated that incorporating microwave susceptible steel-industry by-products significantly increases heating rate, temperature uniformity, and healing efficiency, while reducing energy demand [9,10]. Moreover, the use of steel-based wastes as functional aggregates provides additional environmental benefits by promoting the use of recycled materials, and therefore, contributing to circular-economy practices in BGI techniques.

However, there is still limited evidence regarding how such waste steel-industry modifiers influence hydraulic conductivity when PAM experience structural damage before healing. Addressing this gap, the present work investigates the K-value response of PAM containing blast furnace dust (BFD) under controlled central cracking, establishing a pre-healing reference state that links void structure, tortuosity and mechanical damage to drainage performance in steel-modified permeable pavements.

2 MATERIALS AND METHODS

PAM were produced by replacing 0%, 4%, and 8% of the fine aggregate fraction (0.075–2 mm) with BFD, while keeping a constant PA-16 gradation [11]. A polymer-modified bitumen PG 76-22 was used at 5% by total mixture mass. Aggregates and BFD were dried at 170 °C for 24 h, and the bitumen was heated to the same temperature before mixing. Materials were combined in sequence (coarse aggregates, fine aggregates, bitumen, and filler) and compacted at 160 °C using a Superpave gyratory compactor with 70 gyrations. Cylindrical specimens (100 mm × 62 ± 1 mm) were prepared for physical and void analyses and labelled M0, M4, and M8. Figure 1a presents the materials components of the PAMs.

Hydraulic conductivity (K) was evaluated before and after cracking using a falling-head permeameter following the Florida Method, as illustrated in Figure 1b. The specimens were placed in the permeameter cell, ensuring watertight lateral confinement and vertical flow through the sample. A water column of known height (h_1) was established above the specimen, and the time required for the water level to fall to a second height (h_2) was recorded. This procedure was repeated until three consecutive readings differed by no more than ±4%. The hydraulic conductivity (k_v) was calculated using Darcy's law, considering the geometric characteristics of the device and the hydraulic head variation during the test. For each mixture (M0, M4, M8), the final permeability value corresponded to the mean of ten valid measurements. The schematic also highlights the influence of internal pore structure (connectivity, tortuosity and void size distribution) on flow paths, together with the potential alteration of hydraulic behaviour when cracking is introduced. Structural damage was induced at 5 °C using the Symmetric Disc Bend (SDB) test. In this configuration, a cylindrical PAM specimen (100 mm diameter, 50 mm height, and 10 mm Noch) is symmetrically loaded in a three-point bending fixture, generating a tensile stress field that initiates a central crack along the specimen mid-height, as illustrated in Figure 1b.

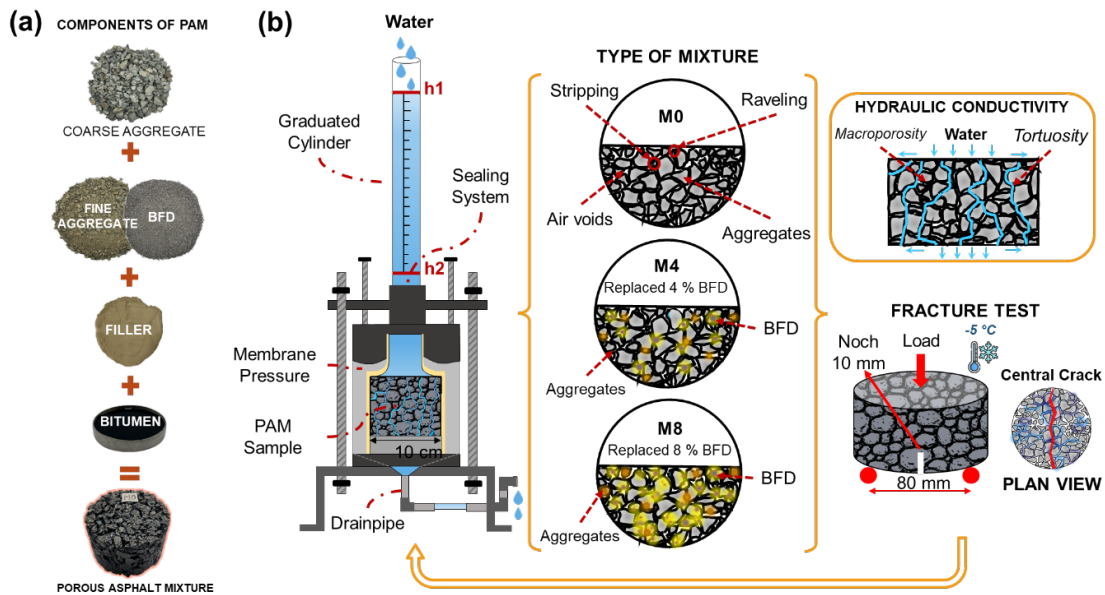


Figure 1. (a) Material components of PAM, (b) Schematic representation of the hydraulic permeability test and controlled mechanical cracking procedure.

3 RESULT AN DISCUSSION

The figure 2 present the comparison of AVC and K values for M0, M4, and M8. The results reveal that cracking increases hydraulic conductivity in all mixtures; however, the magnitude and hydraulic significance of this increase depend strongly on the internal void structure modify by BFD incorporation. Mixture M0 shows the smallest increase in K (4.6%), consistent with its relatively high initial AVC (17.3%), which already supports efficient vertical drainage. This behaviour aligns with standard PAM permeability ranges ($5,800 \times 10^{-5}$ to $7,000 \times 10^{-5}$ cm/s), in which mixtures with $AVC \geq 18\%$ typically exhibit stable, low-tortuosity flow paths.

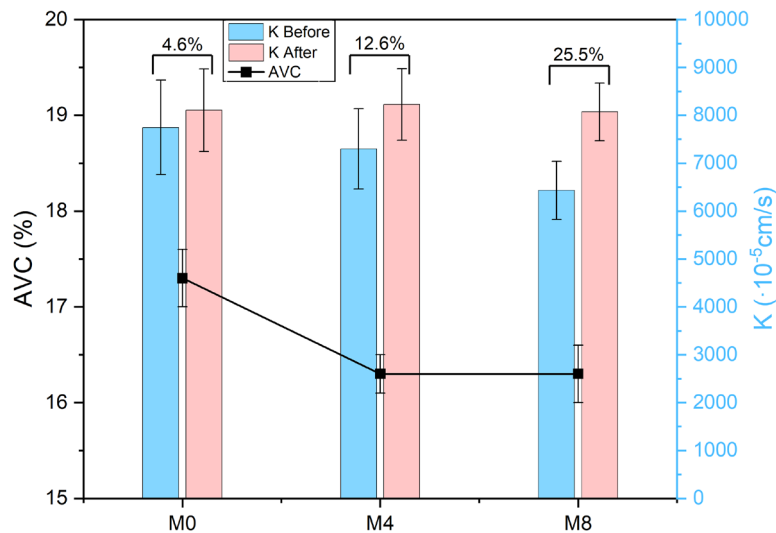


Figure 2. Air Void Content (AVC) and hydraulic conductivity (K) of mixtures in before and after cracking.

Mixture M4 exhibits a more substantial increase in K (12.6%), despite having lower AVC (16.3%). This indicates that cracking reactivates partially disconnected or highly tortuous void regions, improving hydraulic efficiency by reducing the effective flow-path resistance. This result is consistent with previous findings showing that mixtures with AVC between 17–18% can retain K-values comparable to higher-void mixes when tortuosity remains moderate. Indeed, the permeability of M4 remains close to M0, mirroring published results where mixtures with 18.1% AVC maintained values near $7,000 \times 10^{-5}$ cm/s due to favourable pore alignment and low tortuosity [4,12]. Mixture M8 presents the largest increase in K (25.5%), despite having an AVC similar to M4. This indicates that the intact M8 structure has more constricted or discontinuous voids (caused by higher BFD content) which limit

initial flow; the induced crack, therefore, becomes a dominant preferential channel, sharply reducing resistance to vertical flow. Published studies support this interpretation: mixtures with AVC $\leq 17.5\%$ typically exhibit permeability around $6,600 \times 10^{-5}$ cm/s due to restricted pore networks, consistent with the behaviour observed for M8 [4,12].

An integrated analysis of the results establishes that hydraulic conductivity in BFD-modified PAM is governed not merely by AVC but by the interaction between pore continuity, voids patterns, and tortuosity. Structural damage alters the effective flow network, sometimes improving permeability (M4, M8) by bypassing restrictive void regions. Importantly, these hydraulic responses have direct implications for permeable pavements operating as SUDS elements, where maintaining sufficient infiltration capacity after structural degradation is essential for runoff control, peak-flow attenuation, and sustained surface drainage efficiency. Moderate BFD incorporation (4%) strikes the best balance between void preservation, manageable tortuosity, and resilience to damage, maintaining permeability values aligned with standard PAM expectations and avoiding excessive sensitivity to cracking. This highlights that BFD-modified PAM, particularly M4, can contribute to more durable and reliable SUDS installations that remain functional even when subjected to cracking or early-life mechanical degradation.

4 CONCLUSIONS

- ✓ The incorporation of BFD modified the internal structure of the PAM mixtures, lowering AVC in M4 and M8 but maintaining sufficient pore connectivity for effective drainage. Among all mixtures, M4 provided the most stable hydraulic response, preserving conductivity levels comparable to standard permeable asphalt used in SUDS applications.
- ✓ Central cracking increased hydraulic conductivity across all mixtures, although the magnitude of change depended strongly on void structure and BFD content. M0 showed limited variation due to its naturally open void system, while M8 exhibited the highest sensitivity, as the crack formed a dominant preferential flow path within its more constricted pore network.
- ✓ A moderate BFD replacement (4 %) achieved the most balanced behaviour, limiting hydraulic variability after cracking. This demonstrates that M4 offers the most resilient drainage performance, providing a reliable pre-healing condition and reinforcing its suitability for SUDS-oriented permeable pavement design where both hydraulic stability and future microwave-healing interventions are relevant.

LIST OF REFERENCES

1. Tziampou, N.; Coupe, S.J.; Sañudo-Fontaneda, L.A.; Newman, A.P.; Castro-Fresno, D. Fluid Transport within Permeable Pavement Systems: A Review of Evaporation Processes, Moisture Loss Measurement and the Current State of Knowledge. *Constr Build Mater* 2020, 243.
2. Terkura, S.A.; Akib, S. Performance of Permeable Pavement Systems: A Review and Future Solutions 2024.
3. Ma, X.; Jiang, J.; Zhao, Y.; Wang, H. Characterization of the Interconnected Pore and Its Relationship to the Directional Permeability of Porous Asphalt Mixture. *Constr Build Mater* 2021, 269, doi:10.1016/j.conbuildmat.2020.121233.
4. Aboufoul, M.; Garcia, A. Factors Affecting Hydraulic Conductivity of Asphalt Mixture. *Materials and Structures/Materiaux et Constructions* 2017, 50, 1–16, doi:10.1617/s11527-016-0982-6.
5. Watson, D.; Tran, N.H.; Rodezno, C.; Taylor, A.J.; James, T.M. *Performance-Based Mix Design for Porous Friction Courses*; National Academies Press, 2018;
6. Woods-Ballard, B.; Wilson, S.; Udale-Clarke, H.; Iliman, A.; Scott, T.; Ashley, R.; Kellagher, R. *The SuDS Manual*; 2015; ISBN 9780860177609.
7. Garcia, A.; Aboufoul, M.; Asamoah, F.; Jing, D. Study the Influence of the Air Void Topology on Porous Asphalt Clogging. *Constr Build Mater* 2019, 227, 116791, doi:10.1016/j.conbuildmat.2019.116791.
8. Norambuena-Contreras, J.; Concha, J.L.; Varela, M.J.; Trigos, L.; Poulikakos, L.; González, A.; Arraigada, M. Microwave Heating and Self-Healing Performance of Asphalt Mixtures Containing Metallic Fibres from Recycled Tyres. *Materials* 2024, 17, doi:10.3390/ma17235950.
9. Norambuena-Contreras, J.; Garcia, A. Self-Healing of Asphalt Mixture by Microwave and Induction Heating. *Mater Des* 2016, 106, 404–414, doi:10.1016/j.matdes.2016.05.095.
10. Zhu, X.; Ye, F.; Cai, Y.; Birgisson, B.; Lee, K. Self-Healing Properties of Ferrite-Filled Open-Graded Friction Course (OGFC) Asphalt Mixture after Moisture Damage. *J Clean Prod* 2019, 232, 518–530, doi:10.1016/j.jclepro.2019.05.353.
11. Bustos Pretel, G.; Pérez Ibáñez, E. *Pliego de Prescripciones Técnicas Generales Para Obras de Carreteras y Puentes*; 5th ed.; Ediciones Liteam: Madrid, Spain, 2007; ISBN 978-84-95596-88-8.
12. Norambuena-Contreras, J.; Asanza Izquierdo, E.; Castro-Fresno, D.; Partl, M.N.; Garcia, Á. A New Model on the Hydraulic Conductivity of Asphalt Mixtures. *International Journal of Pavement Research and Technology* 2013, 6, 488–495, doi:10.6135/ijprt.org.tw/2013.6(5).488.