Article

APPLICATION OF BIOCHAR AS PARTIAL CEMENT REPLACEMENT WITH POLYPROPYLENE PLASTIC WASTE FOR SUSTAINABLE CONCRETE PAVING BLOCKS

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Abstract

Cement production and sand extraction contribute heavily to carbon emissions and environmental degradation. This study investigates the development of sustainable concrete paving blocks by partially replacing cement with biochar and sand with polypropylene (PP) plastic waste. Concrete blocks with dimensions of 11.25 × 22.5 × 6 cm were cast using a 1:2:1 cement:sand:crushed stone ratio, substituting 5–20% biochar and 2–6% PP, and cured for 3, 7, and 28 days. Tests conducted in accordance with TIS 827-2565 included compressive strength, water absorption, density, and skid resistance. Results indicated that replacing cement with biochar and sand with PP slightly decreased the density; however, mixtures containing up to 5% biochar and 2% PP maintained density values comparable to the control mix. The optimum performance occurred at 5% biochar and 2% PP, achieving a compressive strength of 52.11 MPa with acceptable water absorption and skid resistance. The findings highlight a practical and eco-efficient approach for reusing natural and plastic wastes in construction, reducing reliance on virgin materials while producing standardized and sustainable concrete suitable for practical applications.

Keywords: Biochar, Polypropylene Waste, Cement Replacement, Paving blocks, Sustainability

1. Introduction

The construction industry plays a pivotal role in global development but remains one of the largest contributors to greenhouse gas emissions. Recent analyses from the International Energy Agency (IEA, 2024) [1] indicate that the construction and building materials sector is responsible for nearly 37% of global energy-related CO_2 emissions, with cement production alone contributing about 7.5–8% of the total [2, 3]. According to the IPCC 2023 Sixth Assessment Report, cement manufacturing not only emits CO_2 directly through calcination but also indirectly via energy-intensive processes powered by fossil fuels, emphasizing the urgency for decarbonization strategies [4].

Recent studies advocate for the integration of carbon capture, utilization, and storage (CCUS) and alternative binders such as geopolymer and bio-based admixtures to align with the IEA Net Zero by 2050 scenario [5, 6]. Simultaneously, the depletion of natural sand resources and the growing accumulation of non-biodegradable plastic waste have intensified environmental pressures, calling for innovative circular-economy approaches in sustainable construction material design. These include substituting virgin sand with recycled or bio-based alternatives and reusing plastic waste as aggregate materials, thereby mitigating emissions and reducing resource extraction burdens [7]. Furthermore, researchers have investigated the use of supplementary cementitious materials, including fly ash, rice husk ash, and silica fume, to reduce cement dependency and environmental footprint in sustainable concrete applications [8]. Beyond these pozzolanic materials, biochar, a carbon-rich byproduct from biomass pyrolysis, has attracted increasing interest due to its high porosity, carbon sequestration capability, and microstructural refinement potential that improve both strength and durability in cementitious systems

[9, 10].

Simultaneously, the reuse of recycled plastics, particularly polypropylene (PP) and polyethylene terephthalate (PET), has emerged as a promising approach to mitigating plastic pollution while improving concrete performance [11, 12]. PP incorporation in concrete has been found to enhance impact resistance, ductility, and surface wear resistance, making it suitable for paving applications. Such practices align with TIS 827-2565 (Thai Industrial Standard for Concrete Paving Blocks), which emphasizes compressive strength, water absorption, and abrasion resistance as key quality parameters for sustainable infrastructure development.

Addressing both carbon emissions and plastic waste management simultaneously can lead to transformative advances in sustainable construction materials. Integrating biochar and recycled polypropylene (PP) in concrete paving blocks not only valorizes waste but also promotes resource efficiency and community-scale manufacturing, contributing to the broader goal of carbon neutrality in the construction sector [13]. The recent studies highlight that biochar-based materials, when combined with recycled plastics, can improve compressive strength, permeability, and long-term durability while sequestering carbon and reducing embodied energy [14]. This approach aligns with the United Nations Sustainable Development Goals (SDGs 9, 11, and 12), emphasizing innovation, sustainable cities, and responsible production. Furthermore, integrating these waste-derived materials supports small and medium-sized enterprises (SMEs) and local economies, which are central to regional resilience and circular economic transitions [15].

Thailand's Bio-Circular-Green (BCG) Economy Model, adopted as a national sustainability framework since 2021 [16], provides a strong foundation for the integration of waste-derived materials in construction. In rural areas, where agricultural biomass and plastic residues are readily available, the combined use of biochar and recycled polypropylene (PP) presents a low-cost, scalable solution for local SMEs to manufacture sustainable paving blocks in accordance with TIS 827-2565. This approach not only reduces municipal waste and construction costs but also promotes eco-industrial development aligned with Thailand's BCG policy, fostering localized circular economy transitions [17]. Accordingly, this study aims to develop and evaluate concrete paving blocks by partially replacing cement (5–20%) with biochar and sand (2–6%) with PP waste, focusing on optimizing mix proportions to meet the required compressive strength, water absorption, density, and skid resistance specified by the Thai Industrial Standard (TIS 827-2565).

This research contributes a novel combination of biochar and polypropylene waste as dual replacements for cement and sand in concrete paving blocks. The results are expected to provide a practical framework for producing standardized, eco-friendly paving materials suitable for both industrial and community-based applications. By aligning material innovation with sustainability objectives, this study bridges environmental responsibility and engineering performance in the concrete industry.

2. Materials and methods

2.1 Materials

Ordinary Portland Cement (OPC) Type I conforming to ASTM C150 was employed as the primary binder throughout the study. The cement used was commercially available from the Elephant brand (The Siam Cement Public Company Limited, Thailand). No chemical or physical modifications were applied to the cement prior to use.

The biochar utilized in this research was produced from bamboo biomass through a slow pyrolysis process at temperatures ranging from 500 to 600°C. After production, the biochar was ground and sieved to obtain particles 0.300 mm (Sieve No. 50) and 0.150 mm (Sieve No. 100). The material was used in its raw, unwashed condition without activation or surface modification. The general chemical compositions of the bamboo derived bio-chars used in this study are referenced and summarized in Table 1. Observations revealed that the bamboo biochar exhibited a fine powder texture, indicating its suitability as a partial replacement for cement in concrete applications.

Table 1 Composition of bio-char obtained from bamboo feedstocks at various pyrolysis temperatures.

Feedstock	Temperature	C (%)	H (%)	O (%)	N (%)	Ash (%)
Phyllostachys pubescens [18]	500–800°C	76.3–88.1	1.8–2.9	9.1–18.4	0.6–1.0	4.2–6.0
Mixed bamboo species [19]	450–800°C	65–85	2–4	10–28	0.5–1.2	2–6

Polypropylene (PP) plastic waste in pellet form was used as a partial sand replacement. The PP pellets were similar in size to the coarse aggregate fraction. Although the density of the PP material was was assumed to be approximately 0.90–0.92 g/cm³ according to standard values for polypropylene.

Natural river sand, commercially obtained as dry fine aggregate, served as the fine aggregate. No laboratory characterization of fineness modulus or specific gravity was performed; however, the sand was used in a saturated surface dry (SSD) condition to control moisture content prior to mixing. Crushed stone was employed as the coarse aggregate, consisting of particles passing the 19 mm sieve (¾ in.) and retained on the 9.5 mm sieve (⅜ in.). The aggregates were used in their natural state without any chemical treatment. All mixtures were prepared using potable tap water at ambient temperature, with a constant water-to-cement ratio of 0.33. The control mix had a fixed cement:sand:crushed stone ratio of 1:2:1 by weight, serving as the baseline for all replacement levels.

Bamboo was selected as the raw material and air-dried prior to carbonization. The biochar was produced using a traditional bottomless steel drum kiln placed directly on the ground. Combustion was initiated with dry leaves and small branches, after which bamboo pieces were gradually added as the fire strengthened. The temperature during pyrolysis was maintained at approximately 500–600 °C. Once the combustion subsided, water was sprayed to extinguish the fire. The resulting charcoal was cooled, crushed into small fragments, and subsequently ground and sieved through No. 50 and No. 100 meshes to obtain fine biochar powder suitable for concrete applications, The Preparation process shown in **Figure 1** The prepared bamboo biochar was ground and sieved to obtain two particle size fractions 0.300 mm and 0.150 mm.

Figure 1: Preparation process of bamboo biochar

2.2 Mix Proportion Design

The mix proportions for all concrete paving block specimens were designed based on a fixed binder-to-aggregate ratio of 1:2:1 by weight (cement:sand:crushed stone), following the conventional mix used for non-structural paving applications. The water-to-cement ratio (w/c) was kept constant at 0.33 across all mixtures to maintain comparable workability. Biochar was incorporated as a partial cement replacement at levels of 5%, 10%, 15%, and 20%, while polypropylene (PP) plastic waste pellets were introduced as a partial sand replacement at 2%, 4%, and 6% by weight.

All materials were weighed using a digital balance with ±1 g accuracy before mixing. The mix design ensured homogeneity and reproducibility suitable for laboratory-scale production of paving blocks. The detailed quantities of each constituent material in all mix combinations are summarized in **Table 1**.

Table 1: Mix Proportion Design for Concrete Paving Blocks Containing Biochar and Polypropylene Waste

Mix ID	Biochar (% of cement)	PP (% of sand)	Cement (g)	Biochar (g)	Sand (g)	PP (g)	Crushed stone (g)	Water (g) w/c=0.33
B00-PP00	0	0	1000	0	2000	0	1000	330
B00-PP02	0	2	1000	0	1960	40	1000	330
B00-	0	4	1000	0	1920	80	1000	330

Mix ID	Biochar (% of cement)	PP (% of sand)	Cement (g)	Biochar (g)	Sand (g)	PP (g)	Crushed stone (g)	Water (g) w/c=0.33
PP04								
B00-PP06	0	6	1000	0	1880	120	1000	330
B10-PP00	10	0	900	100	2000	0	1000	297
B10-PP02	10	2	900	100	1960	40	1000	297
B10-PP04	10	4	900	100	1920	80	1000	297
B10-PP06	10	6	900	100	1880	120	1000	297
B15-PP00	15	0	850	150	2000	0	1000	280.5
B15-PP02	15	2	850	150	1960	40	1000	280.5
B15-PP04	15	4	850	150	1920	80	1000	280.5
B15-PP06	15	6	850	150	1880	120	1000	280.5
B20-PP00	20	0	800	200	2000	0	1000	264
B20-PP02	20	2	800	200	1960	40	1000	264
B20-PP04	20	4	800	200	1920	80	1000	264
B20-PP06	20	6	800	200	1880	120	1000	264
B05-PP00	5	0	950	50	2000	0	1000	313.5
B05-	5	2	950	50	1960	40	1000	313.5

Mix ID	Biochar (% of cement)	PP (% of sand)	Cement (g)	Biochar (g)	Sand (g)	PP (g)	Crushed stone (g)	Water (g) w/c=0.33
PP02								
B05-PP04	5	4	950	50	1920	80	1000	313.5
B05-PP06	5	6	950	50	1880	120	1000	313.5

Remark : - Bxx : the percentage of cement replaced by biochar and PPxx : the percentage of sand replaced by polypropylene (PP) plastic waste. Example, the mixture code B05–PP06 refers to a composition containing 5% biochar as a partial cement replacement and 6% PP as a partial sand replacement.

2.3 Mixing and Casting Procedures

All concrete mixtures were prepared using the base proportion of 1:2:1 by weight (cement:sand:crushed stone) with a fixed water-to-cement ratio of 0.33. The biochar and polypropylene (PP) plastic waste were incorporated as partial replacements for cement and sand, respectively. The replacement levels were 5%, 10%, 15%, and 20% for biochar, and 2%, 4%, and 6% for PP by weight. The prepared mixtures were then placed into steel molds with internal dimensions of 11.25 × 22.5 × 6 cm to produce rectangular paving blocks.

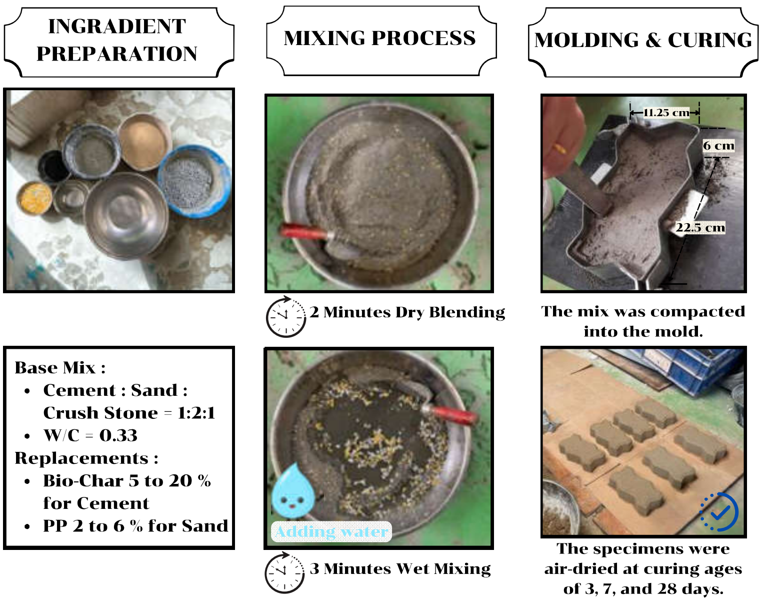

Figure 2: Mixing and Molding Process of Concrete Paving Blocks

Following demolding, all specimens were cured under ambient air conditions (approximately 27 ± 2°C) for periods of 3, 7, and 28 days. At the end of each curing period, the blocks were removed from the water, surface-dried, and prepared for subsequent testing according to the standard procedures described in Section 2.4.

2.4 Testing Methods

2.4.1 Compressive Strength Test

Compressive strength was determined using a hydraulic compression testing machine, following the procedure outlined in TIS 827-2565 and ASTM C140/C140M. Each paving block specimen (11.25 × 22.5 × 6 cm) was loaded uniformly at a constant rate of 0.5 ± 0.05 MPa/s until failure. The compressive strength (σ_c) was calculated using Equation (1):

$$\sigma_c = \frac{P}{A}$$ Equation (1)

where P is the maximum load at failure (N), and A is the loaded area (mm²). The mean value of three specimens was reported for each curing age.

(a)

(b)

Figure 3: Compressive strength testing of concrete specimens: (a) specimen positioned in the compression testing machine during loading; (b) typical failure mode observed after testing, showing crushed surfaces and internal cracks under compressive stress.

2.4.2 Water Absorption Test

Water absorption was measured according to TIS 827-2565, which follows the principles of ASTM C140/C140M and BS EN 1338. Specimens were oven-dried at 105 ± 5°C until a constant mass (M_{dry}) was achieved, then immersed in water at 27 ± 2°C for 24 hours. After immersion, surface water was removed using a damp cloth, and the saturated mass (M_{wet}) was recorded. The percentage of water absorption (W) was computed using Equation (2):

$$W(\%) = \frac{M_{Wet} - M_{Dry}}{M_{Dry}} \times 100$$ Equation (2)

2.4.3 Density Test

The density of the paving blocks was determined using the dry-mass method as specified in TIS 827-2565. The oven-dried mass of each specimen was divided by its measured volume (calculated from average dimensions). The average density of three specimens was reported for each mixture.

2.4.4 Skid Resistance Test

Surface skid resistance was assessed following the procedure described in BS EN 1338, using a pendulum-type tester (British Pendulum Tester, BPT). The test was carried out on both dry and wet surfaces at room temperature. Each specimen was cleaned and placed horizontally before the pendulum arm was released to slide across the test surface. The average British Pendulum Number (BPN) from five readings per specimen was recorded. A BPN value greater than 45 indicates satisfactory slip resistance for pedestrian paving surfaces, as recommended by TIS 827-2565 and BS EN 1338.

3. Results and discussion

3.1 Density Variation

The measured densities of all mixtures are summarized in **Error! Reference source not found.**. It was observed that the inclusion of biochar and PP resulted in a slight reduction in bulk density compared with the control mix (B00–PP00). The density decreased progressively with increasing biochar content due to its lower specific gravity and highly porous structure, which introduced additional voids within the matrix. In contrast, the replacement of sand with PP pellets exhibited a minor effect on density reduction since the PP had a lower density (≈0.9 g/cm³).

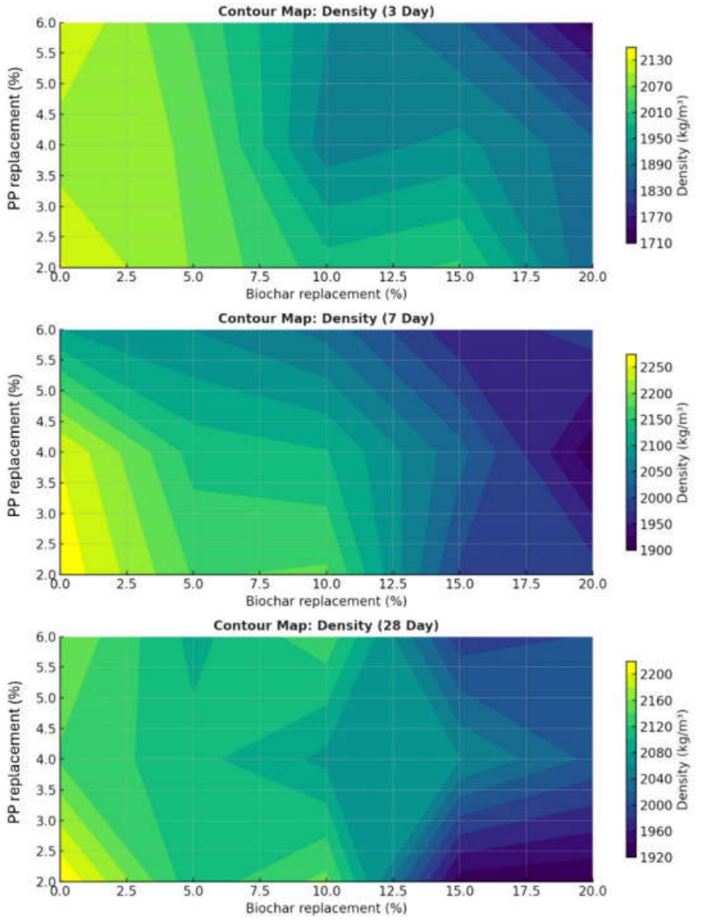

Figure 4 Relationship between the replacement ratios of polypropylene (PP) plastic waste (as sand substitute) and biochar (as cement substitute) on the density of concrete paving blocks.

3.2 Compressive Strength

The compressive strength results for all mixtures at 3, 7, and 28 days are presented in Figure 3.2. Overall, strength development followed a typical hydration trend, increasing with curing age for all mixes. The control mix (B00–PP00) achieved 48.5 MPa at 28 days, while the mixture containing 5% biochar and 2% PP (B05–PP02) recorded the highest strength of 52.11 MPa.

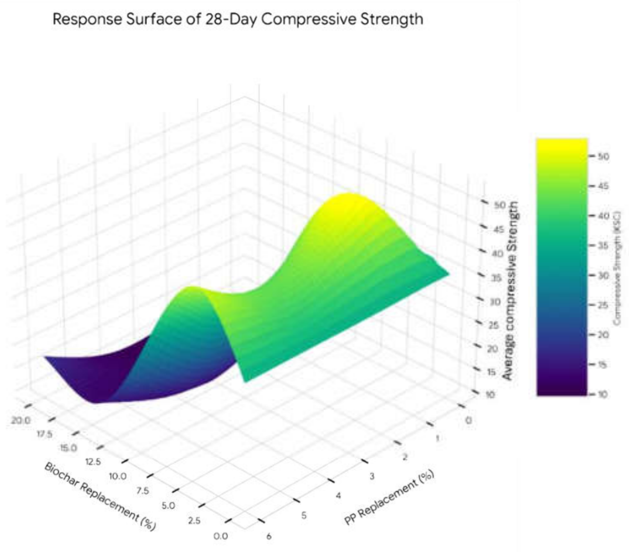

Figure 5 Response surface of compressive strength as a function of biochar and polypropylene (PP) replacement levels for concrete paving blocks at 28 days.

Beyond 5% biochar or 2% PP, the strength declined steadily due to the dilution of cementitious content and poor bonding at the PP–cement interface. The results align with findings by Liu et al. (2022) [20], who reported strength improvement at 5% biochar substitution, and Senadheera et al. (2023) [21], who observed similar trends with recycled plastic aggregates.

3.3 Water Absorption

The incorporation of biochar led to a gradual increase in water absorption with higher replacement ratios, mainly due to the porous and hydrophilic nature of biochar. In contrast, the inclusion of PP slightly reduced water absorption at lower percentages, as the hydrophobic PP particles hindered capillary suction and reduced pore connectivity.

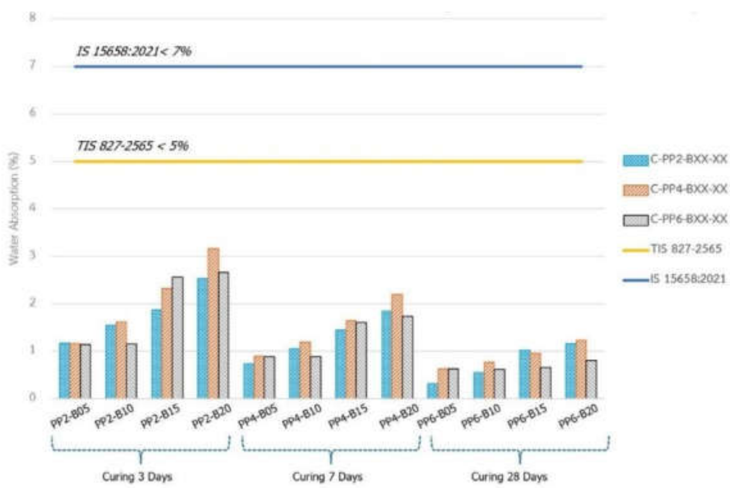

Figure 6: Water absorption of concrete paving blocks at curing ages of 3, 7, and 28 days.

The influence of biochar and polypropylene (PP) plastic waste on the development of concrete paving blocks, it was observed that the amount of biochar had a pronounced effect on increasing water absorption. At the 28-day curing age, an increase in biochar content from 5% to 20% led to a consistent rise in water absorption across all PP replacement levels. However, the mixtures incorporating the lowest biochar content exhibited the most favorable performance, characterized by the lowest water absorption values particularly for mix C-PP2-B05-28, which recorded only 0.31%, and C-PP6-B05-28, with 0.63%.

3.4 Skid Resistance

The skid resistance test was conducted using a Skid Resistance Tester under both wet and dry surface conditions. The results were evaluated in accordance with BS EN 1338:2003, which specifies a minimum acceptable value of 45 British Pendulum Number (BPN) for concrete paving blocks. The obtained test results are presented as follows.

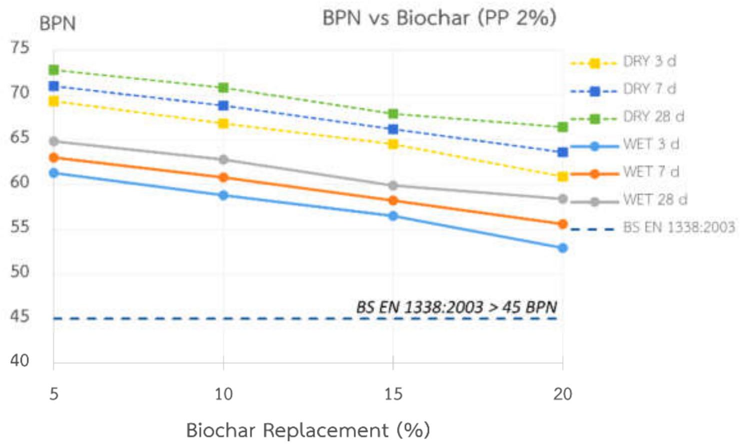

Figure 4: Skid resistance test results of concrete paving blocks containing 2% polypropylene (PP) plastic waste as a sand replacement.

Error! Reference source not found. The results revealed an inverse correlation between BPN and biochar content across all curing ages. Under dry conditions, the BPN decreased from approximately 72.8 at 5% biochar to 66.4 at 20% biochar after 28 days, while under wet conditions, it dropped from 64.8 to 58.4 over the same range.

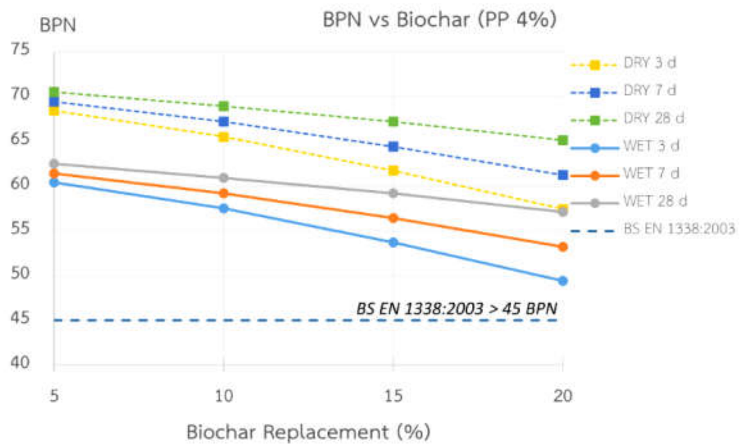

Figure 5: Skid resistance test results of concrete paving blocks containing 4% polypropylene (PP) plastic waste as a sand replacement.

Error! Reference source not found. shows that the skid resistance (BPN) decreased with increasing biochar content under both dry and wet conditions. After 28 days of curing, the BPN declined from approximately 72.8 to 66.4 in dry tests and from 64.8 to 58.4 in wet tests as biochar replacement increased from 5% to 20%.

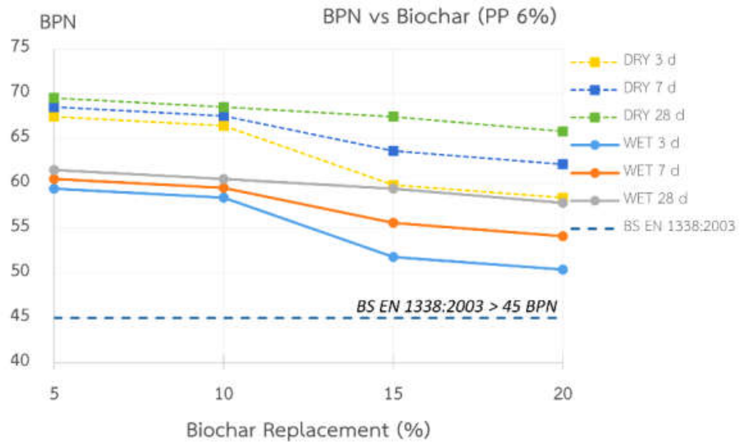

Figure 6: Skid resistance test results of concrete paving blocks containing 6% polypropylene (PP) plastic waste as a sand replacement.

Error! Reference source not found. shows that the skid resistance (BPN) decreased with increasing biochar content under both dry and wet conditions at all curing ages. After 28 days of curing, the BPN dropped from about 69.5 to 65.8 under dry conditions and from 61.5 to 57.8 under wet conditions as the biochar replacement increased from 5% to 20%.

4. Conclusions

This study aimed to develop sustainable concrete paving blocks by partially replacing cement with biochar and sand with polypropylene (PP) plastic waste. Based on the experimental results, the following conclusions can be drawn:

1. The experimental results revealed that the density of the concrete paving blocks showed no significant variation across curing ages, though a slight decrease was observed with increasing biochar and polypropylene (PP) contents. This reduction corresponded to the porous structure of biochar and the low specific gravity of PP. At replacement levels up to 10% biochar and 4% PP, densities remained within the standard limits.

2. The compressive strength increased to its peak at 5% biochar and 2–6% PP, achieving values above the minimum requirement of 35 MPa specified in TIS 827-2565. Beyond 10% biochar, strength declined consistently due to excessive porosity and reduced matrix cohesion.

3. The skid resistance (BPN) increased progressively with curing time, averaging 63.5, 66.5, and 68.5 for dry conditions and 55.5, 58.5, and 60.8 for wet conditions at 3, 7, and 28 days, respectively. The difference between dry and wet surfaces averaged about 8 BPN units. All mixes exceeded the minimum requirement of 45 BPN (BS EN 1338), confirming that paving blocks incorporating biochar and PP are

safe and suitable for practical use in pedestrian applications.

5. Ethical Approval

This study does not involve human participants or animals; therefore, ethical approval was not required.

6. Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work the author(s) used ChatGPT in order to assist with the overall review of the manuscript, including checking formatting consistency, identifying potential spelling or grammatical errors, and supporting reference management. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

7. Acknowledgements

This research was funded by Faculty of Technical Education, King Mongkut's University of Technology North Bangkok (KMUTNB) Contract FTE-2568-14

8. Author Contributions

Paoleng, P.: Conceptualization, Methodology, Investigation, Funding acquisition, Writing – original draft.; Kongsomsaksakul, S.: Data curation, Formal analysis, Validation, Writing – review & editing.; Meepon, I.: Resources, Supervision, Visualization, Software, Investigation.; Maneekaew, S.: Project administration, Writing – review & editing.

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