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Green Eco-Friendly Paver Blocks Integrating Textile Dyeing Effluent Sludge (TDES) Alongside Raw River Water Influent Sludge (RRWS)

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Abstract

The growing emphasis on sustainable construction materials has led to the exploration of industrial waste as viable alternatives. This study investigates the use of textile dyeing effluent sludge (TDES) and raw river water influent sludge (RRWS) in the production of eco-friendly paver blocks, aiming to promote sustainability while maintaining structural performance. Paver blocks were prepared with varying proportions (5%, 10%, 15%, and 20%) of TDES and RRWS to assess their impact on physical, chemical, and mechanical properties. Physical characterization included specific gravity and particle size analysis, while chemical composition was examined using X-ray Diffraction (XRD) and Scanning Electron Microscopy with Energy Dispersive X-ray Spectroscopy (SEM-EDX). Mechanical testing evaluated compressive strength, density, water absorption, and initial rate of absorption. A control mix was used for comparison. TDES exhibited a low specific gravity (0.87), indicating poor suitability for structural applications. In contrast, RRWS showed greater stability (1.91), with particle grading favorable for flexibility. XRD and SEM-EDX confirmed the presence of cementitious compounds like silicon oxide (SiO_2) and calcite ($CaCO_3$), supporting the potential for partial replacement of traditional materials. Results showed that increasing TDES and RRWS content led to reduced compressive strength and increased porosity. However, the 5% RRWS mix achieved a compressive strength of 47.58 MPa, only slightly lower than the control (52.65 MPa), suggesting viable use at lower concentrations. In conclusion, the incorporation of TDES and RRWS in paver blocks presents a promising approach to recycling industrial sludge and enhancing the sustainability of construction materials. Optimal performance was observed at 5% RRWS content, balancing environmental benefits and mechanical integrity.

1. Introduction

Malaysia's construction industry is rapidly expanding owing to urbanisation and population growth, driving high demand for concrete and its key components, particularly sand and cement. However, the excessive extraction of these raw materials has led to significant environmental degradation. For instance, unregulated sand mining in Malaysian rivers, such as Sungai Pahang and Sungai Langat, has caused riverbank erosion, increased sedimentation, and the destruction of aquatic habitats [1]. Globally, sand is the second most exploited natural resource after water, with an annual usage of approximately 50 billion tonnes, equivalent to building a wall 27 m high and 27 m wide around the Earth every year [2]. Such high demand disrupts ecosystems, alters river hydrology, and contributes to the loss of biodiversity. To mitigate these impacts, the reuse of industrial waste, such as textile dyeing effluent sludge (TDES) and raw river water influent sludge (RRWS), has emerged as a sustainable alternative in concrete paving block (CPB) production. Replacing traditional materials with TDES and RRWS conserves natural resources and supports waste management efforts by diverting sludge from landfills. This approach aligns with Malaysia's sustainability goals and the construction industry's shift towards more environmentally friendly practices [3].

A promising alternative is textile dyeing effluent sludge (TDES), a byproduct generated in large quantities of approximately 25 m^3 per million tonnes of treated wastewater [4]. This sludge contains various physicochemical components, including precipitated dyes, inert solids, polymers, and heavy metals such as lead (Pb), chromium (Cr), cadmium (Cd), and zinc (Zn). These heavy metals are mainly present in stable forms, such as oxidisable or residual fractions, indicating their potential for safe reuse [5]. Although commonly landfilled, this sludge has properties that make it suitable for repurposing, particularly in construction. The effective utilisation of waste materials can significantly reduce environmental impact by decreasing the volume of waste sent to landfills and reducing dependence on non-renewable raw materials. This approach supports resource conservation and promotes sustainable construction practices.

Concrete paving blocks (CPBs), which are widely used in urban infrastructure owing to their durability and low maintenance, are traditionally made from cement, sand, and gravel. However, with increasing urbanisation, innovations in material composition are essential for enhancing sustainability. Incorporating recycled materials, including textile dyeing sludge and raw river water influent sludge, into CPBs can reduce the reliance on cement and sand, aligning with environmental sustainability goals. TDES consists of fine particles enriched with metal oxides and precipitated compounds, many of which demonstrate pozzolanic activity similar to that of materials such as fly ash. This enables TDES to contribute to improved binding performance and increased packing density in concrete mixtures while supporting the alkaline conditions essential for effective cement hydration [5]. In contrast, RRWS, characterised by its granular structure, functions effectively as a fine aggregate substitute. As a fine aggregate replacement, RRWS enhances concrete workability, decreases brittleness, and improves the resistance to cracking within the matrix [6]. These materials not only reduce the demand for virgin resources but also divert significant amounts of waste from landfills. Given that cement production is a major contributor to global CO_2 emissions, reducing its use through alternative materials presents a viable solution to both environmental and resource challenges

The Malaysian government is committed to sustainable growth by 2030 and is promoting recycling in construction to reduce dependence on natural resources. Researchers advocate the adoption of low-carbon alternatives while ensuring compliance with sustainability standards, such as energy efficiency, environmental impact reduction, and recyclability. With industrial waste expected to reach 27 billion tons by 2050, repurposing these materials for construction offers a strategic approach to waste reduction and eco-friendly development in the construction industry [7].

2. Literature Review

The textile industry produces vast amounts of wastewater filled with harmful pollutants, such as dyes, salts, and suspended solids, creating serious environmental concerns. Chemicals used in dyeing and printing processes are non-biodegradable, making conventional treatment methods less effective and negatively impacting aquatic ecosystems. Protecting water sources for drinking and irrigation requires efficient wastewater treatment systems. Various treatment technologies exist to eliminate pollutants before discharge, including physical, chemical, biological, and hybrid approaches that address the challenges posed by textile wastewater [8].

Among the widely used methods, the activated sludge process relies on microbial action to break down organic contaminants. Although effective, this process generates sludge containing hazardous substances that require careful disposal. Traditional disposal techniques, including incineration and landfilling, contribute to environmental pollution, necessitating the development of sustainable alternatives. One potential solution involves recycling textile dye effluent sludge (TDES) into construction materials, particularly as a cement additive, thereby reducing its environmental footprint. Studies indicate that replacing up to 20% of cement with TDES in M30-grade concrete maintains structural strength, with an optimal replacement level of 15%. Another wastewater byproduct, Raw River Water Influent Sludge (RRWS), can also be utilised in construction, offering a viable solution to disposal challenges.

Coagulation and flocculation are crucial for enhancing sludge treatment by aiding the removal of suspended solids and improving water quality. The use of coagulants, such as aluminium sulphate and iron salts, enhances sludge dewatering and lowers operational costs in wastewater treatment plants. Bio-flocculants derived from natural sources are an eco-friendly alternative to synthetic chemicals, further supporting sustainable treatment solutions. In addition to improving treatment processes, innovative waste management approaches, such as converting textile sludge into activated carbon for pollution control or using vermicomposting to recycle nutrients, provide environmentally responsible disposal options [9].

The development of Green Paver Blocks (GP Blocks) made from textile sludge offers an innovative and practical approach to sustainable construction. Research has demonstrated that these blocks achieve compressive strengths exceeding 20 MPa, making them suitable for use in urban infrastructure. In addition to their mechanical performance, the pigments and residual dyes present in textile sludge may contribute to the natural colouration of the blocks, potentially reducing the need for additional surface treatments or artificial colouring agents [8]. This not only offers aesthetic variation but may also lower production costs. Repurposing textile sludge in construction reduces industrial waste while promoting sustainability and circular economy principles [6]. Further research and development are required to refine these applications for large-scale implementation.

3. Methodology

3.1 Material Preparation

This study utilised various materials sourced from Sincerely Dyeing & Finishing Sdn. Bhd. in Batu Pahat, Johor, including Textile Dyeing Effluent Sludge (TDES) and Raw River Water Sludge (RRWS), as shown in Fig. 1, which served as the main study materials. TDES, collected in a semi-dry state, was further processed in the laboratory by crushing and analysing its chemical and physical properties. For the preparation of the green paver blocks, aggregates, cement, water, TDES, and RRWS were blended as additives. Additionally, industrial wastes such as fly ash and bottom ash were examined separately to evaluate their chemical and physical properties as potential materials for future studies, but they were not incorporated into the control or experimental mixes in this research.

(a) **(b)**

Fig. 1 *(a) Sample TDES; (b) Sample RRWS*

3.2 Mix Proportion

The concrete mix for the green paver blocks was designed in compliance with IS 15658:2021 standards, targeting compressive strengths of 20–35 MPa. An initial trial employed a 1:3:4 ratio of cement, sand, and aggregates, with a water/binder ratio of 1.00 and a superplasticiser dosage of 2% of the cement weight. A naphthalene-based superplasticiser, sourced from Real Point Sdn. Bhd. in Nilai, Negeri Sembilan, was incorporated to improve flowability, reduce the water-cement ratio, accelerate setting, and enhance workability. Table 1 TDS incorporation levels, compliance with standards, and optimisation of mixed performance Specimenimen size amount Thet

Table 1 *Percentage mix proportion of TDS as an additive in GP Block*

Percentage mix proportion of TDS as an additive	Mix name TDS (TDES/RRWS)
0	Control
5	TDS 5
10	TDS 10
15	TDS 15
20	TDS 20

3.3 Specimen Size and Amount

The precise quantities of water, sand, and cement were calculated to achieve the optimal mix ratio for the paver blocks, ensuring quality and performance. Table 2 presents the appropriate proportions for maintaining the balance in the mixture.

Table 2 *Mix proportion of admixture*

Mix name	Cement (kg/m^3)	Sand (kg/m^3)	Coarse aggregate (kg/m^3)	TDES (kg/m^3)	RRWS (kg/m^3)	Water (kg/m^3)	Superplasticizer (kg/m^3)
TDS 5	221	793	1200	39.65	39.65	221	4.42
TDS 10	221	793	1200	79.30	79.30	221	4.42
TDS 15	221	793	1200	118.95	118.95	221	4.42
TDS 20	221	793	1200	158.60	158.60	221	4.42

3.4 Experimental Testing

The physical, chemical, and mechanical properties of the materials were analysed at the University of Tun Hussein Onn Malaysia (UTHM). Physical characteristics, such as specific gravity and particle size distribution, were examined at the Geotechnical Engineering Laboratory of FKAAB. The chemical composition was assessed using Scanning Electron Microscopy (SEM) with energy-dispersive X-ray analysis (EDX) and X-ray Diffraction (XRD) techniques at the Analytical and Environmental Laboratory (FKAAB) and the Materials Science Laboratory (FKMP). Mechanical testing of the paver blocks was conducted at the Advanced Material Laboratory, FKAAB, to evaluate the density, compressive strength, water absorption, and initial rate of absorption. The density and compressive strength tests adhered to IS and BS standards, while the water absorption and IRA tests measured porosity and permeability. To ensure durability, performance, and structural integrity, the samples were cured and tested at designated intervals.

4. Results and Discussion

4.1 Raw Materials Specimen

This section explores the physical and chemical properties of raw material specimens. The physical properties of TDES and RRWS, including specific gravity and particle size, were assessed following ASTM and British Standards. The chemical properties were examined using SEM and XRD analyses on the same materials, with samples sieved through a 0.063 mm mesh for testing.

4.1.1 Specific Gravity for Raw Materials Specimen

The SG values of the materials highlight their density variations, influencing their suitability for various applications and compliance with IS 10262:2009 in concrete mix design.

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Table 3 *Specific gravity for all materials*

Material	Specific gravity	
	From Experiment	From Standard (as per IS 10262-2009)
TDES	0.87	-
RRWS	1.91	-
Cement	-	3.15
Sand	-	2.61
Coarse aggregate	-	2.88

Lightweight materials such as TDES (0.87) are ideal for low-weight packaging or buoyancy-related products, whereas RRWS (1.91) is suitable for reducing concrete density and enhancing sustainability. Sand (2.61) and coarse aggregates (2.88) are ideal for structural applications, and cement, with the highest SG (3.15), reflects its dense nature. Accurate SG measurements are essential for proper material proportioning, optimal performance, and adherence to the design standards. Specific gravity is a measure of the density of a material compared to that of water. These values help determine the appropriate proportions of each material in the mix, influencing factors such as the water-cement ratio, overall density, and workability of the concrete.

4.1.2 Particle Size Analysis for Raw Materials Specimen

Particle size analysis is crucial for evaluating the physical properties of TDES and RRWS, aiding in the determination of their composition, structural features, and potential interactions. As shown in Fig. 2 and Table 4, TDES exhibited good interlocking potential, whereas RRWS exhibited adequate interlocking and flexibility. Fly ash is more suitable as a filler material for durability and reduced porosity. Bottom ash is suitable for strength and stability. The combination of well-graded materials with finer additives can balance the strength, durability, and workability. Further testing is recommended to achieve optimal performance.

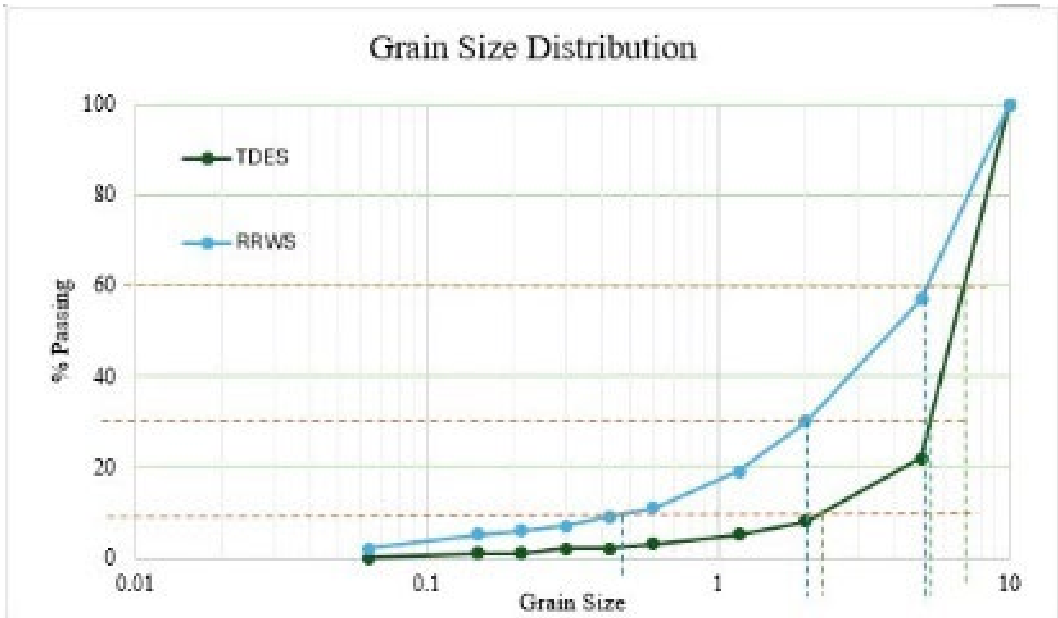


Fig. 2 *Graph particle size versus percentage passing for all materials.*

$$Uniformity\ Co-efficient, Cu = \frac{d_{60}}{d_{10}} \tag{1}$$

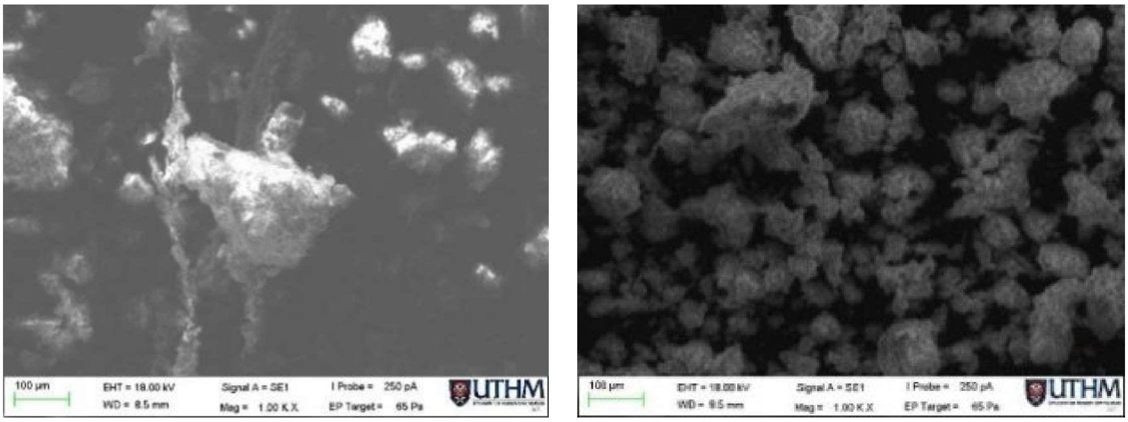
$$Co-efficient\ of\ Curvature, Cc = \frac{d_{30}^2}{d_{60}d_{10}} \tag{2}$$

Table 4 *Data analysis for all materials*

Sample type	d_{10}	d_{30}	d_{60}	C_u	C_c
TDES	2.30	5.30	7.00	3.04	1.74
RRWS	0.48	2.10	5.20	10.83	1.77

4.1.3 Scanning Electron Microscope (SEM) with Energy Dispersive X-Ray Analysis (EDX) for Raw Material Specimens

SEM-EDX analysis was conducted on all material specimens to examine the microstructure and chemical composition of the concrete. This technique provides detailed insights into the elemental composition of a material, confirming key elements, assessing homogeneity, and identifying impurities. Fig. 3 highlights SEM's role of SEM in analysing the topography and composition, while Table 5 presents the EDX spectrum and elemental distribution, illustrating the relative intensities of the identified elements.



(a) **(b)**

Fig. 3 *SEM image (a) Sample TDES; (b) Sample RRWS*

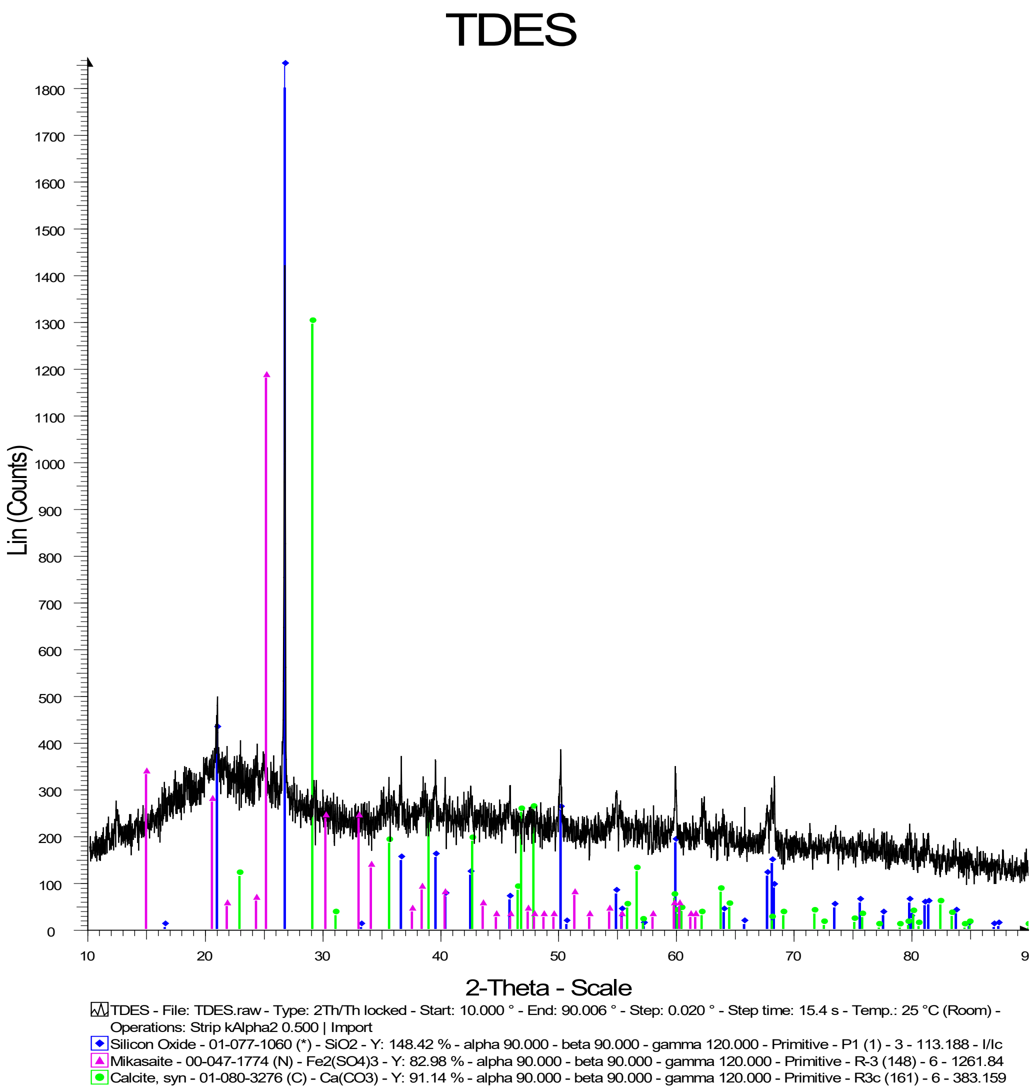
Table 5 *Percentage weight for TDES and RRWS*

	TDES (%)	RRWS (%)
Carbon (C)	65.48	31.20
Oxygen(O)	27.48	47.06
Sulfur (S)	1.81	-
Silicon (Si)	1.67	9.07
Aluminium (Al)	1.55	11.17
Iron (Fe)	0.98	1.50
Calcium (Ca)	0.54	-
Potassium(K)	0.49	-
Chlorine (Cl)	-	-
Magnesium (Mg)	-	-
Titanium (Ti)	-	-
Phosphorus (P)	-	-
Sodium (Na)	-	-

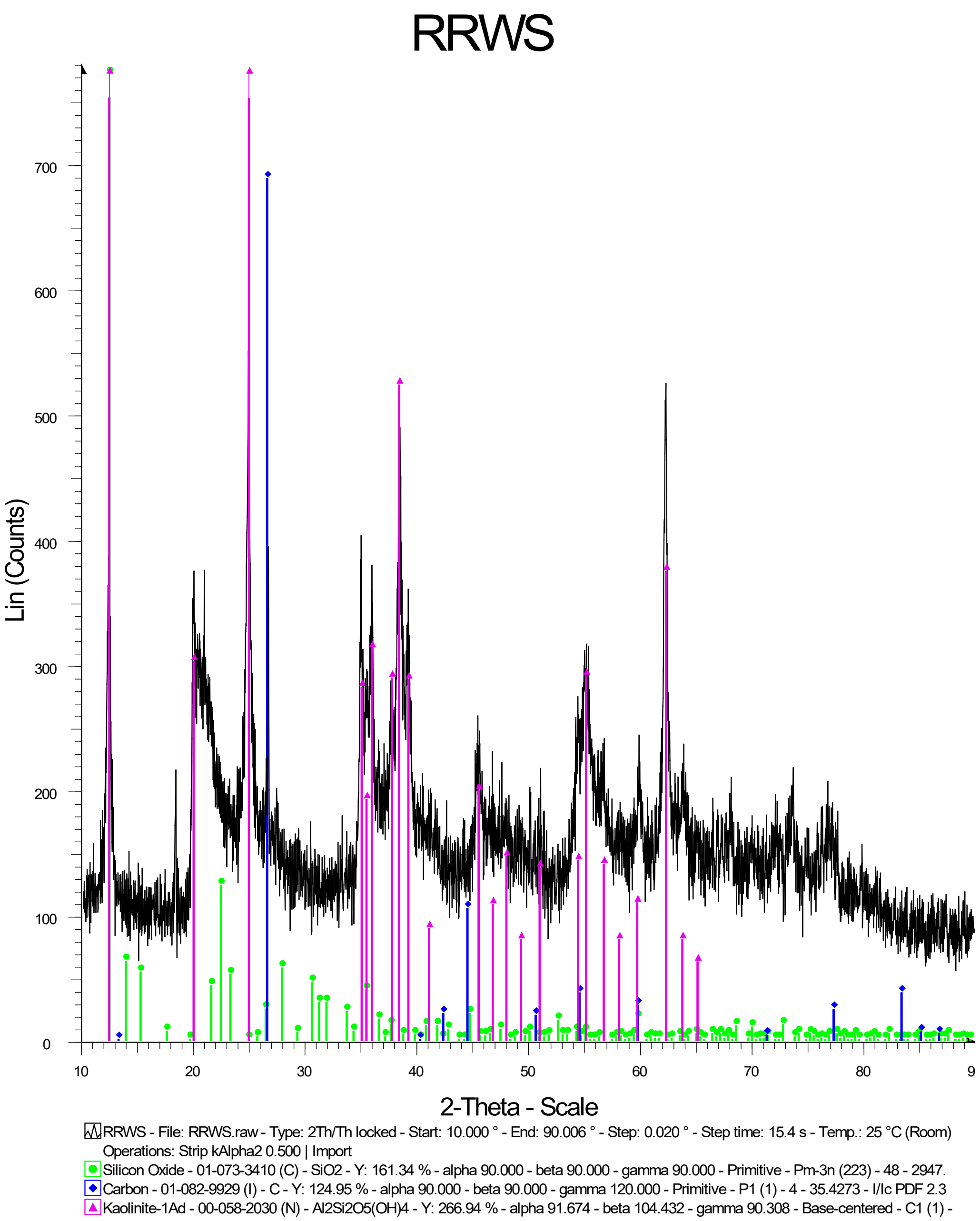
The similarities observed in the SEM analysis between TDES and RRWS can be attributed to their origins and treatment processes. TDES and RRWS were derived from wastewater treatment processes at Sincerely Dyeing & Finishing Sdn. Bhd. exhibit porous microstructures and irregular particle shapes formed through agglomeration and chemical phase changes during flocculation and coagulation treatments. These methods naturally produce materials with porous structures, high surface areas, and heterogeneity, which are common features identified in SEM analysis. TDESES exhibited a high carbon content (65.48%) and low oxide levels, indicating an organic-rich structure that limits its suitability for structural application. RRWS, with higher silicon (9.07%) and aluminium (11.17%) contents, demonstrated stronger pozzolanic characteristics, making it more suitable as a cement substitute. The SEM analysis in this study revealed porous and irregular surface morphologies in both TDES and RRWS, consistent with the fragmented, amorphous textures observed in textile dyeing sludge by Patil et al. [11]. Additionally, the oxide composition of the RRWS aligns with the findings of Maierdan et al. [10], supporting its use in cementitious materials. The RRWS exhibited similar oxide trends, whereas TDES's elevated sulfur (1.81%) and low calcium (0.54%) contents of TDES may compromise its mechanical strength. These results confirm RRWS's higher potential of RRWS in enhancing green paver block performance, whereas TDES is more suitable for nonstructural, sustainability-driven applications.

4.1.4 X-Ray Diffraction (XRD) for Raw Material Specimens

XRD was used to analyse the crystalline structure and phase composition of the materials, including identifying phases, assessing crystallinity, and detecting impurities. As shown in Fig. 4, the XRD analyses of TDES and RRWS highlight their crystalline structures and phase compositions, which are crucial for understanding their contributions to the properties of the green paver block.



(a)



(b)

Fig. 4 *Result XRD (a) Sample TDES; (b) Sample RRWS*

TDES contains silicon oxide (SiO_2), mikasaite ($Fe_2(SO_4)_3$), and calcite ($CaCO_3$), which contribute to mechanical strength, sulfate resistance, and carbonation potential, respectively. RRWS contains silicon oxide (SiO_2), carbon (C), and kaolinite ($Al_2Si_2O_5(OH)_4$), where SiO_2 and kaolinite enhance pozzolanic activity and durability, whereas carbon may affect water absorption. The 2-theta scale in the XRD patterns represents the diffraction angles, with sharp peaks indicating crystalline phases. The peak positions provide insights into the crystal structures, unit cell dimensions, and lattice systems, whereas the widths reveal the crystallite sizes and lattice strains. The intensities also provide quantitative information on the relative abundance of the phases, emphasising the structural properties and potential applications of these materials.

4.2 Green Paver Block (GP Block)

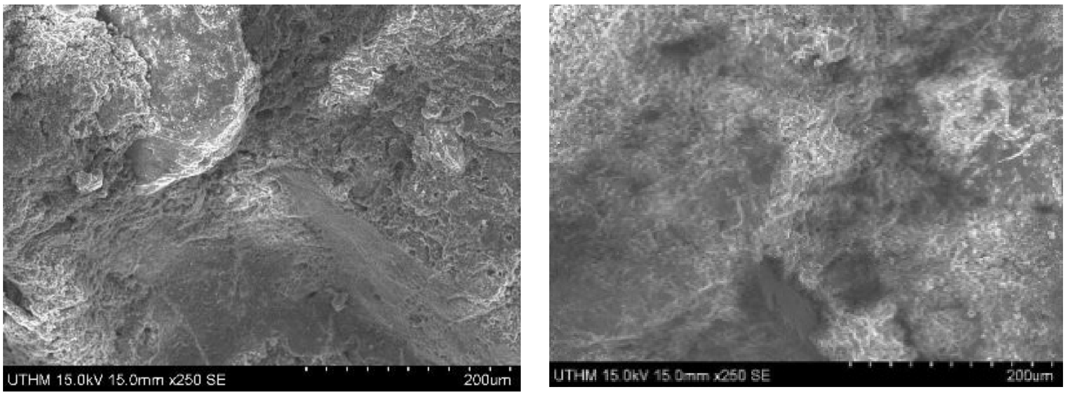
This section investigates the chemical and mechanical characteristics of green paver blocks incorporating Textile Dyeing Effluent Sludge (TDES) and Raw River Water Influent Sludge (RRWS) as additives. The chemical properties were assessed using SEM-EDX on samples sieved through a 0.063 mm mesh, whereas the mechanical properties were evaluated in terms of density, compressive strength, water absorption, and initial rate of absorption. A total of 60 paver block samples, including control specimens, were cast and cured for 7 and 28 days to analyse the effects of different TDES and RRWS mix proportions on their structural integrity and sustainability.

4.3 Scanning Electron Microscope (SEM) with Energy Dispersive X-Ray Analysis (EDX) for Green Paver Block

SEM-EDX analysis was performed on all paver block casting specimens, including TDES and RRWS, to study their microstructure and chemical composition at 7 and 28 days curing periods. The SEM results provided insights into the topography and composition, while the EDX data showed the elemental distribution and relative intensities of the identified elements.

4.3.1 Control

Referring to fig. 5, the 7th-day control specimen exhibits a rough, uneven surface with noticeable pores, indicating higher porosity and incomplete curing. By the 28th day, the surface, although still rough, showed reduced porosity and improved density, reflecting better curing progress. The texture remained heterogeneous at both stages, but the 28-day specimen displayed a more uniform appearance. Both specimens exhibited irregular, amorphous shapes without distinct geometric forms. Overall, the 28-day specimens demonstrated enhanced curing, which is critical for ensuring long-term durability in concrete or paver block applications. In addition, as listed in Table 6, the 28-day control specimen exhibited reduced porosity and improved surface uniformity compared to the 7-day specimen, indicating better curing. Elemental analysis showed increased silicon, aluminium, and oxygen, and decreased calcium, confirming ongoing hydration reactions.



(a) **(b)**

Fig. 5 *SEM image (a) Sample control at 7th days curing period; (b) Sample control at 28th days curing period.*

Table 6 *Percentage weight for all materials*

	7th-days control (%)	28th-days control (%)
Oxygen (O)	51.13	56.04
Sodium (Na)	-	1.98
Aluminium (Al)	1.04	5.88
Silicon (Si)	18.82	20.99
Potassium (K)	0.57	2.77
Calcium (Ca)	28.44	12.34

4.3.2 GP Block Incorporated with TDES

As shown in Fig. 6, on the 7th day, both the 5% and 20% TDES-incorporated samples exhibited rough, uneven surfaces with random patterns and varying shapes. The 5% TDES sample appeared slightly more irregular than the 20% TDES sample, suggesting lower compaction and slower early hydration. At 28 days, the surface roughness persisted in both samples, but the 20% TDES sample exhibited more pronounced irregularities and inconsistent shapes, indicating intensified material transformations at higher TDES content. When compared to the conventional (control) paver block, which showed improved surface uniformity and reduced porosity by 28 d, the TDES-modified samples, particularly at 20%, displayed greater texture irregularity. This suggests that while TDES incorporation alters the microstructure, a higher content may negatively impact surface integrity and compaction, potentially affecting the long-term performance and durability of the paver blocks.

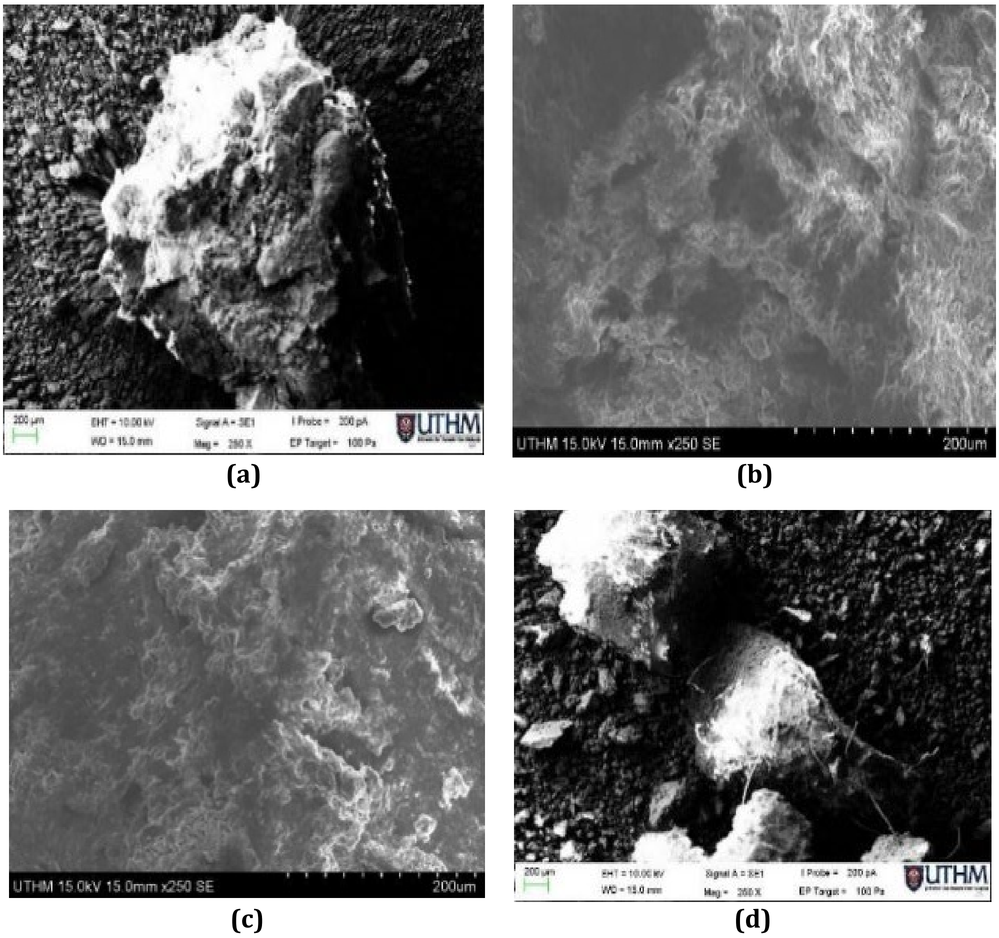


Fig. 6 *SEM image (a) Sample 5% TDES at 7th day curing period; (b) Sample 5% TDES at 28th day curing period; (c) Sample 20% TDES at 7th day curing period; (d) Sample 20% TDES at 28th day curing period*

Table 7 *Percentage weight for all materials*

	7th-days		28th-days	
	5% TDES (%)	20% TDES (%)	5% TDES (%)	20% TDES (%)
Carbon (C)	16.81	18.06	19.44	45.19
Oxygen (O)	42.01	52.74	45.56	31.80
Sodium (Na)	-	0.33	-	-
Aluminium (Al)	7.01	0.60	1.54	2.16
Silicon (Si)	13.37	20.54	13.15	8.33
Potassium (K)	-	-	0.56	-
Calcium (Ca)	20.81	7.74	-	10.77
Bromine (Br)	-	-	-	1.76

As listed in Table 7, by 28 days, the TDES-modified paver blocks, especially those with 20% TDES, exhibited increased surface irregularity and compositional imbalance compared to the control. Elevated carbon and reduced silicon and oxygen levels suggest disrupted hydration, which potentially affects compaction and long-term durability.

4.3.3 GP Block Incorporated with RRWS

As shown in Fig. 7, the 5% and 20% RRWS-incorporated paver block samples exhibited rough and uneven surfaces with granular textures at both 7 and 28 days. Gradual surface smoothing was observed over time, indicating ongoing curing and material consolidation.

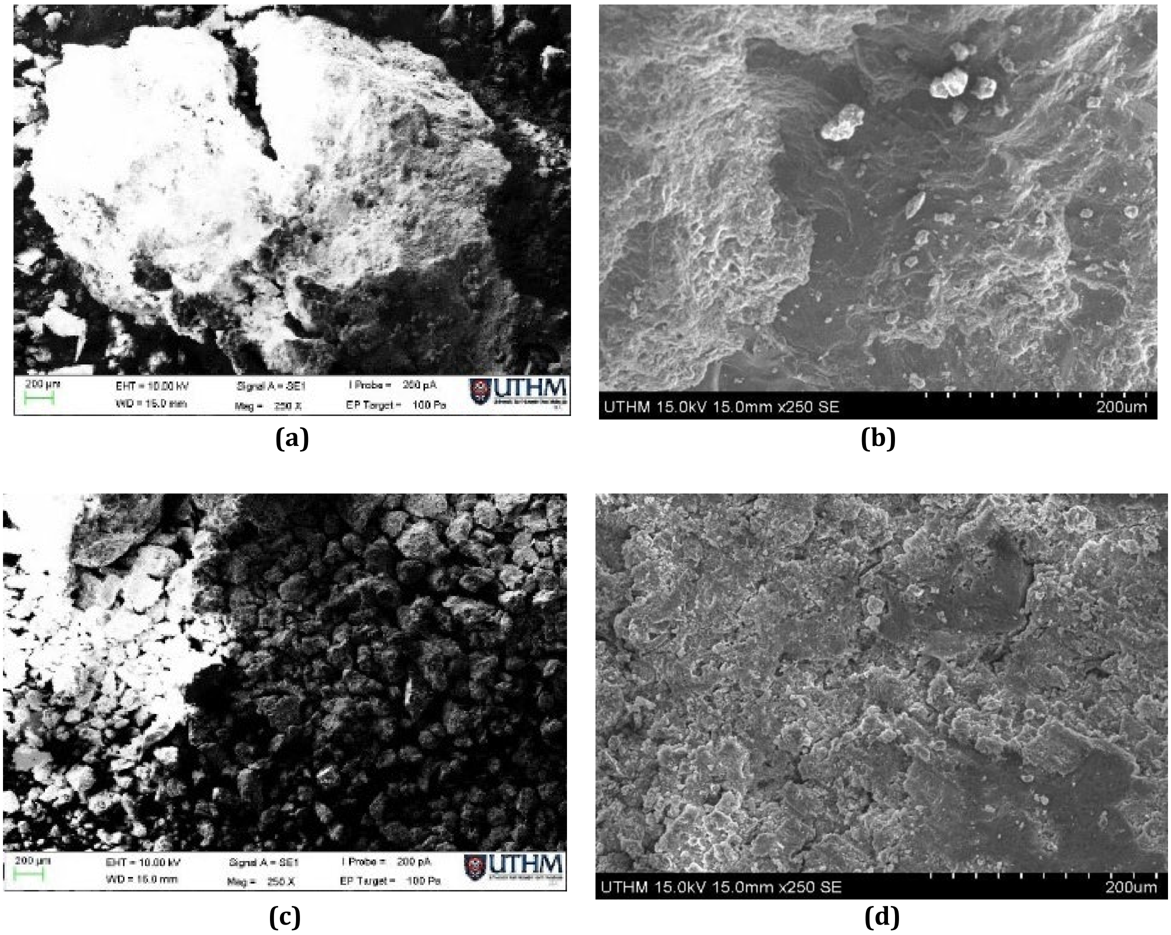


Fig. 7 *SEM image (a) Sample 5% RRWS at 7th days curing period; (b) Sample 5% RRWS at 28th days curing period; (c) Sample 20% RRWS at 7th days curing period; (d) Sample 20% RRWS at 28th days curing period*

Table 8 *Percentage eight for all materials*

	7th-days		28th-days	
	5% RRWS (%)	20% RRWS (%)	5% RRWS (%)	20% RRWS (%)
Carbon (C)	13.26	13.15	12.15	6.15
Oxygen (O)	41.62	44.80	42.11	57.57
Sodium (Na)	-	-	0.86	0.53
Aluminium (Al)	4.09	8.52	4.73	5.40
Silicon (Si)	12.00	13.24	19.69	10.48
Potassium (K)	-	-	7.88	0.01
Calcium (Ca)	20.05	20.29	12.58	19.85
Sulfur (S)	1.93	-	-	-
Magnesium (Mg)	0.72	-	-	-
Gold (Au)	6.32	-	-	-

However, the patterns remained irregular and asymmetrical, with randomly arranged particles and no clear structural formations. The overall shapes were amorphous and undefined, suggesting limited compaction and cohesion in the matrix. Compared to the conventional paver block, which demonstrated a more uniform and compact surface by 28 days, the RRWS samples, especially at higher content, showed less improvement in surface quality. This may be due to the inert or less reactive nature of the RRWS, which could hinder effective bonding and densification. Therefore, while the RRWS-modified samples showed some curing progress, their irregular texture and lack of a defined structure suggest inferior surface quality and potentially reduced durability compared to the control. The RRWS-incorporated paver blocks showed limited surface improvement by 28 days, especially at 20% content. As shown in Table 8, elemental analysis revealed reduced silicon and carbon levels, indicating weaker bonding and hydration. Compared to the control, higher RRWS content resulted in a poorer surface quality and potentially lower durability.

4.4 Density for Green Paver Block

The density test measures the mass per unit volume of a material, providing key insights into its properties. Conducted per IS 156658:2021, the test analysed 30 block samples (215 mm × 100 mm × 65 mm) with varying TDES and RRWS proportions. Tables 9 and 10 summarise the results for the different mixes.

4.4.1 GP Block Incorporated with TDES

Table 9 and Fig. 8 show the average results for density GP Block incorporated with TDES. The density reduction in the TDES content increases owing to the lightweight organic and inorganic components, irregular shapes, and porous structures. These components replace denser materials, such as fine aggregates, resulting in a reduction in the overall block density. TDES particles also created air voids within the paver block matrix, further contributing to the decrease in density. Higher TDES levels also reduced the compaction efficiency, resulting in less dense blocks. The slight increase in density in the TDS 20TDES mix may be due to densification effects during curing; however, it is insufficient to counteract the overall trend. While a reduction in density can produce lightweight paver blocks, decreased overall strength may compromise their structural performance and limit their suitability for load-bearing applications

Table 9 *Average density result for GP Block incorporated with TDES*

Mix Name	Mix Proportion	Density (kg/m^3)
Control	0	2216
TDS 5TDES	5	2161
TDS 10TDES	10	2018
TDS 15TDES	15	1965
TDS 20TDES	20	2023

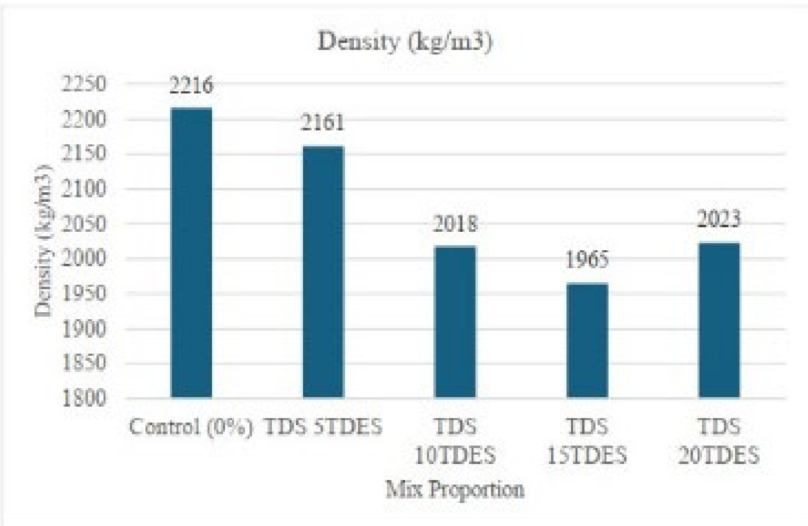


Fig. 8 *Graph variation of density with different mix proportions of TDES*

4.4.2 GP Block Incorporated with RRWS

Table 10 and Fig. 9 show the average results for density GP Block incorporated with RRWS.

Table 10 *Average density result for GP Block incorporated with RRWS*

Mix Name	Mix Proportion	Density (kg/m^3)	
		7^{th} day	28^{th} day
Control	0	2308	2357
TDS 5RRWS	5	2298	2299
TDS 10RRWS	10	2261	2233
TDS 15RRWS	15	2284	2323
TDS 20RRWS	20	2151	2066

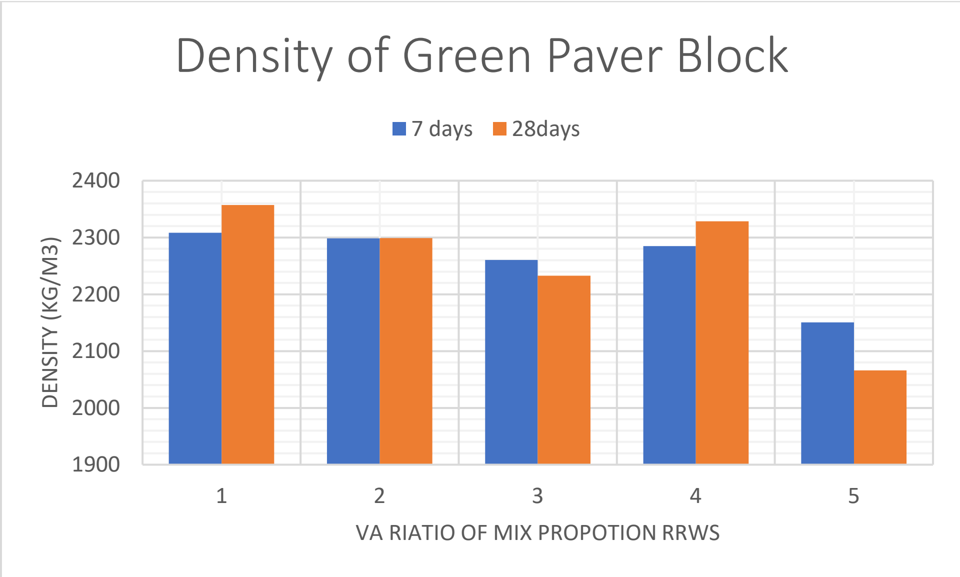


Fig. 9 *Graph variation of density with different mix proportions of RRWS*

The density test results for green paver block show a significant impact of RRWS mix percentage on the material's density. The control sample with 0% RRWS had the highest density value, while the sample with 20% RRWS had lower density. This is due to the addition of textile dyeing sludge, which causes waste in the mixing process. According to IS 15658:2021, the minimum required density for paver blocks is 2200 kg/m^3, though only certain samples met this criterion. This result shows, it is acceptable to used RRWS up to 15% in green paver blocks which these mixed still meet the required density standard.

4.5 Water Absorption for Green Paver Block

The water absorption test, conducted per IS 15658:2021, evaluated 30 block samples (215 × 100 × 65 mm) after 7 and 28 days of water curing. Table 11 and 12 present the average water absorption results for different TDES and RRWS mix proportions.

4.5.1 GP Block Incorporated with TDES

Table 11 and Fig. 10 indicate the average water absorption for GP Block incorporated with TDES. The density test results for the green paver block showed a significant impact of the RRWS mix percentage on the material density. The control sample with 0% RRWS had the highest density value, whereas the sample with 20% RRWS had a lower density. This was due to the addition of textile dyeing sludge, which caused waste during the mixing process. According to IS 15658:2021, the minimum required density for paver blocks is 2200 kg/m^3, although only certain samples met this criterion. This result shows that it is acceptable to use RRWS up to 15% in green paver blocks, as these mixed still meet the required density standard.

Table 11 *Average water absorption result for GP Block incorporated with TDES*

Mix Name	Average water absorption (%)		Percentage difference between control and TDES based block (%)	
	7th day	28th day	7th day	28th day
Control	4.03	3.17	0	0
TDS 5TDES	5.63	6.39	28	67
TDS 10TDES	8.64	8.50	73	91
TDS 15TDES	7.93	7.41	65	80
TDS 20TDES	9.10	7.24	77	78

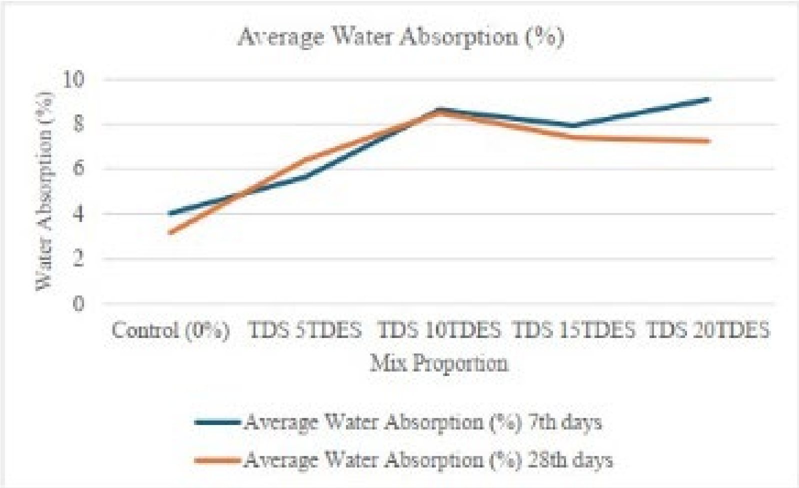


Fig. 10 *Graph variation of water absorption with different mix proportions of TDES*

Higher TDES content in paver block mixes led to increased water absorption due to the porous and irregular structure of TDES particles, which created more voids in the concrete matrix. TDS 10TDES exhibited the highest absorption rates, reaching 8.64% at 7 days and 8.50% at 28 days, significantly higher than the control. While TDS 15TDES and TDS 20TDES showed slightly lower absorption at 28 days, likely due to particle rearrangement during curing, the overall trend remained high. The increased absorption compromised the compactness and impermeability of the blocks, potentially limiting their suitability for applications requiring durability and low permeability.TDS 5TDES was the closest to the control mix, which was considered the most effective mixture.

4.5.2 GP Block Incorporated with TDES

Table 12 and Fig. 11 indicate the average water absorption for GP Block incorporated with RRWS.

Table 12 *Average water absorption result for GP Block incorporated with RRWS*

Mix Name	Wet specimen after full immersed, W_{wet} (g)		Dry specimen weight after dry oven, W_{dry} (g)		Percentage absorption (%)	
	7th day	28th day	7th day	28th day	7th day	28th day
Control	3226	3294	3097	3163	4	4
TDS 5RRWS	3212	3213	3108	3084	3.3	4
TDS 10RRWS	3159	3120	3033	2996	4	4
TDS 15RRWS	3193	2887	2989	2685	6.8	7.5
TDS 20RRWS	3005	3254	2720	2929	10.5	11

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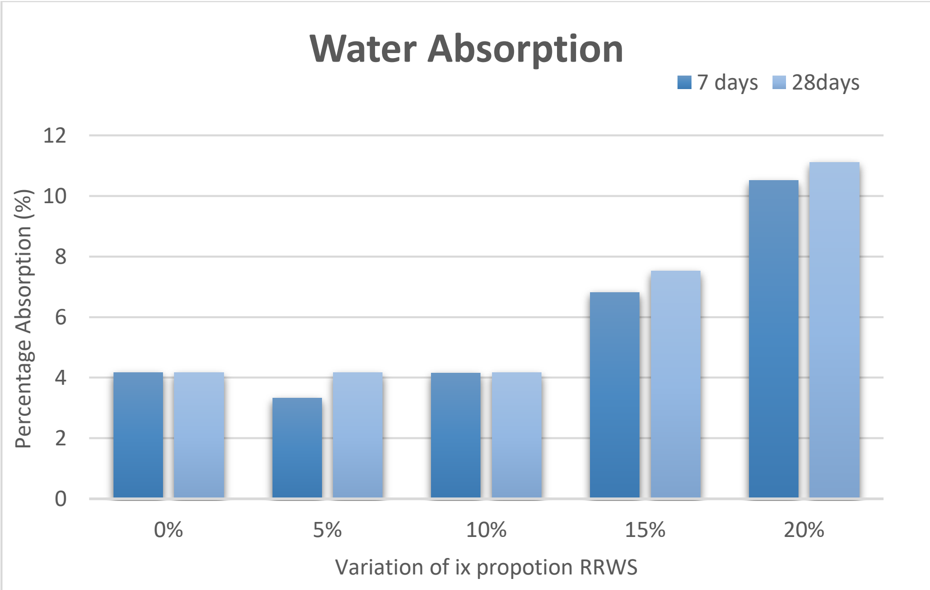

Fig. 11 *Graph variation of water absorption with different mix proportions of RRWS*

The results showed that the control specimen and those with 5% and 10% RRWS maintained a consistent water absorption rate of 4% over 7 and 28 days. However, specimens with 15% and 20% RRWS exceeded the 6% water absorption limit set by BS EN 1338:2003, reaching 7% and 10%, respectively, which is unacceptable. 5% RRWS demonstrated good performance, maintaining a consistent value of 4% at both 7 and 28 days which offers an ideal balance between sustainability and performance, making it the most appropriate proportion for application among the studied mixes.

4.6 Initial Rate of Absorption for Green Paver Block

The initial rate of absorption (IRA) test, conducted per ASTM C1585, was performed on 30 blocks (215 × 100 × 65 mm) after 7 and 28 days of water curing. Tables 13 and 14 display the average IRA values for different mixes with varying TDES and RRWS proportions.

4.6.1 GP Block Incorporated with TDES

Table 13 and Fig. 12 demonstrate the initial rate of absorption results for GP Block which was incorporated with TDES.

Table 13 *Average initial rate of absorption result for GP Block incorporated with TDES*

Mix Name	Average initial rate of absorption ($g/cm^2/min$)		Percentage difference between control and TDES based block (%)	
	7th day	28th day	7th day	28th day
Control	0.08	0.05	0	0
TDS 5TDES	0.06	0.06	29	18
TDS 10TDES	0.05	0.05	46	0
TDS 15TDES	0.05	0.05	46	0
TDS 20TDES	0.10	0.05	22	0

IRA values fluctuated with increasing TDES content because of its porous and irregular structure, which affected the surface porosity and absorption. At 5% TDES, IRA remained stable, whereas 10% TDES showed a sharp reduction at 7 days but normalised at 28 days due to microvoid filling. Similarly, 15% TDES maintained a reduced IRA, suggesting improved uniformity. However, 20% TDES initially increased the IRA due to uneven distribution but normalised with curing. These variations highlight the influence of TDES on permeability, with lower contents enhancing compaction and higher levels introducing excessive porosity.

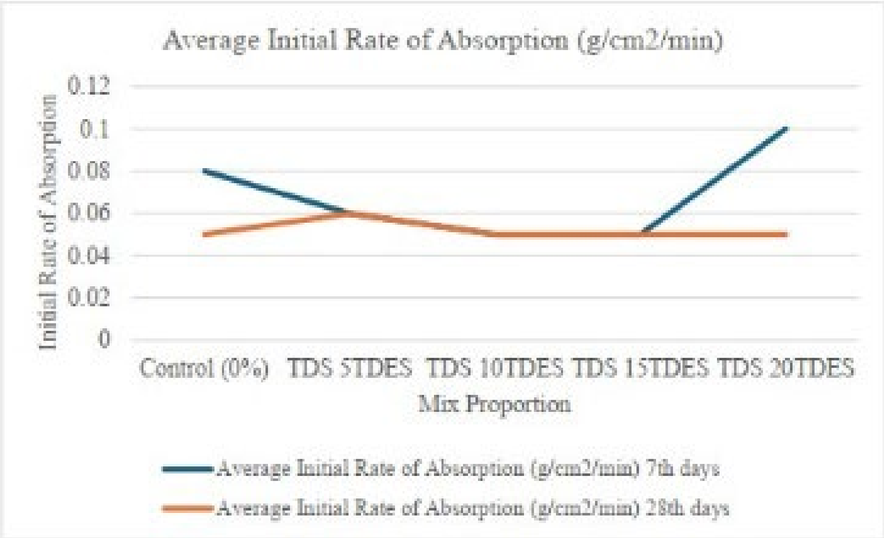

Fig. 12 *Graph variation of initial rate of absorption with different mix proportions of TDES*

4.6.2 GP Block Incorporated with RRWS

Table 14 and Fig. 13 demonstrate the initial rate of absorption result for GP Block which incorporated with RRWS.

Table 14 *Average initial rate of absorption result for GP Block incorporated with RRWS*

Mix name	Average initial rate of absorption (g/cm²/min)	
	7th day	28th day
Control	0.0529	0.0529
TDS 5RRWS	0.051	0.0402
TDS 10RRWS	0.0544	0.0308
TDS 15RRWS	0.1037	0.1109
TDS 20RRWS	0.1246	0.1311

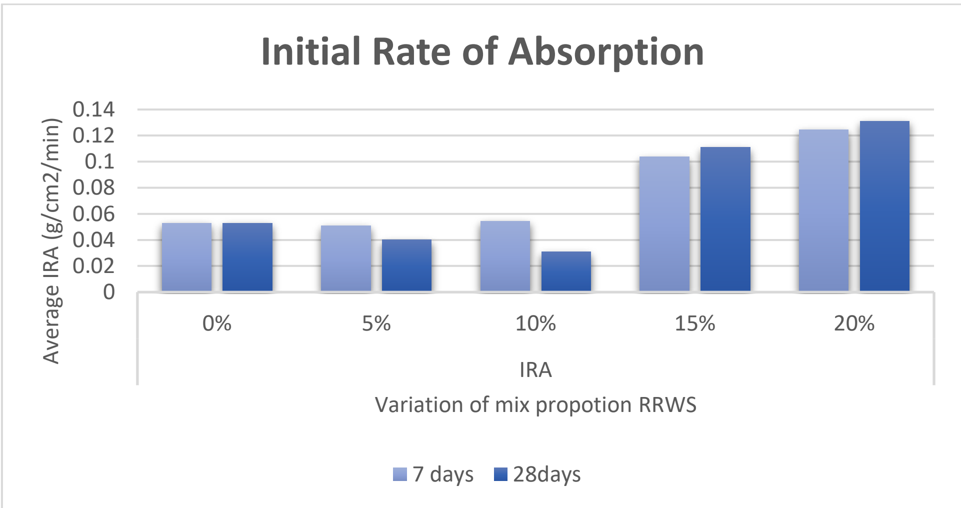

Fig. 13 *Graph variation of initial rate of absorption with different mix proportions of RRWS*

Fig. 13 illustrates the initial rate of absorption results. The specimen containing 20% RRWS exhibited the highest absorption rate at both 7 and 28 days of curing. The graph indicates that as the RRWS content increased, the initial rate of absorption also increased. Adding more RRWS caused the concrete to absorb water faster, which increased the permeability of the material. Based on the results, specimens containing 5% and 10% RRWS still fulfilled the requirement standard, which is below 0.10 ml/m2/s, and the proportion of the mix may not affect the durability of the concrete.

4.7 Compressive Strength for Green Paver Block

The compressive strength test followed the BS EN 12390-3:2009 standards on 30 blocks (215 mm × 100 mm × 65 mm). The samples were cured in water for 7 and 28 days. Tables 15 and 16 present the average compressive strengths for different mixes with varying TDES and RRWS proportions, respectively.

4.7.1 GP Block Incorporated with TDES

Table 15 and Fig. 14 present the compressive strength result for the GP Block which is incorporated with TDES. Higher TDES content (≥10%) significantly reduced the compressive strength owing to poor particle packing, increased voids, and uneven dispersion, leading to structural weaknesses. Mixing challenges, inadequate compaction, and improper superplasticiser incorporation further degrade the strength by causing segregation and non-uniformity. Additionally, the porous nature of TDES accelerated moisture loss, hindering hydration and strength development. While TDS 5TDES remains viable for low-demand applications, excessive TDES weakens the matrix, emphasising the need to limit its use or introduce supplementary materials to improve its performance.

Table 15 *Average compressive strength result for GP Block incorporated with TDES*

Mix Name	Average Compressive Strength (MPa)		Average Compressive Strength (kN)		Percentage difference between control and TDES based block (%)	
	7th day	28th day	7th day	28th day	7th day (-ve)	28th day (-ve)
Control	35.67	52.65	766.83	1105.73	0	0
TDS 5TDES	13.53	17.13	290.68	368.28	62	67
TDS 10TDES	1.15	4.04	24.75	86.99	97	92
TDS 15TDES	1.38	4.14	29.67	89.07	96	92
TDS 20TDES	1.36	1.80	29.25	83.35	96	96

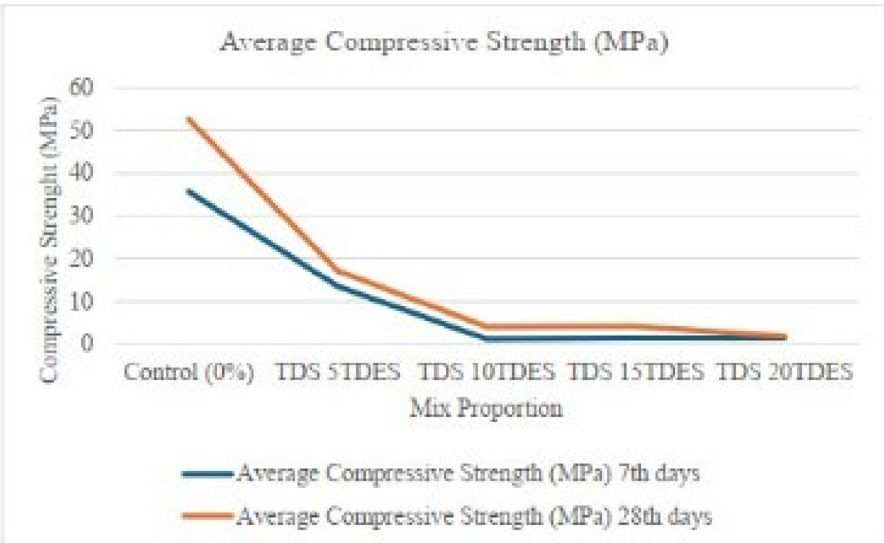

Fig. 14 *Graph variation of compressive strength with different mix proportions of TDES*

4.7.2 GP Block Incorporated with RRWS

Table 16 and Fig. 15 show the compressive strength result for the GP Block, which was incorporated with RRWS. The compressive strength of the paver blocks decreased as the RRWS content increased. The control mix (0% RRWS) had the highest strength (52.65 MPa at 28 days), whereas 5% RRWS slightly reduced the strength but remained above the 30 MPa requirement. Higher RRWS levels (10–20%) significantly weakened the blocks owing to increased porosity and reduced bonding, with 20% RRWS yielding the lowest strength (10.29 MPa at 28 days). Nevertheless, the strength generally increased over time, which helped to reduce drying shrinkage and the risk of cracking.

Table 16 *Average compressive strength result for GP Block incorporated with RRWS*

Mix Name	Maximum Load (kN)		Average Compressive Strength (MPa)		Percentage difference between control and TDES based block (%)	
	7^{th} day	28^{th} day	7^{th} day	28^{th} day	7^{th} day	28^{th} day
Control	908.24	1105.73	43.25	52.65	-	-
TDS 5TDES	790.69	999.25	37.83	47.58	12.53	9.63
TDS 10TDES	460.05	551.84	21.91	26.28	49.34	50.09
TDS 15TDES	190.19	316.59	12.26	15.08	71.65	71.36
TDS 20TDES	190.19	216.06	9.05	10.29	79.08	80.46

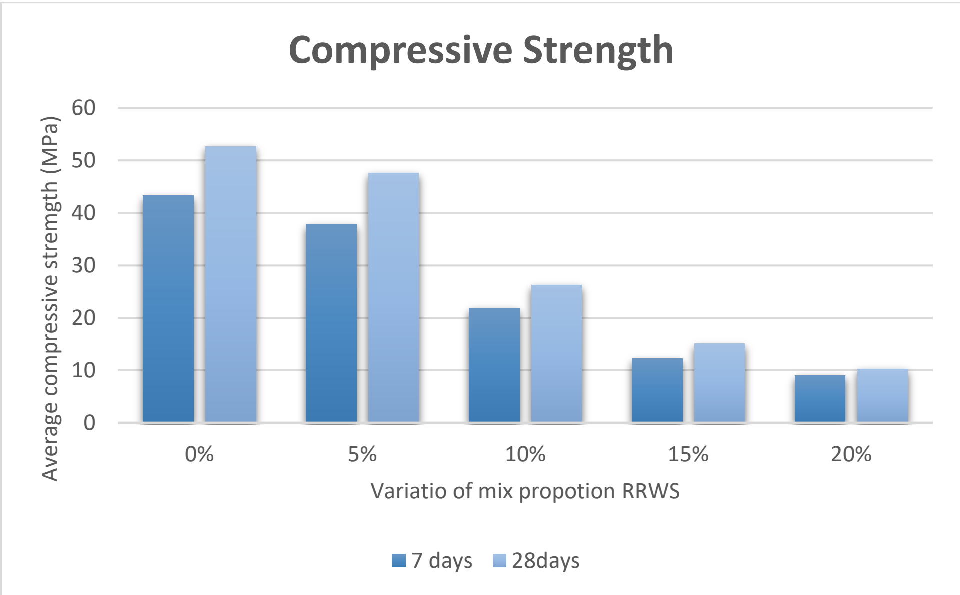

Fig. 15 *Graph variation of compressive strength with different mix proportions of RRWS*

5. Discussion

The key results of this study indicated that paver blocks incorporating varying proportions of Recycled Rubber Waste Sludge (RRWS) showed limited surface improvement and inferior surface quality compared to the control blocks. Specifically, the RRWS-modified samples exhibited irregular textures and a lack of defined structure, suggesting reduced durability. Elemental analysis revealed lower silicon and carbon levels in the RRWS samples, indicating weaker bonding and lower hydration. The SEM analysis highlighted that both the 5% and 20% RRWS samples had rough, uneven surfaces with granular textures at both 7 and 28 days, with gradual smoothing but remaining asymmetrical and amorphous. The compressive strength results showed that the control mix had the highest strength, whereas the RRWS-modified blocks demonstrated significantly lower compressive strength, particularly at higher RRWS contents, indicating a negative impact on mechanical performance. Overall, this study emphasised the challenges of using RRWS in paver block production, particularly regarding surface quality and structural integrity.

6. Conclusion and Recommendations

This study investigated the feasibility of using textile dyeing effluent sludge (TDES) and raw river water sludge (RRWS) as sustainable additives in green paver block (GP block) production to minimise landfill waste and dependence on conventional materials. Material characterisation revealed that sludge composition influences block properties, with TDES enhancing moisture resistance, thermal insulation, and UV resistance but raising concerns about heavy metal contamination and workability, necessitating stabilisation and plasticisers. Mechanical testing showed that increasing TDES reduced density (up to 11.33% at 15% TDES), significantly lowered compressive strength (67% reduction at 28 days for 5% TDES), and increased water absorption, making a 5% TDES mix ideal for decorative applications. Similarly, incorporating RRWS provided environmental benefits, with a 5% mix achieving optimal strength (37.83 MPa) and durability for roads and pathways, whereas higher proportions (10–20%) reduced strength and increased porosity, limiting construction viability. Managing colour variations with carbon black, ensuring compliance with curing standards, and further refining the testing methods are essential for expanding GP block applications in sustainable construction.

This study highlights the significance of using SEM technology for accurate material characterisation to improve the sustainability and performance of GP blocks. Future research should optimise material ratios by incorporating industrial byproducts, such as fly ash and bottom ash, while evaluating the possibility of using substitute materials, such as TDES and RRWS, to develop an advantageous substance. Additionally, investigating the long-term durability, environmental impacts, and chemical interactions of TDES-based paver blocks, refining the mix ratios, and integrating superplasticisers can improve their performance. This study also highlights RRWS's potential of RRWS for lightweight block applications owing to its low specific gravity and suggests optimising mix designs with supplementary cementitious materials, such as fly ash or silica fume, for enhanced strength and durability. These efforts collectively aim to advance eco-friendly construction, reduce carbon emissions, and foster innovation in sustainable building material 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:*** *Dr Goh Wan Inn;* ***data collection:*** *Low Ci Yi, Wong Khiing Yung, Ikmal Danial Bin Suraiadi;* ***analysis and interpretation of results:*** *Low Ci Yi, Wong Khiing Yung, Ikmal Danial Bin Suraiadi;* ***draft and final manuscript preparation:*** *Dr Qadir Bux alias Imran Latif. All authors reviewed the results and approved the final version of the manuscript.*

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