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Innovative Eco-Porous Paver Materials as a Sustainable Approach with Recycled Tyres and Polyurethane

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Abstract

This paper will help to consider Crumb Rubber (CR) with Polyurethane Binder (PU) as one of the sustainable materials for porous pavers besides increasing tire waste. Three mix ratios were considered: Sample A (90% CR : 10% PU), Sample B (80% CR : 20% PU) and Sample C (70% CR : 30% PU). The eco-porous paver samples are tested for water permeability test (ASTM D2434) and slip resistance test (ASTM E303-93). All mixes attained minimum standard values of British Pendulum Number, however, the permeability coefficients are much below the required limits. The results clearly state mechanical, environmental and economical aspects or benefits of using tire waste in constructions related to Sustainable Development Goals (SDGs) 9, 11 and 15 besides potentials for urban infrastructure and green building applications.

1. Introduction

The biggest environmental challenge comes with the increase of urban population and industrial activity, particularly from solid waste management where used tires pose a big problem because they do not decompose. They occupy landfill space and create health problems besides space issues hence an alternative creative recycling method is urgently needed. One innovation involves using shredded used tires as materials for making permeable pavement known as eco-porous pavers that allow stormwater in urban areas to be effectively managed while still posing a challenge on how their permeability together with structural integrity can be maintained [1]. A mixture crumb rubber (CR) and polyurethane (PU) binder has good permeability plus durability which addresses both issues of managing stormwater resistance on weather conditions [2]. The project targets finding an economical, sustainable and long-lasting pavement solution through investigation of different material properties and mixed ratios.

Waste tires are not biodegradable. They would take hundreds of years to break down even if they were disposed of in landfills [3]. They support infrastructure, public health and ecosystem. The sustainable solution is recycling them into CR for use in construction materials. However, challenges arise since there is a loss of strength when incorporating CR into paving without proper binders. A good binder will be required so as to ensure stability within the pavement structure by preventing dissolution particles as well as making sure water permeability which shall act on stormwater management hence requiring an eco-porous paver properly designed PU is recommended due to its ability porosity weather resistance durability optimal ratios between CR and PU required attain sustainability paving solutions balancing permeability strength flexibility [4].

This study is based on the development, production and testing of eco-porous paver materials comprising CR and PU binder with three different mixes as Sample A (90% CR : 10% PU), Sample B (80% CR : 20% PU) and Sample C (70% CR : 30% PU). The results from varying ratios have been analyzed in terms of the effects on mechanical strength, permeability and performance properties. The findings reveal that bond strength between mixtures increases with an increase in a PU biner thereby enhancing durability together with other properties of

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the mixtures. Permeability test results besides slip resistance values conducted according to ASTM specification pedestrian application targeting composite optimum both strong yet highly permeable.

Porous pavers made from CR and PU binders support the reduction in use of natural raw materials, meanwhile promoting the recycling of waste tires to reduce soil pollution by aiding sustainable development. Improvements added to durability make these eco-friendly materials much better than conventional porous pavers that crack easily under stress. Low production temperatures imply energy consumption and carbon footprints which benefit two different aspects yet harm none. The project addresses several Sustainable Development Goals (SDGs) through building material innovation, a sustainable city concept, conservation practiced through utilization of waste as an additional resource hence green infrastructure environmental sustainability advancement [5].

2. Methodology

The materials used in the experiment were CR and PU binder. The experimental program was systematically designed including sample preparation, curing, and test methods to ensure result accuracy and repeatability. Different binder to rubber ratios was used to study their impact on mechanical as well as surface properties of the porous pavers. Since slip resistance and permeability tests represent the main functional characteristics of porous pavement materials; surface safety and water infiltration capacity; the sample design has been made to satisfy these requirements.

2.1 Materials

CR and PU binder as shown in Figure 1 were selected as the primary materials of this study on mechanical performance for eco-porous paver. The material selection was based on proven compatibility and suitability to meet performing requirements of sustainable porous pavement systems. Mechanical strength characteristics ensure sufficient while maintaining functional characteristics required for eco-porous paver applications.

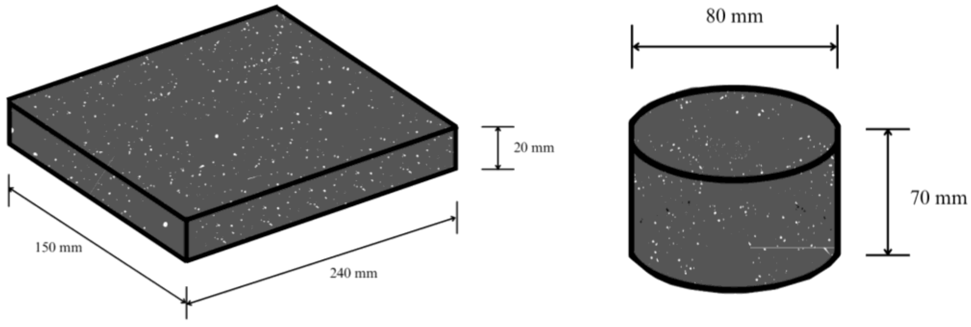
(a) (b)

Fig 1. *Materials Used (a) Crumb Rubber (b) Polyurethane Binder*

CR obtained from waste tires, is always preferred due to its durability [6]. Other important factors in selecting CR include particle size 1mm – 3mm for uniformity in size particles and completely washed and dried so that adhesion between PU and particles can be improved [7]. PU is selected due to high adhesive property, flexibility, long-lasting durability therefore suitable to be used outdoors [8]. Major factors considered while selecting PU include high quality specification meant for outdoor usage with strong adhesive strength which plays a vital role in holding composite material structurally [9][10][11].

2.2 Procedure

A test procedure is defined with two shapes of samples in Figure 2; (a) rectangular and (b) circular. The rectangular sample will be used in slip resistance testing with a flat surface in contact with slip test apparatuses, simulating pedestrian walkways and investigating friction behavior and safety performance. The circular sample will be chosen for the permeability test to provide a consistent flow path for vertical infiltration and assume isotropic water flow in playground and pedestrian area as a real application. Both designs are important to achieve an accurate and reliable assessment of composite performance characteristics.



(a) (b)

Fig 2. *Design (a) Rectangular Sample (b) Circular Sample*

The preparation of samples is key to the assessment of pavement performance using CR and PU binder mixture in certain volume-based ratios that ensure consistent dispersion of CR as well as control over the quantity of material used. The material composition as in the Table 1 and Table 2, which by mass, of eco-porous paver samples (derived from sample volume) defines the mass distribution between CR and PU for both rectangular and circular sample compositions; this has been tabulated. The fabrication process involves material preparation, mould preparation and a systematic process for mixing, weighing and curing to obtain uniform and reliable samples which are then subjected to mechanical property testing after 24 hours initial curing plus another 7 days under controlled conditions.

Table 1 *Rectangular Slip Resistance Sample Composition*

Sample	Size (mm) (l x w x h)	Volume		CR		PU	
		mm³	kg	%	kg	%	liter
A	240 x 150 x 20	7.2 x 10⁵	0.72	90	0.648	10	0.072
B	240 x 150 x 20	7.2 x 10⁵	0.72	80	0.576	20	0.144
C	240 x 150 x 20	7.2 x 10⁵	0.72	70	0.504	30	0.216

Table 2 *Circular Permeability Sample Composition*

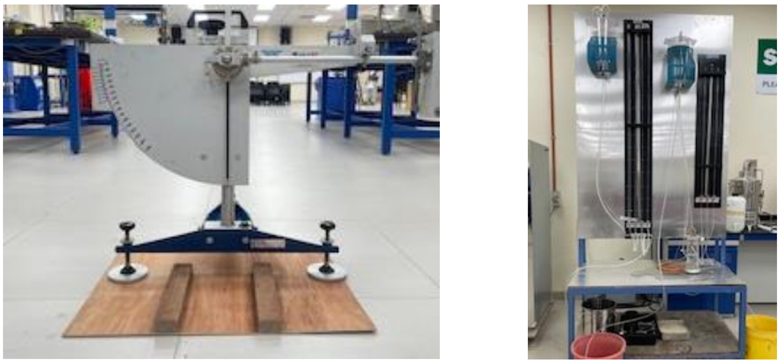
Sample	Size (mm)	Volume		CR		PU	
		mm³	kg	%	kg	%	liter
A	d: 80, h: 70	3.52 x 10⁵	0.352	90	0.317	10	0.035
B	d: 80, h: 70	3.52 x 10⁵	0.352	80	0.282	20	0.070
C	d: 80, h: 70	3.52 x 10⁵	0.352	70	0.246	30	0.106

Fig 3. *Sample Eco-Porous Paver*

Eco-porous paver samples prepared for laboratory testing as shown in Figure 3, consist of cylindrical samples designated for the permeability test and rectangular samples designated for the slip resistance test. Dimensions and specified ratios of CR:PU binder were maintained in each sample. The samples were properly labelled, and then cured under controlled conditions at room temperature. The samples then were kept at room temperature until it underwent the respective laboratory testing procedures

2.3 Characterization

The study focuses on laboratory testing the CR:PU materials, specifically in terms of slip resistance and permeability. Slip resistance test is vital for applications like pedestrian and playground surfaces, while permeability testing assess water flow through the composite, contributing to effective drainage and reducing flooding risks. This test is aimed at checking environmental performance together with functional safety of CR:PU material.



(a) (b)

Fig 4. *Test Machine (a) British Pendulum Test (b) Constant Head Permeability Test*

2.3.1 Slip Resistance

As per ASTM E303-93 standard, the British Pendulum Test (BPT) as shown in Figure 4 (a) was used to determine the slip resistance of CR:PU composites by measuring surface micro-texture. Several steps are involved in this testing procedure which include weighing the sample; positioning platform for BPT firmly on floor; setting machine calibration with trial swing; performing actual pendulum test and taking several readings to average out a value of lip resistance for each sample. Same set of steps has been followed for all samples tested.

2.3.2 Permeability

According to ASTM D2434, the test was carried out on CR:PU composites to determine the water permeability by means of a constant head permeability test as shown in Figure 4 (b). The steps involved sample and apparatus preparation, dry mass determination of samples, setting up the permeability apparatus allowing water flow into the sample without overflow carefully monitoring manometer levels so as to maintain a constant head difference recording flow rates with time computation of k using Darcy's Law (Eq 1). This is very instrumental in applications involving stormwater management.

$$k = \frac{q}{Ai} \qquad \text{(Eq 1)}$$

Where,	k	=	Coefficient of permeability (cm/s)
	q	=	Rate of flow water (m^3/s)
	A	=	Cross-sectional area of the specimen (m^2)
	i	=	Hydraulic gradient

2.4 Data Analytic Strategy

Test findings were analyzed statistically and graphically. Descriptive statistics such average values facilitated a summary of the performance for each combination and highlighted comparisons between different CR:PU ratios through graphical representation, which clearly exhibited patterns and relationships between mix composition and mechanical p0erformance of eco-porous paver.

The performance of each composite mixture was tested against key pavement performance criteria. To determine whether the slip resistance and permeability values met minimum acceptable requirements for porous pavement applications, recognized standards for water permeability test (ASTM D2434) and slip resistance test (ASTM E303-93) were used with which to compare the investigated results [12][13]. The test confirmed that the designed eco-porous paver attained appropriate levels of permeable performance and slipping safety.

Subsequently an optimization evaluation was carried out by taking into account the combined results of permeability performance and slip resistance. The best CR:PU ratio was determined by analyzing the relationship between surface friction and water infiltration capacity. Based on its capacity to delivery balanced performance and practical applicability for actual porous pavement applications, the optimal combination was chosen.

3. Results

The results of slip resistance and permeability tests conducted on eco-porous paver samples with different CR:PU ratio mixtures are presented and discussed. Summary values for the permeability coefficient in cm/s and slip resistance expressed in BPN, are shown in Table 3. The result was used to determine the effects on water infiltration capacity as well as surface friction performance due to increasing content of PU. Sample A, B and C have been compared to determine an optimum mix ratio that provides a balanced performance suitable for use in porous pavement applications.

Table 3 *Result Findings*

Sample	Mixture Ratio CR:PU	Weight Sample		Test Results	
		Rectangular (g)	Circular (g)	Slip Resistance (BPN)	Permeability (cm/s)
A	90% CR : 10% PU	585.4	628.5	24.4	4.25×10^{-9}
B	80% CR : 20% PU	738.7	711.0	61.6	6.96×10^{-9}
C	70% CR : 30% PU	814.1	575.6	66.4	4.62×10^{-9}

3.1 Slip Resistance Result

Slip resistance is critical in pavement safety involving walking control. Hence, testing ensures that materials contribute to surface roughness and friction performance [14]. The test was conducted following ASTM E303-93 using a British Pendulum Test (BPT) to determine the slip resistance of eco-porous paver samples concerning pedestrian pavement safety. Results in Figure 5 shows a higher British Pendulum Number (BPN) values at high propositions of PU binder, hence better slip resistance. Sample A recorded the lowest average BPN value of 24.4, while Sample B and Sample C recorded higher BPN values of 61.6 and 66.4, respectively under wet conditions.

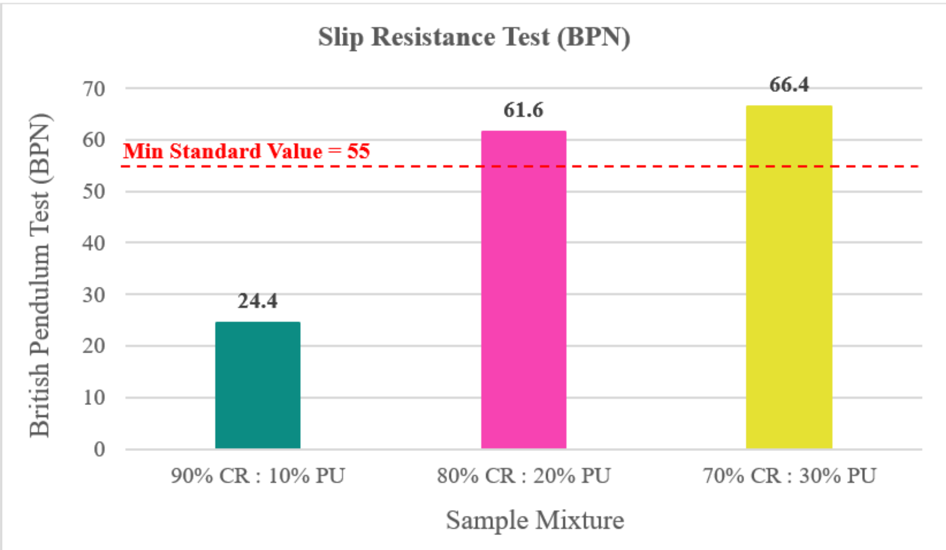


Fig 5. *Graph of Slip Resistance Result*

Sample A gave the lowest value of BPN at 24.4, which indication of poor slip resistance because the content of CR is high. On the other hand, Sample B and Sample C recorded very high and stable values of BPN at 61.6 and 66.4 respectively thus categorized as excellent and good in slip resistance. The minimum standard for pedestrian surface is 55 BPN (ASTM, 2022). Therefore, from the results obtained it can be inferred that decreasing CR while increasing PU binder improves slip resistance with optimum mixtures containing 20% - 30% PU binder suitable for walkway applications

3.2 Permeability Result

Permeability testing is very crucial in stormwater management to check if material such as eco-porous paver absorb water effectively, especially when installed in high rainfall regions [15]. The test basically determines the flow rate and permeability coefficient (k) under controlled conditions referenced by standard ASTM D2434 (ASTM, 2000). This hence shows how different mixtures of eco-porous paver perform with calculated values of k showing low permeability on all samples thus these materials do not meet the necessary drainage requirement. The findings in Figure 6 shows there is a need for improved water infiltration for sustainability on urban water management.

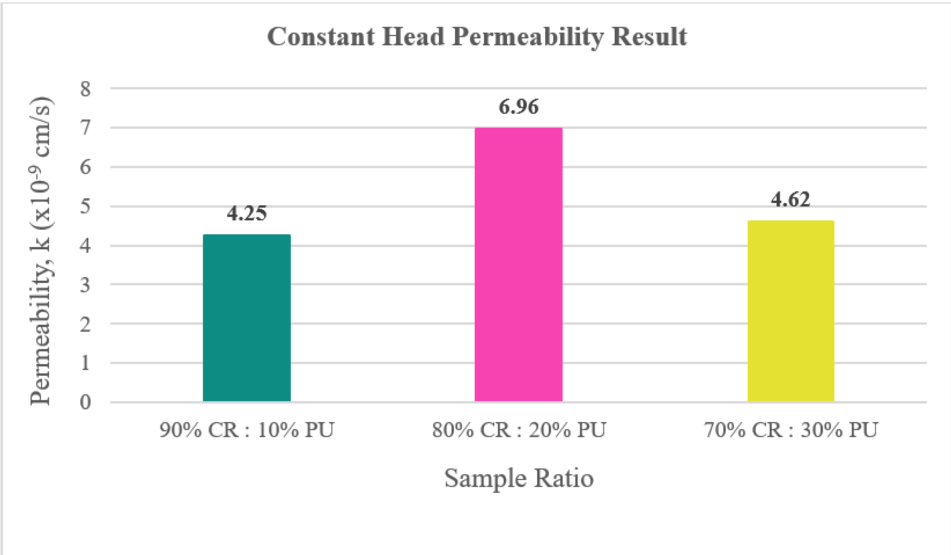


Fig 6. *Graph of Permeability Result*

Permeability test was conducted in accordance with ASTM D2434. However, none of the samples attained the minimum required permeability for pedestrian porous pavement. Sample A, Sample B and Sample C recorded permeability coefficient values of Sample A: 4.25 x 10^{-9} cm/s, Sample B: 6.96 x 10^{-9} cm/s and Sample C: 4.62 x 10^{-9} cm/s respectively which could be classified as lowest and slightly higher permeability.

4. Discussion

The BPT was carried out to determine the slip resistance value of eco-porous paver while permeability test using Constant Head Permeability method was also conducted as summarized in Table 4. Sample A recorded a value of 24.2 BPN which is much lower than 55 BPN minimum requirement for pedestrian pavements hence indicating insufficient friction. However, Sample B and Sample C recorded 61.6 BPN and 66.4 BPN respectively both within standard limitations. The results clearly indicate that by enhancing particle bonding and stability on the surface, higher content of PU binder reduces the surface friction.

All samples illustrated permeability coefficients within the range of 10^{-1} cm/s, hugely less than the typical requirement for porous pavement of between 10^{-3} and 10^{-2} cm/s. None of the samples achieved the allowed range of permeability. This clearly indicates that water infiltration was restricted by combined effects of PU binder concentration and CR gradation which reduced pore connectivity (permeability paths). The results showed a highlighted implication that compaction and binder content possess an influence on hydraulic performance regarding eco-porous paver. The evaluation of both slip resistance and permeability tests result were shown in Table 4. The results were compared to ASTM standard to fulfill the pedestrian's requirement safety.

Table 4 *Evaluation of Test Results*

Sample	Mixture Ratio CR:PU	Results		Remarks
		Test	Value	
A	90% CR : 10% PU	Slip Resistance	24.4 BPN	Poor – Below Standard
		Permeability	4.25×10^{-9} cm/s	Lowest
B	80% CR : 20% PU	Slip Resistance	61.6 BPN	Good – Within Standard
		Permeability	6.96×10^{-9} cm/s	Slightly higher
C	70% CR : 30% PU	Slip Resistance	66.4 BPN	Excellent – Meets Max Limit
		Permeability	4.62×10^{-9} cm/s	Lower

There was, overall, a clearly noticeable relationship between permeability and slip resistance. More binder content improves slip resistance at the price of permeability while higher CR content tends to boost porosity but lowers surface safety. Sample C is considered the best option for pedestrian porous pavement applications since it offered the most balanced performance among the studied combination. However, to get sufficient drainage performance without sacrificing surface safety, additional mixture design optimization is required that includes modifications to the binder content and CR gradation.

5. Limitation and Recommendation

Despite the well thought out planning of the experimental technique, there re a few limitations which should be noted. Slight variations in material properties due to differences in source and quality of PU binder and CR may affect result reproducibility. All tests were conducted under completely controlled laboratory conditions that do not represent real environmental factors such as traffic loading, temperature variation, rainfall and wind exposure. This automatically dictated, by time and resources available for the study, number of samples tested hence could have impact on statistical confidence as well as generalization of the findings.

The eco-porous paver samples tested in this study only barely met the minimum permeability requirements. Further optimization is necessary. On options for material composition enhancement includes adjusting the PU binder content to improve void interconnectivity without having an excess amount that could potentially block flow paths. Future research may consider alternative binders which occupy less pore space, larger or well-graded aggregates to promote a more open pore structure, and use of natural fiber additives or foaming agents to increase porosity and consequently drainage efficiently. Permeability increased with lower compaction pressure hence mixing, compaction and curing conditions optimizations can also targeted for better mechanical performance. Reinforcement techniques such as geogrid pr polymer fibers can be incorporated to enhance the durability and load-bearing capability for intended pavement applications.

6. Conclusion

Eco-porous paver has passed different tests. Sample B and Sample C results show that the minimum slip resistance requirement according to ASTM E303-93 is satisfied for safe walking conditions, but permeability results do not even reach values recommended together with standards of ASTM D2434. Test results prove the eco-porous paver supports CR from waste tires in the application of circular economy concepts within sustainable infrastructure, it contains materials recovered form recycling processes which demonstrate reduced reliance on nonrenewable resources as cost construction material with durable, slip resistance pavement suitability [16].

Sample C proved good performance from the results of all tests conducted. It had a very balanced performance with a slip resistance value of 61.1 BPN, safe enough for pedestrians, though slightly lower permeability requirements to qualify as good for stormwater management. Its structure still needs further connectivity improvement in mix design since, among samples it has the highest permeability and apparent connected pores. The selection shall inculcate sustainable construction through recycled materials while enhancing safety sustainability environmentally in a circular economy concept where future research shall focus on optimum particle size and content binder [5].

Eco-porous paver composites containing CR:PU is an effective alternative solution to conventional paving materials with safe slip resistance and adequate durability, meanwhile permeability needs further optimization which also supports the practice of a circular economy since this material utilizes waste such as CR. The innovation fits several Sustainable Development Goals (SDGs) mainly by improving infrastructure quality (SDG 9) and better stormwater management (SDG 11) through enhanced porous pavements while reduce landfill disposal on environmental degradation (SDG 15). Eco-porous paver is indeed one big leap toward sustainable construction and urban development.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Nornishah Azani, Sufyan Abdullah, Hilmi Kosnin;* ***data collection:*** *Nornishah Azani;* ***analysis and interpretation of results:*** *Nornishah Azani;* ***draft manuscript preparation:*** *Nornishah Azani. All authors reviewed the results and approved the final version of the manuscript.*

The author confirms sole responsibility for the following: study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

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