IJIE

INTERNATIONAL JOURNAL OF INTEGRATED ENGINEERING
ISSN: 2229-838X e-ISSN: 2600-7916

Vol. 18 No. 5 (2026) 324-332
https://publisher.uthm.edu.my/ojs/index.php/ijie

Sand-Rubberchips as Retaining Earth Wall Backfill: Permeability Characteristics

Salina Sani[1], Chee-Ming Chan[1,2]*, Mohammad Aliff Shah Shahrudin[3], Poi-Chong Tan[4], Nurul Syakeera Nordin[5]

[1] *Department of Civil Engineering Technology, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, 84600 Pagoh, Johor, MALAYSIA*
[2] *Research Centre for Soft Soils, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Johor, MALAYSIA*
[3] *Maha Asia Global Sdn Bhd, 51200 Kuala Lumpur, MALAYSIA*
[4] *Reinforce Soil Engineering Sdn Bhd, 81100 Johor Bahru, Johor, MALAYSIA*
[5] *Centre for Diploma Studies, Universiti Tun Hussein Onn Malaysia, 84600 Pagoh, Johor, MALAYSIA*

*Corresponding Author: chan@uthm.edu.my
DOI: https://doi.org/10.30880/ijie.2026.18.05.028

Article Info

Received: 3 April 2026
Accepted: 29 September 2026
Available online: 30 October 2026

Keywords

Backfill, retaining wall, recycled tyre, rubberchips, permeability

Abstract

Backfills are crucial in retaining wall construction, ensuring stability, structural integrity and adequate drainage. Traditionally, sand has been the primary backfill material, but it is a limited natural resource. This study explores the partial replacement of sand with recycled tyre rubberchips to reduce reliance on natural sand while enhancing sustainability. Since permeability governs the drainage capacity and long-term stability of backfills, the effect of rubberchips substitution on permeability was examined using a constant head test at substitution levels ranging from 10% to 80%. The sand had a D50 of 0.35 mm while the rubberchips had a D50 of 0.9 mm, introducing coarser particles into the matrix. Results showed a progressive increase in the permeability coefficient with increasing rubberchips content, reaching nearly twice the value for pure sand at 100% substitution. Theoretically, this can be explained by the larger void ratios and reduced inter-particle contact in the sand–rubber composite, which create more continuous flow paths. Water absorption by rubberchips was minimal, indicating a negligible risk of additional lateral pressure on the retaining wall. The 80% sand–20% rubberchips mixture yielded permeability values closest to those of sand while maintaining good drainage. These findings suggest that sand–rubberchip backfills can serve as a sustainable, high-permeability material for retaining structures, although further verification of their strength and load-bearing capacity is necessary before field application.

1. Introduction

The global rise in traffic and vehicle ownership has resulted in an ever-increasing accumulation of waste tyres. These end-of-life tyres present a significant environmental challenge due to their bulkiness, low biodegradability,

This is an open access article under the CC BY-NC-SA 4.0 license.

and unsafe disposal practices such as landfilling, stockpiling, and open burning [1]-[2]. Advances in tyre production have mainly focused on performance and durability, with limited attention to recyclability [3]. Consequently, waste tyres accumulate at alarming rates, reinforcing the need for innovative recycling strategies that support the circular economy and sustainable development goals [4].

In civil and geotechnical engineering, recycled rubber has been explored in various applications. Rubber inclusions have demonstrated benefits in transportation and infrastructure, including improving rail track stability [5], reducing pavement deformation [6], decreasing the thermal conductivity of soil–rubber composites [7], and moderating soil deformations [8]. Studies on fine-grained soils have also shown that rubber admixtures can reduce swelling and enhance ductility [9]-[11]. Beyond static behaviour, tyre-derived materials have been applied in liquefaction mitigation and seismic isolation, improving resilience of foundations and shallow structures under dynamic loading [14]-[16]. These findings highlight the engineering potential of recycled rubber, though performance often depends on the particle size, shape, and proportion used in the soil matrix.

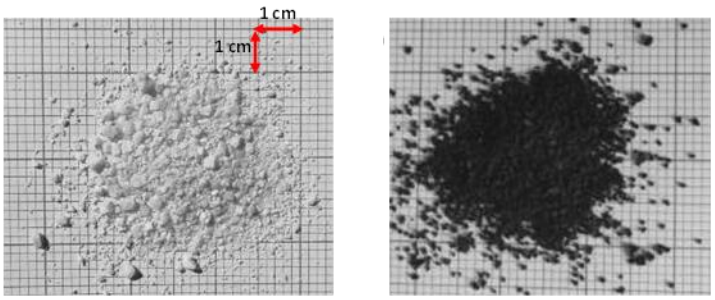
Given its granular, lightweight nature, rubberchips from shredded tyres may be a practical substitute for sand in retaining-wall backfills. In such applications, permeability is a critical property, as it governs the rate of pore water dissipation and overall drainage performance. Efficient drainage reduces hydrostatic pressure buildup, lowering lateral stresses on the retaining structure and enhancing stability. Varying the proportion of rubberchips alters the void ratio and particle interactions within the backfill, directly influencing permeability. Moreover, as rubberchips absorb minimal water, the resulting permeability is mainly dictated by particle geometry and inter-particle void distribution rather than swelling behaviour. Building on these theoretical considerations, the present study examines the permeability characteristics of sand–rubberchip mixtures with different substitution ratios, offering insights into their potential as sustainable alternatives for backfill applications.

2. Experimental Work

2.1 Materials

The sand used in this study was of river origin. Yellowish in colour, of medium size range (0.42 – 2.00 mm), it contained primarily of SiO_2 (80%) and Al_2O_3 (10%), with the presence of minimal organic content (< 0.5%), average water content of 0.8%, specific gravity of 2.75 and bulk density of 1.62 g/cm^3. Fig. 1(a) depicts the sand sample as passed through a sieve with a size of 2 mm. Pre-sieving was performed to isolate sand grains ≥ 2 mm. It was necessary for the sample to conform to the requirements of the complementary direct shear test, which was the other primary focus of the exploratory work.

The rubberchips, as shown in Fig. 1(b), were derived from used tyres. Black in appearance, irregularly shaped but with relatively angular surface texture, the rubberchips had an average specific gravity of 1.34 g/cm^3. Only chips passing a 2 mm sieve were adopted for sample preparation for the same reason. However, the rubberchips consisted of coarser fractions than the sand, and a narrower band of grain size range (see Fig. 5), which made the material of poor gradation with a singularly uniform particle size distribution.



(a) **(b)**

Fig. 1 *(a) Medium sand; and (b) Rubberchips. Both are < 2 mm in particulate size*

2.2 Tests and Measurements

2.2.1 Soaking Test

The soaking test was performed in mini glass jars, as shown in Fig. 2. Each jar was filled with the same amount of rubberchips and distilled water. The jars were shaken and left to rest for five days, with daily readings taken throughout the period. Daily, each jar would be shaken to agitate the rubberchips in the water, then left to settle under observation of the sinking time. The measurement indicates the time lapse for the agitation to subside and the rubberchips to settle down. Regardless of the rest period, some rubberchips would remain afloat or suspended

Int. Journal of Integrated Engineering Vol. 18 No. 5 (2026) p. 324-332

in the water column, while most saturated ones would be found settled at the bottom. No apparent expansion of the material was observed after soaking. Neither was the pH of the distilled water altered post-test.

2.2.2 Test

Fig. 3 shows the standard compaction test apparatus, consisting of the compaction mould (101.6 mm in diameter and 116.4 mm in height) with collar and base, and the 2.5 kg rammer. Referring to BS1377: Part 4:1990 [17], 3 kg of sample was compacted in the mould in three layers, with each layer subjected to 25 blows from a rammer dropped from a height of 305 mm. Distilled water was gradually added to each trial until a drop in density was recorded. Simple computations would then yield the dry density and corresponding water content for plotting the compaction curves. Only three samples were examined through this test: pure sand (100S), rubberchips (100R) and sand-rubberchip (50R50S).

2.2.3 Permeability Test

The constant head permeability test is commonly used to determine the permeability of reconstituted or disturbed granular soil samples, such as sands and gravels, that contain little or no silt. The test procedure is prescribed in BS1377: Part 5:1990 [18]. Water flows by gravity from an elevated, constant-level tank through the cylindrical sample in the permeameter (100 mm in diameter and 127 mm in height) at constant pressure (see Fig. 4). Recording the volume of discharge (Q) through the sample over time (t), the flow rate (q) can be readily computed. The coefficient of permeability (k) is then defined as the discharge rate under laminar flow conditions through the sample's length (l) and cross-section (A) under the hydraulic gradient induced by pressure head (h):

$$k = \frac{Ql}{Aht} \tag{1}$$

Generally, a more porous material with greater void volume would exhibit a higher k value. However, caution should be exercised regarding the material's water absorption.

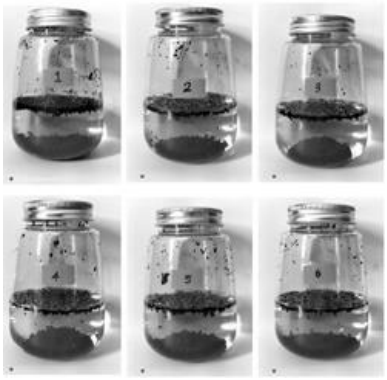


Fig. 2 *Soaking test*



Fig. 3 *Compaction test*



Fig. 4 *Permeability test*

3. Results and Discussions

3.1 Particle Size Distribution

As both sand and rubberchips were particulate materials, a conventional sieve analysis was conducted to determine their grading curves. The result is shown in Fig. 5. The overlying sand plot shows finer particles than the rubberchips, with median particle sizes (D50) of 0.35 mm and 0.90 mm, respectively. In fact, the rubberchips were almost a singular size range, 0.6 to 1.1 mm. With D50 practically 3 times that of sand, the rubberchips were apparently coarser than the sand. Both materials also recorded Uniformity (C_u) and Curvature (C_c) Indices of no more than 6 and 3, respectively.

According to ASTM D2847 [19], both sand and rubberchips fell under the category of poorly graded sand, which was not surprising as the materials were pre-sieved over a 2 mm aperture to ensure compliance with the test material to mould proportionate ratio of the experiments conducted for the programme. Nonetheless, the relatively uniformly sized materials were necessarily expedient for drainage purposes as a backfill, where the inter-particulate voids could not be adequately infilled and sealed by the fines, leading to premature blockage and retarded drainage capacity.

Soil texture refers to the size of individual particles, while soil structure refers to the arrangement of particles into aggregates. Regarding permeability, soil texture indicates that larger particles generally do not pack closely

together, resulting in larger connecting voids that allow water to flow through the medium. This phenomenon could also be influenced by the surface smoothness of the material, i.e. rubberchips with irregular surface morphology could have reduced inter-particle contact, resulting in larger voids for water to pass through. Soil structure, on the other hand, can be influenced by fines and impurities present in the medium. For instance, the sand-rubberchip composite could presumably have the finer sand particles bridging the gaps between the larger, jagged surface rubberchips. These particulate characteristics and interactions would significantly affect the mixture's permeability.

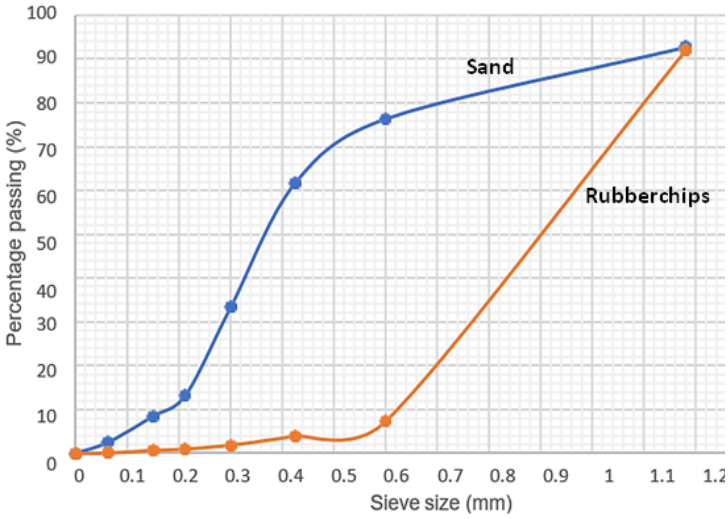


Fig. 5 *Particle size distribution plots for sand and rubberchips*

3.2 Soaking Test for the Rubberchips

Fig. 6 shows the time required for the rubberchips to settle to the bottom of the test bottle after prolonged soaking. As the soaking procedure effectively drove out air from the inherent voids, the rubberchips were pre-soaked to attain saturation. This was undertaken to determine the material's water absorption, which could adversely affect its permeability as a sound backfill. The plot is almost linear over 5 days of soaking. However, the soaking time required was no more than 35%, suggesting minimal water absorption of the rubberchips despite the inherent voids and porous surface morphology. This observation was deemed essential for estimating a possible increase in lateral pressure exerted by the sand-rubberchip backfill on the retaining wall. A higher water absorption rate could necessitate the inclusion of additional weight, thereby increasing stress on the back of the wall and introducing an unwelcome element to the innovative backfill material introduced in the present work. This is in line with observations by Lu et al. [20], where mixing scrap-tire rubber with expansive soils was found to alter the permeability and mechanical behaviour, primarily via the mixture's volume change, strength and water flow properties.

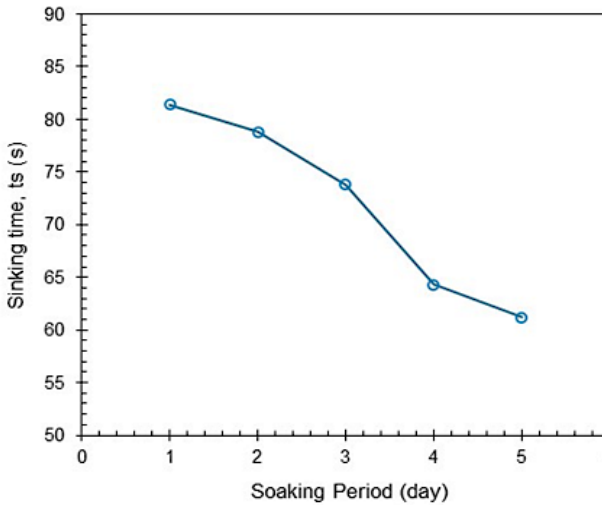


Fig. 6 *Sinking time of the pre-soaked rubberchips*

Int. Journal of Integrated Engineering Vol. 18 No. 5 (2026) p. 324-332

3.3 Compaction Data

The compaction curves for the pure sand (100S), rubberchips (100R) and sand-rubberchip (50R50S) are shown in Fig. 7, where the Y-axis depicts the dry density (ρ_d) while the X-axis represents the water content (MC). Note that the accompanying OMC values were not found to be significantly different, i.e. 15% and 19% for 100S and 100R, respectively. However, the ρ_{dMAX} values were obviously dependent on the denser sand particles, where 50% rubberchips substitution resulted in a density drop of approximately 15%. Also, it is interesting to observe the 100% increment in OMC between samples 50R50S and 100R, corroborating earlier discourse on potential effects of the voids and porosity of the rubberchips on water adsorption at the particulate level. Saparudin et al. [21] reported that adding crumb tyre rubber to clayey sand reduces ρ_{dMAX} due to rubber's low specific gravity and high compressibility, while increasing OMC as a result of greater void ratios and moisture retention. Although rubber improves ductility, it reduces stiffness and shear strength at higher percentages. Similarly, Abrantes et al. [22] found that soil–rubber mixtures exhibit lower unit weight but enhanced deformability and energy absorption, making them suitable for lightweight embankment applications. It was further demonstrated that moderate rubber contents can improve resilience and post-peak behaviour, whereas excessive amounts reduce strength.

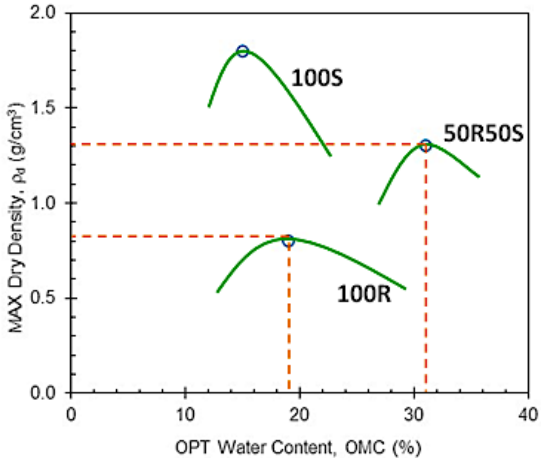


Fig. 7 *Compaction curves of the sand-rubberchip*

On the other hand, at the inter-particulate level, ρ_{dMAX} increased by 40% between samples 50R and 100R. This is attributed to the incompatibility of the sand-rubberchip particle sizes, i.e., the rubberchips being relatively larger than the sand grains, leading to the inevitable larger inter-particle voids of the matrix as evidenced by the highest OMC value for 50R50S. Notwithstanding the larger matrix pore size, the denser sand particles imparted skeletal structurisation to the composite material, as evidenced by the much higher ρ_{dMAX} than 100R. Recent studies by Afrazi et al. [23] found that rubber inclusion alters dry density, optimum moisture content and compressibility, affecting compaction efficiency and mechanical strength. Benzerra et al. [24] reported that sand–crumb rubber backfills in mechanically stabilised walls also reduce displacement and settlement under seismic loads, reflecting improved deformability despite lower compaction density. Together, these findings corroborate the present findings, highlighting that sand–rubber composites can offer a balance between compaction characteristics and mechanical resilience, making them suitable for sustainable backfill applications.

Looking at the influence of rubberchips content on the compaction test results in Fig. 8, the linear decline of ρ_{dMAX} with R clearly indicates the dominance of sand particles in the composite's load-bearing structure. The accompanying OMC plot supports the hypothesis that more water is required to fill the interparticulate voids. The drop in OMC at 100R goes on to prove 2 points: (i) the water absorption capacity of the rubberchips was negligible, and (ii) the pure rubberchips (100R) sample, though poorly graded, had a sufficient array of grain sizes to form a reasonably dense and well-packed matrix with minimal inter-particulate voids, not dissimilar to that of the pure sand (0R).

Comparatively, Kou et al. [25] showed that incorporating rubber particles into loess increases inter-particle voids, resulting in lower dry density and higher OMC. Discrete element modelling simulations also confirmed particle-size incompatibility as the main driver of reduced compaction efficiency. However, rubber–loess mixtures demonstrated improved deformation tolerance. Sun et al. [26] found that rubber–sand mixtures exhibit lower density and higher compressibility due to rubber's low specific gravity, while the dynamic compaction test revealed enhanced vibration damping and energy absorption relative to pure sand. These results indicate that optimal performance is achieved at low to moderate rubber contents, providing a balanced improvement in flexibility and stability.

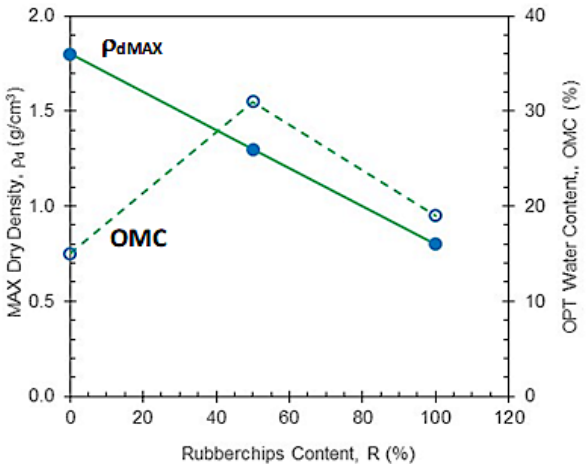


Fig. 8 *Compaction data per rubberchips content (R)*

3.4 Flow Rates and Permeability

The pure sand (100S) and rubberchips (100R) samples were examined for flow rate as controls in the test programme. Plotted against normalised time for ease of comparison, 100R showed flow rates almost twice that of 100S. This was most likely due to the higher porosity of the rubberchips because of their singularly uniform size range and larger particle size compared to the sand. In addition, the plots in Fig. 9 indicate stabilisation of the flow rate over time, with the 100R flow rate appearing to drop slightly before reaching the plateau. This can be related to the pre-existing pores in the rubberchips from the manufacturing process, though the water absorption rate was not excessive. All in all, the information on flow rate for both materials points to the potential for improved permeability and drainage capacity of the composite as backfill on site [20], [22], [26].

With rubberchips substitution ranging from 10 to 80 %, the average flow rate (Q_{AVG}) was recorded for each sample and presented in Fig. 10. Note that the slight drop in the flow rate at R = 70% could be attributed to impurities in the rubberchips, which remained intact despite the thorough cleaning before mixing the materials. Considering the initial rough use and outdoor disposal of the parent source of waste tyres, anomalies such as these may be expected in future reference. Nevertheless, the sand-rubberchip samples exhibited good drainage capacity within the high-permeability category of geomaterials, often associated with clean sands in conventional geo-construction practice. This is a positive indicator of rubberchips as a partial substitute for sand backfills. Ashiq et al. [27] demonstrated that rubber-modified backfill can offer stable, low-absorption performance with reduced permeability and unit weight, and altered moisture behaviour.

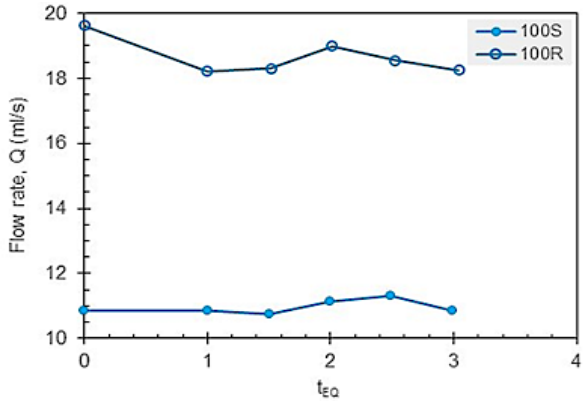


Fig. 9 *Flow rate (Q) of the sand and rubberchips*

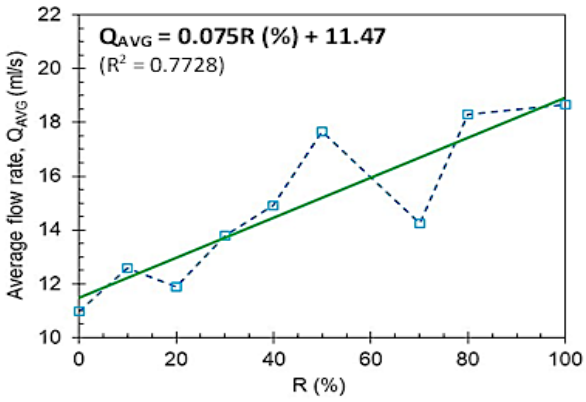


Fig. 10 *Flow rate versus rubberchips content (R)*

The flow rate generally increased with higher rubberchips content (R), where the relationship between Q_{AVG} and R was fairly linear. With a correlation levelling at ≈77%, Q_{AVG} can be related to R via a linear regression plot. At 0% R, i.e. for the pure sand condition, interpretation of the flow rate of approximately 11.5 m/s by the linear plot corresponded well with the measured flow rate of the sand, thus validating the reliability of the proposed correlation. Similar observations can be made of the 100R samples, where the flow rate was about 18.5 m/s. This correlation could serve as a quick guide for estimating the flow rate of the sand-rubberchip composite during field implementation, without subjecting the materials to time-consuming laboratory permeability tests.

Int. Journal of Integrated Engineering Vol. 18 No. 5 (2026) p. 324-332

Fig. 11 presents the coefficient of permeability (k) for the sand-rubberchip samples. As mentioned earlier, the more rubberchips were admixed with the sand, the better the performance in terms of flow rate. The positive rising trend can be modelled as an exponential equation, with a relatively high correlation coefficient (R) of over 98%. It also demonstrates that a 50% rubber-chip substitution could double the permeability of pure sand, enabling more efficient drainage as a backfill material. This would significantly reduce the risk of water retention and lateral stress induced behind the retaining structure, which could lead to undesirable wall deformation and damage. Therefore, the k–R relationship suggests that rubberchips are expedient as a sand substitute, specifically in improved drainage capacity for compliance with standard requirements.

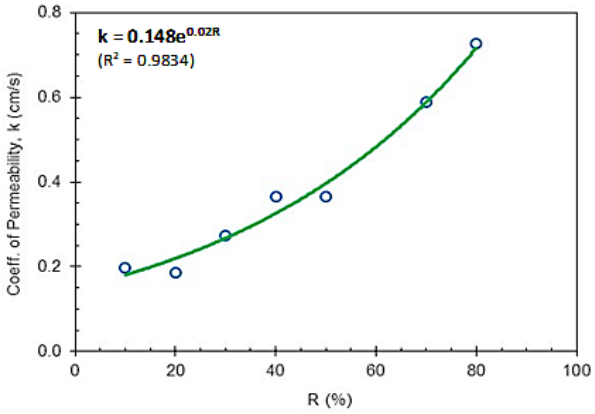


Fig. 11 *Coefficient of permeability (k) for the sand-rubberchip samples*

The permeability trends observed can be explained by fundamental principles of soil mechanics. Increasing the rubberchips content introduces coarser, irregularly shaped particles, thereby increasing the composite material's void ratio. Larger voids form more interconnected flow channels, thereby enhancing permeability. At moderate substitution levels (e.g., 20–50%), sand particles partially fill the voids between rubberchips, balancing structural packing and flow continuity. At higher substitution levels, the lack of finer particles reduces inter-particle contact, further increasing permeability. Additionally, the minimal water absorption of rubberchips ensures that the permeability rise is predominantly governed by geometric void structure rather than material swelling. This interaction among particle size distribution, void ratio, and limited absorption explains the nearly exponential increase in permeability with rubber chip content.

Fu et al. [28] conducted discrete element modelling simulations to show how rubber elasticity, particle shape and size affect microstructural behaviour, contact mechanics and void structure, directly influencing compaction efficiency and flow pathways. Likewise, Zhang et al. [29] demonstrated that layered or homogeneous sand–rubber configurations respond differently under cyclic loads, affecting particle rearrangement and pore connectivity. These findings align with the experimental results, in which increasing rubberchips content enhanced permeability by creating larger and more interconnected voids while maintaining sufficient packing through partial sand infill at moderate substitution levels. The nearly exponential rise in the coefficient of permeability with rubberchips content can thus be attributed to the combined effects of particle geometry, void ratio, and limited water absorption. Together, this study confirms that sand–rubberchip composites can be potentially engineered to optimise both drainage performance and structural stability in backfill applications.

4. Conclusions

This study investigated the permeability behaviour of sand–rubberchip mixtures as potential backfill materials for retaining walls. Laboratory tests, including soaking, compaction, and constant-head permeability, revealed that rubber-chip inclusion consistently increased permeability relative to pure sand. Theoretical considerations can explain the rise in permeability: coarser rubberchips introduce larger void ratios and reduce inter-particle contact, creating more continuous flow channels. At the same time, minimal water absorption ensures that drainage behaviour is governed primarily by geometric effects rather than material swelling.

Among the tested mixes, the 80% sand–20% rubber chip blend achieved permeability values closest to those of pure sand, providing balanced performance with good drainage capacity. Higher substitution ratios further enhanced permeability, with a 50:50 mix doubling the permeability coefficient relative to sand, demonstrating the potential for efficient pore-water dissipation. These results classify the sand–rubberchip composite as a highly permeable backfill material comparable to clean sands traditionally used in practice.

In conclusion, incorporating recycled rubberchips offers a sustainable and cost-effective approach to reducing natural sand consumption while addressing the environmental burden of waste tyres. Beyond sustainability, the improved drainage capacity of these composites suggests tangible geotechnical advantages for retaining

structures. Future work should extend to pilot-scale and field investigations focusing on shear strength, compressibility, and load-bearing capacity to establish the full engineering viability of sand–rubberchip backfills in real-world construction.

Acknowledgement

This research was funded by Reinforce Soil Engineering S/B via Industry Grant M151. Technical support rendered by the laboratories at the faculty is also acknowledged.

Conflict of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***Study conception and design:*** *Salina Sani, Chee-Ming Chan, Poi Chong Tan;* ***Data collection:*** *Mohammad Aliff Shah Shahrudin, Salina Sani;* ***Analysis and interpretation of results:*** *Chee-Ming Chan, Mohammad Aliff Shah Shahrudin;* ***Draft manuscript preparation:*** *Salina Sani, Chee-Ming Chan, Nurul Syakeera Nordin. All authors reviewed the results and approved the final version of the manuscript.*

References

[1] Bowles, A. J., Fowler, G. D., O'Sullivan, C., & Parker, K. (2020). Sustainable rubber recycling from waste tyres by waterjet: A novel mechanistic and practical analysis. Sustainable Materials and Technologies, 25, e00173. https://doi.org/10.1016/j.susmat.2020.e00173

[2] Mistry, M. K., Shukla, S. J., & Solanki, C.H. (2021). Reuse of waste tyre products as a soil reinforcing material: A critical review. Environmental Science and Pollution Research, 28, 24940–24971. https://doi.org/10.1007/s11356-021-13522-4

[3] Abbas-Abadi, M. S., Kusenberg, M., Shirazi, H. M., Goshayeshi, B., & Van Geem, K. M. (2022). Towards full recyclability of end-of-life tires: Challenges and opportunities. Journal of Cleaner Production, 374, 134036. https://doi.org/10.1016/j.jclepro.2022.134036

[4] Dabic-Miletic, S., Simic, V., & Karagoz, S. (2021). End-of-life tire management: A critical review. Environmental Science and Pollution Research, 28, 68053–68070. https://doi.org/10.1007/s11356-021-16263-6

[5] Qi., Y., & Buddhima, I. (2020). Energy-based approach to assess the performance of a granular matrix consisting of recycled rubber, steel-furnace slag, and coal wash. Journal of Materials in Civil Engineering, 32, 04020169. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003239

[6] Saberian, M., Li, J., & Setunge, S. (2019). Evaluation of permanent deformation of a new pavement base and subbase containing unbound granular materials, crumb rubber and crushed glass. Journal of Cleaner Production 230, 38–45. https://doi.org/10.1016/j.jclepro.2019.05.100

[7] Xiao, Y., Nan, B., & McCartney, J.S. (2019). Thermal conductivity of sand–tire shred mixtures. Journal of Geotechnical and Geoenvironmental Engineering, 145, 06019012. http://dx.doi.org/10.1061/(ASCE)GT.1943-5606.0002155

[8] Ru, F., Bo, Y., Hu, X., Zhou, B., & Coop, M.R. (2023). A micromechanical investigation of sand–rubber mixtures using the discrete element method. Engineering Geology, 318, 107106. https://doi.org/10.1016/j.enggeo. 2023.107106.

[9] Akbarimehr, D., Rahai, A., Eslami, A., & Karakouzian, M. (2023). Deformation characteristics of rubber waste powder–clay mixtures. Sustainability, 15, 12384. https://doi.org/10.3390/su151612384

[10] Ghareh, S., Akhlaghi, F., & Yazdani, K. (2020). A study on the effects of waste rubber tire dimensions on fine grained soil behavior. Journal of Rehabilitation in Civil Engineering, 8, 15–33. https://doi.org/10.22075/jrce. 2020.17762.1340

[11] Bekhiti, M., Trouzine, H., & Rabehi, M. (2019). Influence of waste tire rubber fibers on swelling behavior, unconfined compressive strength and ductility of cement stabilized bentonite clay soil. Construction and Building Materials, 208, 304–313. https://doi.org/10.1016/j.conbuildmat.2019.03.011

[12] Soltani, A., Deng, A., Taheri, A., & Mirzababaei, M. (2018). Rubber powder-polymer combined stabilization of south Australian expansive soils. Geosynthetics International, 25, 304–321. http://dx.doi.org/10.1680/jgein. 18.00009

[13] Eslami, A., Akbarimehr, D., Rahai, A., & Karakouzian, M. (2024). Investigation of constitutive properties of high plasticity clay soils mixed with crushed rubber tire waste. Heliyon, 10, e26655. https://doi.org/10.1016/j.heliyon.2024.e26655

[14] Nikitas, G., & Bhattacharya, S. (2023). Experimental study on sand-tire chip mixture foundations acting as a soil liquefaction countermeasure. Bulletin of Earthquake Engineering, 21, 4037–4063. https://doi.org/10.1007/s10518-023-01667-1

[15] Pistolas, G.A., Pitilakis, K., & Anastasiadis, A. (2020). A numerical investigation on the seismic isolation potential of rubber/soil mixtures. Earthquake Engineering and Engineering Vibration, 19, 683–704. https://doi.org/10.1007/s11803-020-0589-3

[16] Paramasivam, B., Dashti, S, & Liel, A.B. (2020). In-ground gravel–rubber panel walls to mitigate and base isolate shallow-founded structures on liquefiable ground. Journal of Geotechnical and Geoenvironmental Engineering, 146, 04020087. http://dx.doi.org/10.1061/(ASCE)GT.1943-5606.0002310

[17] BS1377: Part 4 (1990). Methods of Test for Soils for Civil Engineering Purposes- Compaction-Related Tests. British Standards Institution.

[18] BS1377:Part 5 (1990). Methods of Test for Soils for Civil Engineering Purposes- Compressibility, Permeability and Durability Tests. British Standards Institution.

[19] ASTM D2487 (2000). Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System). ASTM International.

[20] Lu, Y., Zhang, Y., Liu, S., Guo, W., & Xu, F. (2022). Mechanical behaviour and permeability of expansive soils mixed with scrap tire rubbers subjected to freeze–thaw cycles. Cold Regions Science and Technology, 199, 103580. https://doi.org/10.1016/j.coldregions.2022.103580

[21] Saparudin, M. A., Zainorabidin, A., Tajudin, S. A. A., Kalatehjari, R., & Hassan, W. N. F. W. (2022). Compaction behaviour of clayey sand mixed with crumb tyre rubber under varying rubber content. IIUM Engineering Journal, 23, 87–98.

[22] Abrantes, L. G., Mahler, C. F., Riccio Filho, M. V., Soares, D. A. C., & Cury, A. A. (2025). Mechanical parameters of soil–rubber mixtures for sustainable geotechnical projects. Soils and Rocks, 48, 1–13.

[23] Afrazi, M., Armaghani, D. J., Afrazi, H., Mohamad, E. T., & Yaghoubi, M. (2025). Geotechnical implications of sand–rubber mixture in transportation infrastructure: Assessing shear strength and compressibility characteristics. Innovative Infrastructure Solutions, 10, 21. https://doi.org/10.1007/s41062-025-02173-w

[24] Benzerra, M., Chehab, A., Sadek, M., & Tatsuoka, F. (2023). Seismic performance of mechanically stabilized earth walls with sand–crumb rubber backfills of varying proportion. Construction and Building Materials, 389, 131630. https://doi.org/10.1016/j.conbuildmat.2023.131630

[25] Kou, W., Bai, J., Li, H., & Liu, Q. (2023). Study on compaction characteristics and discrete element simulation for rubber-particle loess mixed soil. Insight – Civil Engineering, 6, 618.

[26] Sun, W., Xie, Q., Li, H., Chen, J., & Wu, K. (2023). A dynamic assessment of rubber–sand mixtures as subgrade materials during vibratory roller compaction through DEM simulation in 2D. Sustainability, 15, 14238.

[27] Ashiq, H. M., Shahin, H. M., & Sabab, S. R. (2025). Augmenting the geotechnical properties of sandy soil by adding rubber tire crumb waste. NexRes, 2, 100823. https://doi.org/10.1016/j.nexres.2025.100823

[28] Fu, R., Yang, B., Hu, X., Zhou, B., & Coop, M. (2025). Micro-mechanical analysis of sand–rubber mixtures with discrete element method. Acta Geotechnica, 20, 4289–4309. https://doi.org/10.1007/s11440-025-02670-3

[29] Zhang, X., Chen, Y., Wang, Z., Liu, J., & Li, H. (2024). Effect of layering and pre-loading on the dynamic properties of sand–rubber specimens in resonant column tests. Acta Geotechnica, 20, 607–624. https://doi.org/10.1007/s11440-024-02398-6