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New and Sustainable Coal Char-Based Paving Blocks for Roadway Applications

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Abstract: Paving blocks are widely used in engineering construction for durable pavement surfaces characterized by their interlocking capability to enhance structural integrity. This study explores the potential use of char as a byproduct from coal pyrolysis and an alternative raw material to natural aggregates in developing paving blocks, aiming to reduce the associated environmental issues associated with the uncontrolled and excessive mining of natural resources. This study finds the paving blocks made from char to have the required engineering properties as mentioned by ASTM standard C936. Trass and trass-lime are added as supplementary cementitious materials (SCMs) to enhance the performance of char-based paving blocks. The incorporation of SCMs as a cement replacement also aims to reduce the carbon footprint arising from increased cement use. The compressive strength increased from 55.7 MPa to 65.71 MPa at 12.5% cement replacement with trass-lime. The water absorption is reduced to 4.63% from 4.95%. Beneficial effects towards freeze–thaw durability and abrasion resistance are also observed on trass-lime-incorporated paving blocks. This study signifies the remarkable potential use of coal-derived char and SCMs in developing light, high-strength, and durable paving blocks, showcasing their competitive engineering performance. These new char-based paving blocks will contribute towards a more sustainable construction environment and advance the current construction and engineering practices.

Keywords: environment friendly; char; paving block; compressive strength; abrasion resistance

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1. Introduction

Paving blocks are specifically engineered to have adequate mechanical properties and durability for their use in roadway applications [1]. The required mechanical properties of paving blocks may vary depending on the traffic conditions. The traffic conditions where the volume of traffic exceeds 251 daily equivalent single axle loads (ESAL) is considered high volume traffic, with all else considered low volume vehicular traffic [2]. Unlike asphalt and concrete pavements that demand considerable time and capital for maintenance and repair, the use of paving blocks is a more favorable and economically efficient option [3]. When a certain section of pavement needs repair, individual blocks are effortlessly replaced without halting moving traffic for an extended duration [4].

Common raw materials frequently employed for making paving blocks include cement, fine aggregates, coarse aggregates, and water [5]. Paving blocks manufacturing is predicted to increase globally by 4.9% between 2020 and 2032 [6]. This increase in the production rate signifies a corresponding increase in the consumption of raw materials (cement and aggregates) used for manufacturing. Significant issues are raised by this rise in the consumption of raw materials, particularly in light of the use of cement and aggregates, which have been noted as a source of environmental concern worldwide [7].

Cement is a low-cost material in manufacturing and has wide availability [8]. However, producing one metric ton of cement releases a substantial amount of CO_2, i.e., 0.8 tons [9]. Researchers are continuously making efforts to overcome this problem by exploring the beneficial use of ground-granulated blast furnace slag [10], fly ash [11], metakaolin [12], and natural pozzolanas [13] as partial replacements for cement. These materials are also called supplementary cementitious materials, but their availability is limited. So, a balanced approach that finds the optimum uses of these materials is required. The study carried out by Cullu et al. [14] showed that an amount of trass up to 20% cement replacement is effective in increasing in mechanical performance of mortar samples. An increase in strength at 7 days, 28 days, and 90 days by around 5–20% is observed with the incorporation of 18% of trass as a cement replacement [15]. These findings signify the potential use of trass as a partial substitute for cement, not only for improving mechanical performance but also for reducing cement consumption.

Concerns over aggregate use [16] are also raised by environmentalists due to the increase in the manufacturing of paving blocks. This increase in demand highlights the necessity of using a sustainable sourcing and utilization strategy for these vital commodities in the building sector. The conventional form of raw materials, especially fine aggregate and coarse aggregate, are economical in production and hence widely utilized for construction applications [17]. However, the extraction of these natural resources from rocks is of primary concern. It involves the mining of riverbeds and landscapes, disrupting the ecological balance. Uncontrolled and excessive extraction leads to severe environmental degradation (landslides and soil erosion), posing a threat not only to human safety but also to the natural habitats of flora and fauna [18].

The mined resources are transported to industrial facilities for processing, which involves crushing them into various shapes and sizes making them suitable for their various applications [19] in making concrete, mortar, bricks, and paving blocks. The operation of such equipment for crushing requires fuel, typically diesel, for operation, which is another non-renewable source of energy. The combustion of fuels contributes to the depletion of finite energy reserves along with the emission of greenhouse gases and pollutants [20]. Each step in the manufacturing of aggregates raises concerns about sustainability and environmental impact.

To address these issues, novel materials are being unearthed for reducing the reliance on traditional natural resources and for concurrently promoting environmental sustainability [21]. Some researchers have explored the beneficial use of waste tires [22], reclaimed asphalt pavement (RAP) [23], jute fibers [24], and other similar pioneering materials. For manufacturing paving blocks, Euniza et al. [22] prepared the concrete mix by replacing a proportion of aggregates with tires. The resulting mixture was then filled into the molds and left to cure for 24 h. In contrast, Nandi et al. [23] used a vibration table and compaction load in addition to casting the mixture into a mold for producing the paving blocks. A similar methodology of using a vibration table and compaction has been used by Kundu et al. [24] and has reported better engineering properties, particularly the compressive strength of paving blocks produced by this method. Their contributions to finding sustainable alternative materials and efficient methods of manufacturing paving blocks are notable. However, there is a need to search for even more of such materials to fulfill the rapidly increasing demand of the construction industry.

In this paper, the potential use of natural pozzolanas, i.e., trass and trass-lime, are investigated for partially replacing the use of cement in the manufacturing of paving blocks. In addition, an alternative raw material derived from coal (i.e., char) is investigated to entirely replace natural aggregates in the making of paving blocks. Char is a byproduct formed from the coal pyrolysis process [25] and is lightweight. The direct combustion of carbonaceous products releases a significant amount of CO_2 into the atmosphere thereby causing marked environmental problems and health issues [26], and accordingly, industries are shifting towards alternative energy sources for power generation [27]. Hence, there is an obligation to harness coal in the most sustainable way possible, and pyrolysis of coal is one such technique. The coal char is composed of 80% fixed carbon in solid form, which if managed properly can significantly lower the emission of harmful gases. Studies performed by Yu et al. [28,29] in enhancing the engineering performance of geomaterials have revealed insights into the promising potential of char. Hussain et al. [30] attempted to use coal char to build structural elements such as beams and columns. Olayiwola and Ng [31] expanded the research on the partial utilization of coal char for making bricks. Yu et al. [32] also showed the possibility of incorporating char alone without including natural aggregates in making high-strength bricks. Recently, Pandey et al. [33] have shown the possibility of making char-based thin bricks and stone veneers with desired engineering properties, showcasing the economic feasibility of mass production. However, the feasibility of incorporating coal char into manufacturing paving blocks remains unknown and needs to be explored.

In comparison to traditional paving blocks, the mechanical adequacy of the char-based block is the main focus of this paper's study. Trass and trass-lime are used as supplementary cementitious materials in this study. Aggregates are replaced with char. The manufactured paving blocks have adequate compressive strength, good freeze–thaw durability, low abrasion value index, and minimal water absorption. This study examined the feasibility of incorporating char and the potential use of trass and trass-lime in making lightweight paving blocks, thus advancing the promotion of sustainable and efficient construction practices in roadway construction.

2. Materials Properties, Mix Design, and Method of Manufacturing

2.1. Material Properties

The raw materials used for developing the char paving block include coal-derived char, ordinary Portland cement type I/II, trass, trass-lime, superplasticizers (SP), and s ilica fumes (SF).

The pyrosis char is an inert material obtained from the pyrolysis of coal at a temperature of 850 °C and is incombustible. The chemical components of char include fixed carbon (80.05%), ash (12.93%), and moisture (7.02%). The char has a particle form with a black color and has a moisture content of 14%. The received char from the pyrolysis processing plant has 60% of the particles passing through a 300 µm sieve and the remaining 40% of particles passing through a 75 µm sieve. The received char is ground in a ball mill to obtain more than 80% of particles passing through a 300 µm sieve, and this ground char (named fine char) is used here for manufacturing paving blocks. Cement type I/II was used in manufacturing paving blocks. The other materials used in this project include an amorphous micronized grey silicon dioxide pozzolana known as SF and a light yellowish SP powder. The trass and trass-lime used for this study (Figure 1) have more than 99% of the particles passing through a 300 µm sieve. The trass is a brownish-grey pozzolanic material that consists mainly of aluminum oxide (Al_2O_3), silicon oxide (SiO_2), calcium oxide (CaO), magnesium oxide (MgO), and alkalis (Na_2O, K_2O). The trass-lime used in this study (Otterbein trass-lime FL B 2) is a formulated lime according to EN459-1 and is whitish grey. It contains natural hydrated lime NHL 2 and trass powder according to DIN 51043 as a natural pozzolan.

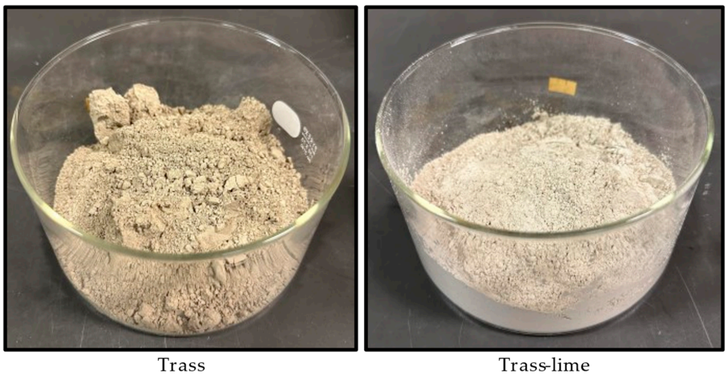

Figure 1. Pozzolanic materials (trass and trass-lime) used for manufacturing char-based paving blocks.

2.2. Mix Design and Method of Manufacturing

A comprehensive study is executed by designing a total of 9 mix designs, as shown in Table 1. The mix design CH30 consisting of 30% char is referred to as the control mix design in which investigation procedures are carried out by replacing a designated amount of cement with trass and trass-lime. Yu et al. [32] developed char-based bricks using 40% char content, SF, and SP, with a maximum compressive strength of 52.5 MPa. The amount of char in these blocks has been reduced to 30% to satisfy the higher compressive strength (≥55 MPa) requirements for paving blocks. Four mix designs designated by T contain trass, and another four mix designs designated by TL contain trass-lime. The mix designs CH30-T1 and CH30-TL1 were formed by a 100% cement replacement ratio with trass and trass-lime in the control mix CH30. The mix designs CH30-T2 and CH30-TL2 were formed by a 50% cement replacement ratio with trass and trass-lime in the control mix CH30. The mix designs CH30-T3 and CH30-TL3 were formed by a 25% cement replacement ratio with trass and trass-lime in the control mix CH30. The mix designs CH30-T4 and CH30-TL4 were formed by a 12.5% cement replacement ratio with trass and trass-lime in the control mix CH30.

Table 1. Mix designs for char-based paving blocks.

Sample ID	Char Content (%)	Cement Content (%)	Trass-Lime Content (%)	Trass Content (%)	SF Content (%)	SP Content (%)	w/b Ratio
CH30	30	63.5	0	0	5.3	1.2	0.37
CH30-T1	30	0	0	63.5	5.3	1.2	0.37
CH30-T2	30	31.8	0	31.7	5.3	1.2	0.37
CH30-T3	30	47.6	0	15.9	5.3	1.2	0.37
CH30-T4	30	55.6	0	7.9	5.3	1.2	0.37
CH30-TL1	30	0	63.5	0	5.3	1.2	0.37
CH30-TL2	30	31.8	31.7	0	5.3	1.2	0.37
CH30-TL3	30	47.6	15.9	0	5.3	1.2	0.37
CH30-TL4	30	55.6	7.9	0	5.3	1.2	0.37

For making a paving block, the raw materials in the required proportions as per the mixture design composition were weighed. Then dry mixing of these materials was carried out in a rotating mixer. Following the dry mixing, a predetermined quantity of water mixed with SP in a designated proportion was added to the dry mixture, and wet mixing was performed for another three minutes to obtain the blended mix as described by Pandey et al. [33].

The 10 mm thick aluminum plates with indentations as shown in Figure 2 have dimensions of 193 × 55 mm (front plate) and 91 × 55 mm (side plate). These plates were placed inside the rectangular mold (254 × 102 × 102 mm) made of high-strength steel to give a unique design to the paving blocks. The indentation on the aluminum plates (two side plates and two front plates) has a base dimension of 25.4 × 7.6 mm and gradually tapers upwards up to a height of 38 mm.

The blended mix was then filled in this steel mold in a tri-layered fashion where each layer was tamped 20 times with a 3.3 kg cylindrical hammer 800 mm long by a 10 mm thick square base, as shown in Figure 3a. The steel pressing plate with grooves was placed over the filled mold and then subjected to a hydraulic press with 7 MPa applied for about one minute, as shown in Figure 3b. The compacted mix is left to cure within the mold for one day.

Following one day of curing, the produced samples were demolded and then placed in a humidity chamber (90% humidity) where they underwent curing for another 28 days. The cured samples were treated with hydrophobic liquid under vacuum suction as discussed by Yu et al. [32] before subjecting the samples to compressive strength tests and other laboratory tests.

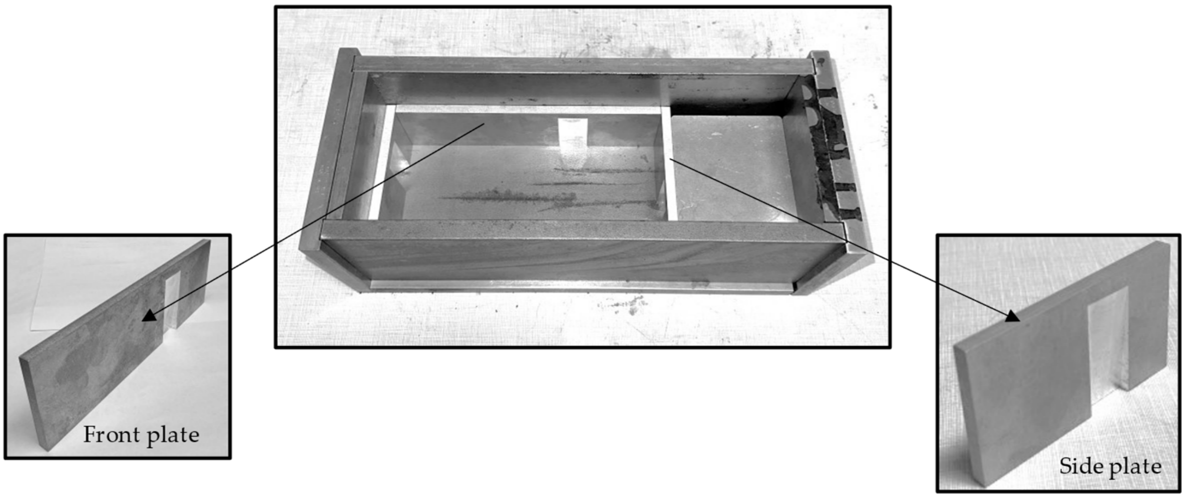

Figure 2. High-strength steel mold and specifically designed front and side plates made of aluminum for giving protrusions to the char-based paving blocks.

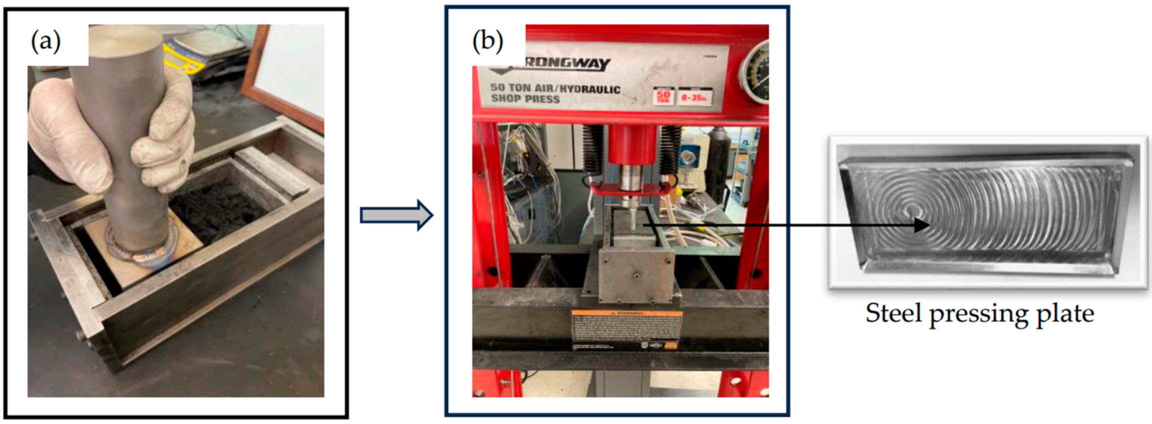

Figure 3. Stages in developing process of char-based paving block: (**a**) initial compaction with cylindrical hammer and (**b**) final compression using a hydraulic press.

The key feature of these char-based paving blocks is the design and location of protrusions. Each face of the paving block has one protrusion at a third of the distance from the closest edge or two thirds of the distance from the farthest edge as shown in Figure 4. The protrusions are wider at the base and taper as they climb up. These protrusions serve the important purpose of maintaining a consistent joint gap between the adjacent paving blocks, thereby simplifying the installation procedure. Compared to conventional pavements, one advantage of these paving blocks is that the load-bearing capacity of the pavement made from paving blocks increases with time. The increase in load capacity is due to the post-stiffening of bedding sand placed between the joints during traffic movement [3]. This consistent joint width further contributes to maintaining the paving blocks' structural integrity and proper interlocking. The water-related issues can be addressed by filling the joints with permeable materials.

Figure 4. Char-based paving block with protrusions.

3. Testing Methods and ASTM Requirements

Laboratory testing was conducted to assess the characteristics of the produced paving blocks and measure their compressive strength, water absorption, freeze–thaw durability, and abrasion resistance as per ASTM C936 [34]. The measured properties were also validated against ASTM C1272 [2] to confirm their application in heavy vehicular traffic areas. For the compressive strength test, the sample of paving blocks was placed below the machine and loaded till failure as shown in Figure 5.

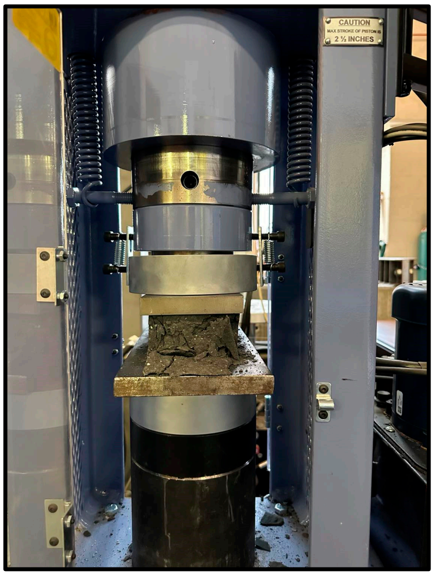

Figure 5. Measurement of compressive strength of char-based paving blocks.

ASTM C936 [34] has recommended a minimum compressive strength of 55 MPa for paving blocks to be used for paved areas. In addition, ASTM C1272 [2] also recommends similar strength requirements (class R type) for its application in vehicular traffic areas where ESAL exceeds 251.

The abrasion index test was performed as per ASTM C418 [35]. The sandblasting cabinet used for the test is shown in Figure 6a. Before testing, the samples were submerged in water for 24 h. The saturated samples after 24 h were then made surface dry to obtain a saturated surface dry condition at the time of the test. The 1.2 mm thick shield made of a steel sheet with a circular hole of diameter 28.70 mm was positioned firmly over the specimen inside the sandblasting cabinet as shown in Figure 6b. Compressed air at 60 psi and abrasive material were injected onto eight sample surfaces for one minute on each spot as shown in Figure 6c. The abraded volume was measured, and the thickness loss was calculated by dividing the measured abraded volume by the sum of the cross-sectional area of all eight spots. The ASTM C936 [34] requires an average abrasion volume loss of 15 $cm^3/50\ cm^2$, and ASTM C1272 [2] has a higher tolerance level up to 85 $cm^3/50\ cm^2$.

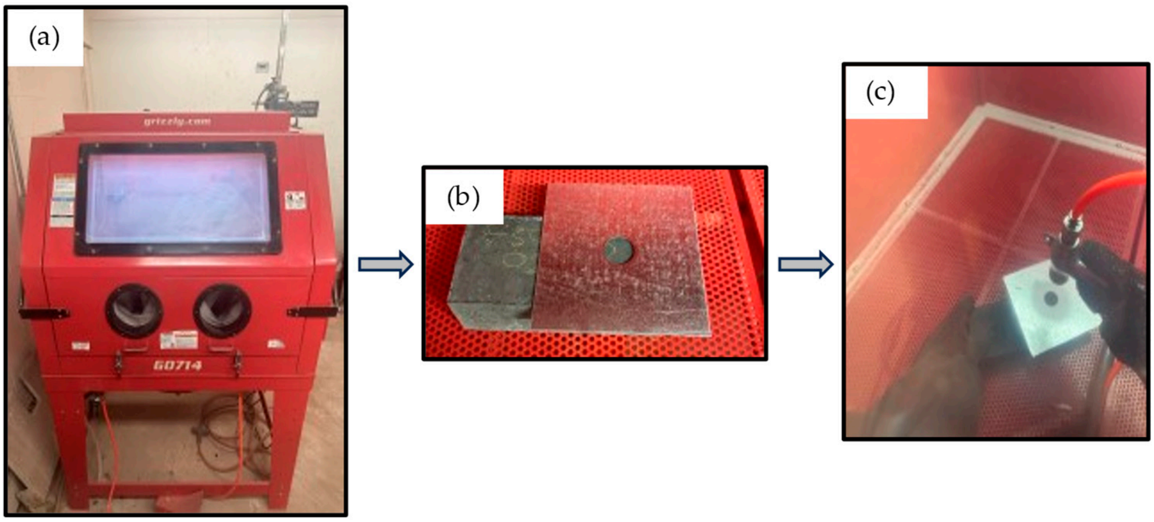

Figure 6. Determination of abrasive resistance of paving blocks: (**a**) sand abrasion equipment used in the study, (**b**) arrangement of sample setup inside the equipment, and (**c**) injection of abrasive materials over the sample.

The water absorption test was carried out on half-sized paving blocks following the ASTM standard C140 [36]. The half-sized samples were submerged six inches below the top surface of the water for 24 h, as shown in Figure 7. The temperature of the water was maintained at 23 ± 2 °C. The completely saturated samples after 24 h were then placed in the oven until two successive readings indicated a difference of less than 0.2%. The water absorption was thereafter calculated by dividing the weight of water absorbed by the sample by the oven-dried weight of the sample. The ASTM C936 [34] recommends water absorption within 5%, and ASTM C1272 [2] has a higher tolerance level of up to 6%.

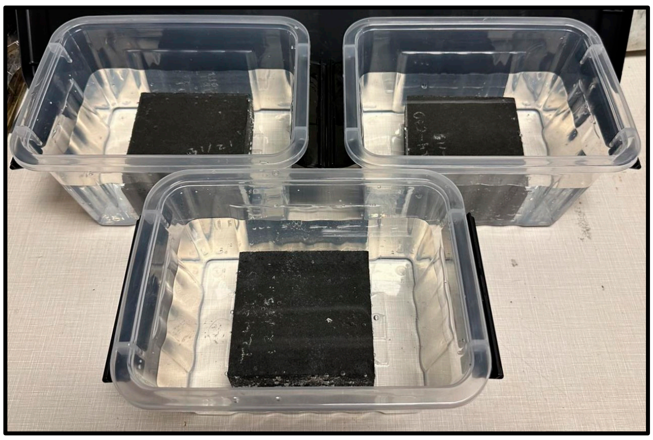

Figure 7. Half-sized block samples submerged in water for water absorption test.

The freeze–thaw test on full-sized paving block samples was conducted in accordance with the ASTM C1645 [37]. The freeze–thaw test was carried out by submerging the paving block samples completely in 3% saline water. For each cycle, the sample was kept in a freezing chamber for 16 h (Figure 8a) and in a thawing chamber for 8 h (Figure 8b). The temperature during freezing was maintained at −15 ± 3 °C for the last seven to twelve hours, and during thawing a minimum of +5 °C was maintained for the last one hour. A total of 28 freeze–thaw cycles were conducted, and the average mass loss should be 225 g/m^2 as per ASTM C936 [34].

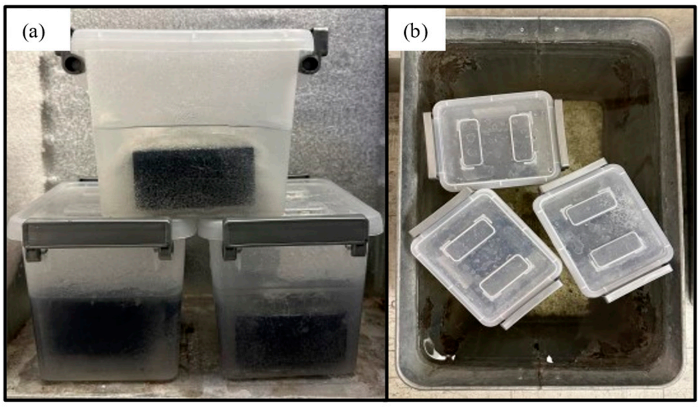

Figure 8. Half-sized block samples in the (**a**) freezing chamber and (**b**) thawing tank.

4. Engineering Properties and Comparison with Commercial Paving Blocks

4.1. Bulk Density

The study shows that the control mix CH30 has the highest bulk density of 1704 kg/m^3 among the mix designs tested in this study, as shown in Figure 9. Lower density values are recorded for paving blocks when cement content is replaced with trass-lime and trass content. The decrease in density is attributed to the replacement of the high-density material cement (1.51 g/cm^3) [38] with low-density materials trass (0.8 g/cm^3) [39] and trass-lime (0.6 g/cm^3) [40]. The cement is a high-density material compared to trass and trass-lime; the reduction in density values is directly associated with the percentage replacement of cement with trass and trass-lime. Specifically, the mix designs CH30-TL1 and CH30-T1 formed by 100% cement replacement with trass-lime and trass have the lowest densities followed by 50% cement replacement mix designs CH30-TL2 and CH30-T2. This is because of the higher proportion of low-density materials (trass and trass-lime) in the design mix. The mix designs CH30-TL3 and CH30-T3 have densities higher than CH30-TL2 and CH30-T2 but lower than CH30-TL4 and CH30-T4, respectively. The density values observed for the CH30-TL4 and CH30-T4 paving blocks are 1670 kg/m^3 and 1690 kg/m^3.

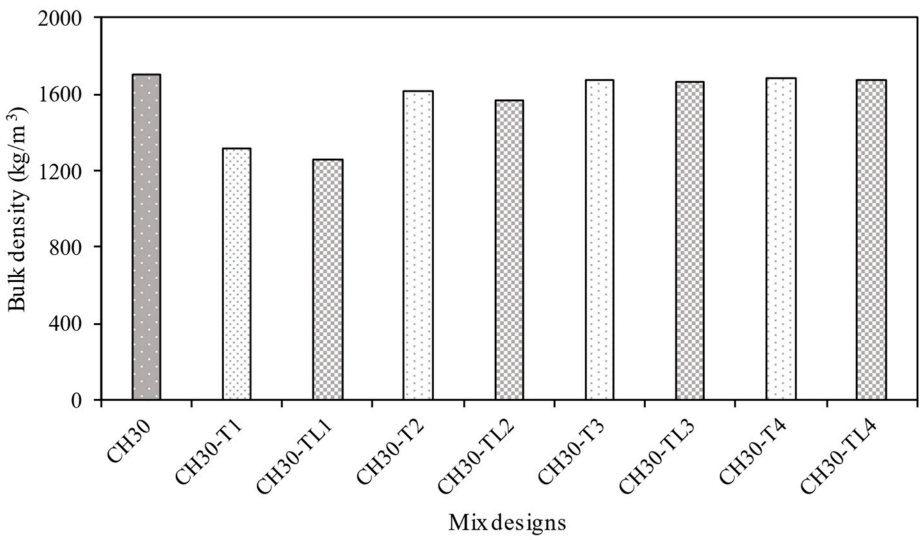

Figure 9. Comparison of bulk density of char-based paving blocks based on various mix designs.

Compared to commercially available paving blocks, the char-based paving blocks designed in this study have a lower density than conventional clay-based paving blocks (2062 kg/m^3 [41]) and concrete paving blocks (2200 kg/m^3 [42]). Comparatively low-density paving blocks offer numerous advantages throughout the construction process. Firstly, they are cost-effective to move from production sites to construction sites by shipping a large quantity of materials at once. This leads to a decrease in transportation costs, which constitutes a significant portion of overall project expenditure. Furthermore, reduced transportation shifts also contribute towards reduced fuel consumption, aligning with environmental sustainability goals by minimizing carbon emissions. As workers can move these char-based paving blocks more easily and have less physical strain when handling heavier typical clay and concrete-based paving blocks, lightweight char-based paving blocks have the potential to speed up the construction timeframe.

4.2. Compressive Strength

Figure 10a shows the average compressive strength of char-based paving blocks at 7 days. For the control mix CH30, the average compressive strength is 49 MPa at 7 days. The study is expanded to study the effect of incorporating trass-lime and trass. The mix designs CH30-T1 and CH30-TL1, formed by a 100% cement replacement ratio with trass and trass-lime, resulted in lower compressive strength values compared to the control mix CH30. The 7-day compressive strength of CH30-T1 and CH30-TL1 paving blocks are 1.3 MPa and 10.4 MPa, respectively. The trass and trass-lime, known for their pozzolanic properties, form additional bonding compounds, especially C-S-H, C-A-S-H, and C-A-H [15]. As the mix designs CH30-T1 and CH30-TL1 lack cement, the formation of additional bonding compounds is hindered, leading to lower compressive strength values than the control mix. However, compared to CH30-T1, CH30-TL1 has higher strength, and this can be attributed to the activation of trass with the lime present in contact with water facilitating the formation of bonding compounds [43].

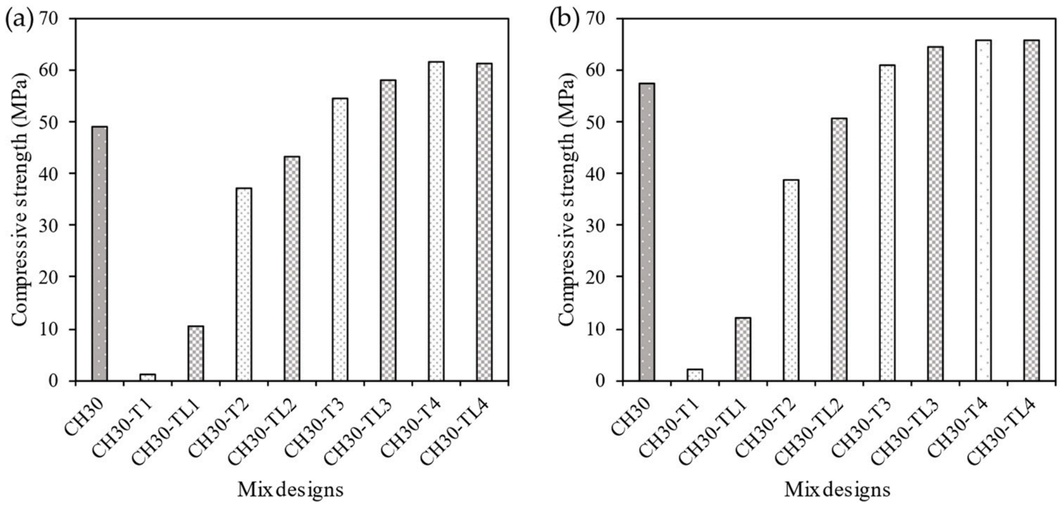

Figure 10. Comparison of compressive strength of char-based paving blocks based on various mix designs: (**a**) 7-day test results and (**b**) 28-day test results.

The mix designs CH30-T2 and CH30-TL2, formed by a 50% cement replacement ratio with trass and trass-lime in the control mix CH30, resulted in comparatively higher compressive strength values compared to CH30-T1 and CH30-TL1. The presence of cement in the mix design undergoes hydration in contact with water to provide the necessary amount of calcium hydroxide upon hydration for trass-lime and trass to form additional binding compounds upon reaction. The 7-day compressive strength for mix design CH30-T2 is measured as 37.2 MPa and is 43.15 MPa for mix design CH30-TL2.

For a 25% cement replacement ratio with trass-lime and trass, the 7-day compressive strengths of mix designs CH30-T3 and CH30-TL3 are recorded as 54.2 MPa and 58.1 MPa, respectively. These results suggest that both materials, trass-lime and trass, are effective in contributing to the strength development of the concrete mix at this replacement ratio. However, the slightly higher compressive strength observed for CH30-TL3 may be attributed to the effect of lime in activating the pozzolanic reaction of trass. The 7-day compressive strengths of CH30-T4 and CH30-TL4 at 12.5% cement replacement ratio with trass and trass-lime are recorded as 61.6 MPa and 61.3 MPa, respectively. This indicates that even at a lower replacement ratio, both materials continue to contribute to the development of the compressive strength of the concrete mix. From this study, the mix design CH30-TL4 is adopted as an optimum mix design and further engineering properties are examined only for the control mix design CH30 and this optimum mix design CH30-TL4.

Figure 10b shows the average compressive strength of char-based paving blocks at 28 days. All the mix designs show a gain in strength from 7 days. The 28-day compressive strength exceeds the minimum 55 MPa in accordance with the ASTM C936 [34] and in accordance with the ASTM C1272 [2] for type R paving blocks. The strength variation behavior in between the mix designs is similar to that observed for the 7-day strength. The control mix CH30 has a 28-day compressive strength of 57.5 MPa and the highest strength at 28 days is shown by CH30-TL4 (65.71 MPa), with little variation to CH30-T4 (65.62 MPa). The similarities in strength performance shown by CH30-T4 with that of CH30-TL4 might be attributed to the complex interplay between trass purity, particle size, quantity, lime presence, and their combined influence on strength development [44,45]. The higher reactivity of pure trass in CH30-T4 due to higher amorphous silica content, finer particle size, and fewer impurities [46] might have balanced the effect of lime on the reduced quantity of trass in CH30-TL4 mixes leading to similar strength performances between these mix designs. The control mix CH30 and the optimum mix design CH30-TL4 are selected for further study of engineering properties.

The comparison studies are carried out among various types of paving blocks to justify the strength adequacy of these char-based paving blocks. The compressive strength of commercial clay red pavers [41] carried in the lab measured at 46.6 MPa. Nandi et al. [23] used a particular mix composition for a control sample based on natural aggregates in their mix design, and the 28-day compressive strength was determined as 66 MPa, which is comparable to that of our char-based paving block CH30-TL4 as shown in Figure 11.

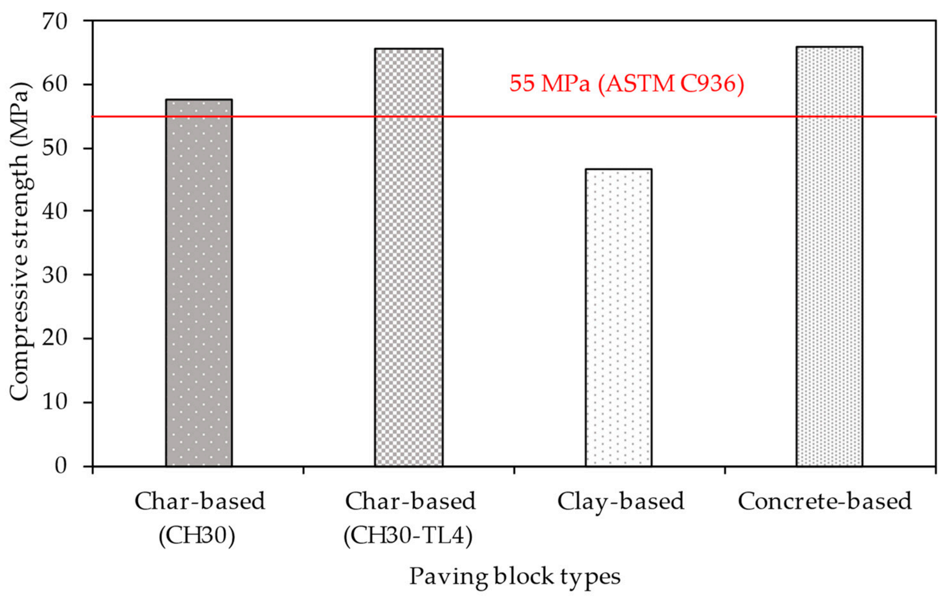

Figure 11. Comparison of compressive strength of char-based paving blocks with clay- [41] and concrete- [23] based paving blocks.

In the context of these comparisons, it is crucial to note that the char-based paving blocks do not have any percentage of aggregates. The char, along with other binding materials, is solely responsible for imparting this high strength. The char occupies 30% of the total dry weight for all mix designs. The porous nature of char [30] allows it to absorb water and cementitious materials during the mixing process. As the cement hydrates, it forms hydration products such as the calcium silicate hydrate (C-S-H) gel and calcium hydroxide ($Ca(OH)_2$). These hydration products penetrate the pores of the char, where they continue to react and solidify, forming a network of hardened material within the existing concrete matrix. This process creates a reinforcing effect, strengthening the overall structure of the concrete by providing additional binding points and increasing its resistance to cracking and deformation.

Silica fume (SF), a pozzolanic material, has a fine particle size and high silica content, which facilitates the strength development process. The SF reacts with the cement hydration product calcium hydroxide to produce additional C-S-H gel, forming a denser microstructure and reducing voids and permeability. In addition, the fine particle size of silica is also effective in filling the void spaces. The reduction of void spaces in the mix is responsible for improving its mechanical performance [47]. Furthermore, the formation of additional C-S-H bonds is responsible for increasing the adhesive bonds between char particles and the cementitious matrix. Superplasticizers (SPs) added to the mix reduce the surface tension of water. The reduction in surface tension increases the surface area of water [48]. This leads to maintaining workability at a lower water content, thereby making denser and more compact microstructures. Furthermore, the lower surface tension of water will allow cement particles to disperse widely within the mix around the char particles [48] and improve the hydration of cementitious material.

4.3. Abrasion Resistance

The average abraded volume for mix designs CH30 and CH30-TL4 per 50 cm^2 surface area are 11.20 cm^3 and 9.26 cm^3. The average thickness loss resulting from the abrasion test of these paving blocks are 2.25 mm and 1.85 mm, respectively, as shown in Figure 12, which is within the permissible range of 3 mm as per ASTM C936 [34] and as per ASTM C1272 [2] for type R paving blocks. The comparatively higher abrasion resistance of char-based mix design CH30-TL4 can be attributed to several factors associated with trass-lime. Firstly, the addition of trass-lime facilitates the formation of additional hydration products leading to a denser and more compact matrix as evidenced by the compressive strength test results [15]. Secondly, the finer particle size distribution of trass-lime can alter the microstructure of the paving block resulting in a reduction in pore spaces [44]. This effect can contribute to reducing the ingress of sand abrasives when injected at high pressure to measure abrasion resistance, thereby improving the abrasive resistance of the paving blocks.

Very few studies have been performed to measure the abrasion index of paving blocks. Nouhy et al. [49] recorded an abrasion volume loss of 13.5 cm^3 per 50 cm^2 and an average thickness loss of 2.7 mm for a concrete paving block. Although this observed abrasion volume loss of the concrete paving block falls within the ASTM C936 [34] specifications, the char-based paving block has less thickness loss indicating a better resistance during traffic abrasion than the concrete paving block depicted in Figure 12. Additionally, when developing paving blocks, Gamage et al. [50] considered the use of coconut coir and crumb rubber. With a 5% crumb rubber content, they found that the abrasion resistance had improved by over 7% when compared to the control sample. However, compared to the abrasion resistance of char-based paving blocks, these recorded values are still higher.

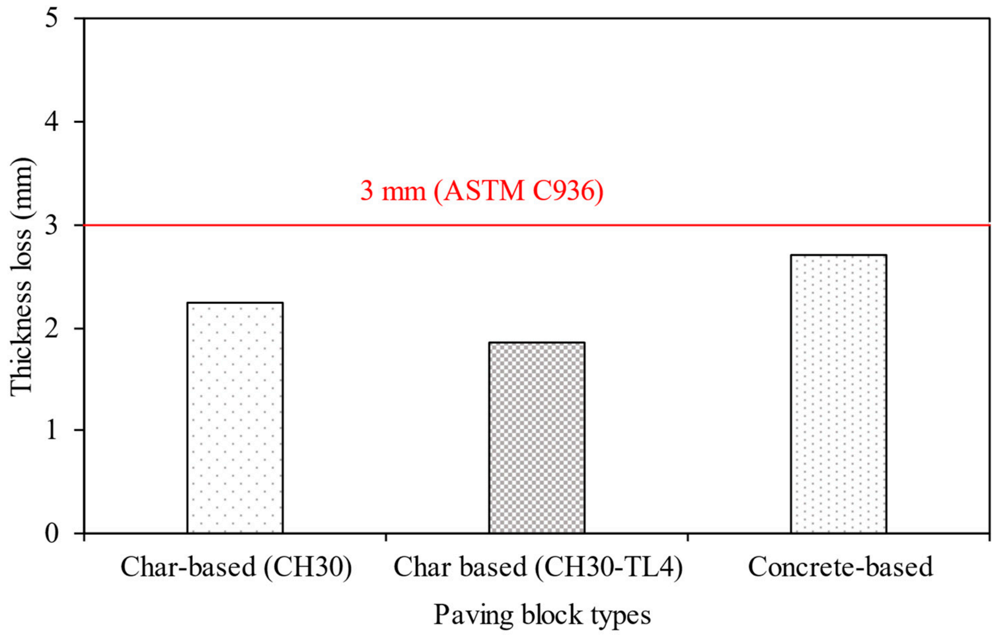

Figure 12. Comparison of abrasion resistance of char-based paving blocks with concrete-based [49] paving blocks.

4.4. Water Absorption

The paving blocks designed based on the control mix CH30 show an average water absorption of 4.95%, which satisfies the ASTM C936 [34] and ASTM C1272 [2] requirements of less than 5% and 6%, respectively. The mix design CH30-TL4 exhibits an even lower water absorption of 4.63%. The trass-lime in CH30-TL4 contributes to the densification of the concrete microstructure [15]. This densification results in the reduction of porosity and fewer numbers and extent of interconnected pores within the paving blocks, limiting the pathways for water to enter into it [13,15]. Trass-lime, because of its fine particle size distribution, helps in the refinement of pore formation and may contribute towards the formation of finer pores along with reducing the connectivity [44].

A water absorption test was also conducted on commercial clay red pavers [41] at the same test conditions as that of char-based paving blocks. The clay red pavers show a water absorption of 7.68%, which is higher than that of the char-based paving blocks. In contrast, Rathan [51] designed a concrete paving block by incorporating coarse and fine aggregates in different compositions along with cement and water. They recorded the lowest water absorption value of 3.75% for the all-mix composition of the concrete paving block as shown in Figure 13. Although the water absorption of char-based paving blocks is comparable to that of concrete paving blocks [51], this study is concerned with the effect of high water absorption towards early deterioration and recommends additional studies aimed at lowering the water absorption. Furthermore, paving blocks with lower water absorption are less porous and resist the penetration of oils and grease from vehicles moving over them [52]. This leads to easier maintenance work and the long-run serviceability of char-based paving blocks. The study performed by Hodul et. al., [53] shows the effectiveness of water-soluble epoxy-based hydrophobization in reducing water absorption by more than 80%.

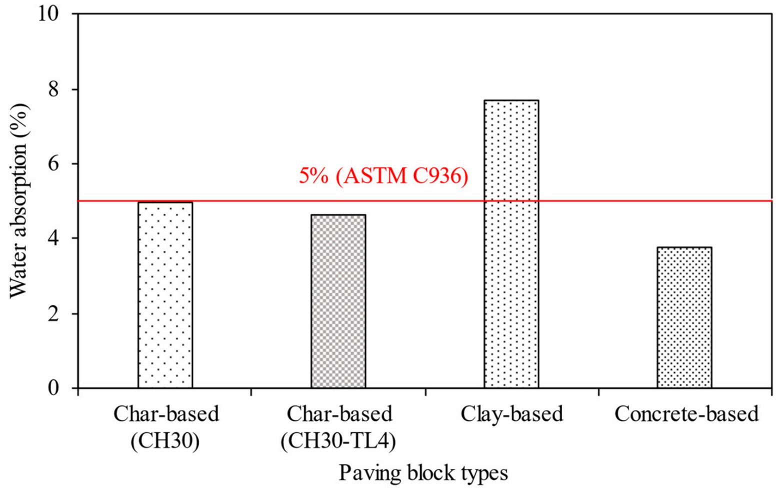

Figure 13. Comparison of water absorption of char-based paving blocks with clay- [41] and concrete- [51] based paving blocks.

4.5. Freeze-Thaw Durability

This study measures an average mass loss of 18.68 g/m^2 and 5.35 g/m^2 for the char-based paving blocks based on mix designs CH30 and CH30-TL4. Furthermore, in compliance with ASTM C1272 [2], the determined mass loss is less than 0.5% of the samples' dry weight for these char-based paving blocks. As discussed earlier, the addition of trass-lime in the mix results in enhanced bond formation and finer pores of smaller size with reduced connectivity [15,44]. This effect contributes to the densification of the mix, thereby improving the durability towards freeze–thaw [13].

In comparison, Bakis et al. [54] reported the mass loss of concrete paving blocks as 350 g/m^2. The substantially lower mass loss recorded for the char-based paving blocks indicates better freeze–thaw durability than the concrete paving block. The average mass loss of the char-based paving blocks also satisfies the maximum requirement of 225 g/m^2 per the ASTM C936 [34], indicating the soundness of the product towards harsh climatic conditions. Additionally, a freeze–thaw durability test was carried out on the commercial clay red pavers [41] under the same conditions. An average mass loss of 38.35 g/m^2 is observed for the clay red pavers. The test results in Figure 14 show the similar performance of char-based paving blocks in comparison to the commercial clay red pavers [41].

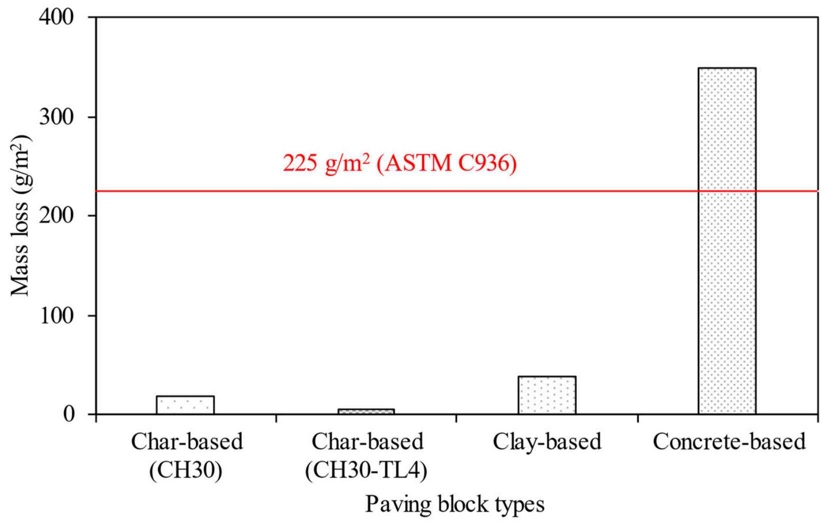

Figure 14. Comparison of freeze–thaw test results of char-based paving blocks with clay- [41] and concrete- [54] based paving blocks.

5. Results and Discussion

The paving blocks designed for roadway applications may be used for heavy vehicular traffic and light vehicular traffic. Depending upon the use of the roadway, the strength requirement as well as other engineering property requirements for paving blocks vary. For instance, heavy vehicular traffic areas [2] demand the use of high-strength paving blocks of 55 MPa and water absorption within 6%. Similarly, light vehicular traffic areas have similar strength requirements but have larger tolerances towards water absorption (8%). The freeze–thaw durability requirement is waived given that they satisfy the cold-water absorption and saturation coefficient requirement as given by ASTM C902 [55]. The paving blocks for these light vehicular traffic areas have higher abrasion loss tolerances of about 85 $cm^3/50\ cm^2$ [55].

The char-based paving blocks presented here are evaluated for their suitability in both heavy vehicular traffic areas (exceeding 251 ESAL [2]) and light vehicular traffic areas (not exceeding 251 ESAL [2]). The mix designs CH30 and CH30-TL4 are suitable for heavy vehicular traffic conditions as shown by their engineering properties discussed above. The compressive strength shown by paving blocks based on mix design CH30 is 57.5 MPa and that of CH30-TL4 is 65.71 MPa. The increase in compressive strength from 57.5 MPa in CH30 to 65.71 MPa in CH30-TL4 and the partial replacement of cement with natural pozzolana demonstrate the efficacy of utilizing pozzolanic materials to improve the mechanical properties of paving blocks. The water absorption of both these mix designs is less than 5%. The comparatively higher water absorption compared to concrete-based paving blocks (3.75%) might be due to the presence of char, a porous material with a high surface area, in the char-based paving blocks [56]. The remarkable resistance to freeze–thaw of these char-based paving blocks further emphasizes their viability for application in regions that frequently experience extremely low temperatures ($-18\ ^\circ C$). Their resistance to cyclic freezing and thawing, which is essential for preserving structural integrity and longevity in such conditions, is demonstrated by the minimal mass loss seen after 50 freeze–thaw cycles: 18.68 g/m^2 for CH30 and 5.35 g/m^2 for CH30-TL4. Over the course of the paving's lifespan, the minimal mass loss linked with CH30-TL4 suggests a better level of durability, which should translate into lower maintenance and repair expenses, making it a more cost-effective alternative in the long run. The resistance of CH30 and CH30-TL4 mix designs to surface wear is shown by the calculated abrasion volume losses. In particular, an improved resistance of the CH30-TL4 mix design to abrasive forces is suggested by the lower abrasion volume loss of 9.26 $cm^3/50\ cm^2$ as opposed to CH30's 11.20 $cm^3/50\ cm^2$. This suggests that, perhaps as a result of its composition, the CH30-TL4 mix provides a denser and more cohesive surface that is less prone to wear away from mechanical action or friction.

The mix designs, particularly CH30-T3 and CH30-TL3, formed by 25% cement replacement with trass and trass-lime, respectively, satisfy the strength requirements for both heavy and light traffic areas. However, the requirement for water absorption can be barely achieved as the optimum mix design CH30-TL4 has a water absorption of 4.63% which is near 5%. The research studies conducted by Pandey et al. [33] have shown char as a porous material and have a direct influence on increasing water absorption [33]. They reported water absorption in the range of 4–7% for treated samples in a mix design containing 40% char [33]. So, paving blocks based on mix design CH30-T3 and CH30-TL3 can be used for light vehicular traffic areas. However, additional study is recommended to validate their suitability. The paving blocks based on mix design CH30-T2 and CH30-TL2, formed by 50% cement replacement with trass and trass-lime, respectively, have compressive strengths of 38.8 MPa and 50.8 MPa which is above 20.7 MPa, confirming the suitability for their use where resistance to freezing is not a factor as per ASTM C902. The ASTM C902 recommends an even higher tolerance of about 14% for water absorption for paving blocks to be used for external use where freezing conditions barely exist.

Char-based paving blocks offer compelling environmental and economic benefits. Environmentally, these blocks contribute to reduced carbon emissions by employing sustainable production methods that minimize energy-intensive processes and utilize by-products of the pyrolysis process, i.e., char [57]. This helps in conserving natural resources by reducing the reliance on natural aggregates and mitigating the environmental degradation associated with their extraction [16]. The manufacturing process involving the use of a hydraulic press also leads to a reduction in the emission of gases that otherwise could have been released into the atmosphere from the burning of fuels in kilns [58]. Considering economic aspects, these paving blocks utilize a byproduct of the pyrolysis process, i.e., char, offering cost savings in material procurement. Moreover, the lower density of these paving blocks compared to commercial paving blocks reduces the transportation cost as higher quantities can be shipped at a time. Easier material handling during installation phases of roadway construction further reduces the labor cost and increases working efficiency.

6. Conclusions

The use of char as an alternative to natural aggregates is successfully presented in this study. Additionally, a 12.5% replacement of cement in the control mix by natural pozzolana, i.e., trass-lime is found to be beneficial in increasing the compressive strength from 57.5 MPa to 65.71 MPa. The paving blocks based on the control mix design CH30 and optimal mix design CH30-TL4 both satisfied the ASTM C936 [34] and ASTM C1272 [2] requirements for their application in constructing paved surfaces. This study found that they are compatible for application in high-traffic volume areas with ESAL exceeding 251. Comparing clay- and concrete-based paving blocks, the char-based paving blocks, especially based on mix design CH30 and CH30-TL4, exhibit promising engineering properties. The char-based paving block based on the optimum mix design CH30-TL4 measures an average thickness loss of 1.85 mm along with a volume loss of 9.26 $cm^3/50\ cm^2$. Furthermore, the char-based paving block exhibits a lower water absorption of 4.6% for the optimum mix design CH30-TL4. The char-based paving blocks based on mix design CH30-TL4 showcase a durability towards harsh freeze–thaw conditions as evidenced by the mass loss of only 5.35 g/m^2. Furthermore, the char-based paving blocks based on mix design CH30-TL4 satisfy the required engineering properties for their application in heavy vehicular traffic areas based on the laboratory test results discussed in this paper.

The paving block mix designs CH30-T3 and CH30-TL3 satisfy the strength requirements for both heavy and light vehicular traffic areas but owing to the possibility of higher water absorption (higher than 5%), these can be suitable for light vehicular traffic areas (ESAL not exceeding 251). The paving blocks based on mix design CH30-T2, CH30-T3, and CH30-TL2 satisfy the strength requirements for their application in light traffic volume areas where resistance to freezing is not a factor. For the potential application of paving blocks based on these mixed designs in light traffic volume areas (ESAL not exceeding 251), additional study is recommended to examine other engineering properties such as water absorption, freeze–thaw, and abrasion resistance. In summary, this study shows the promising potential of char-based paving blocks (CH30-TL4) as sustainable, environment-friendly, and high-performance products for roadway applications in heavy traffic volume areas.

7. Patents

The content presented in this manuscript is part of the international patent application number PCT/US23/26075.

Author Contributions: Conceptualization, H.Y. and K.N.; methodology, validation, S.P.P.; formal analysis, S.P.P.; investigation, S.P.P. and C.L.; resources, C.L.; data curation, S.P.P.; writing—original draft preparation, S.P.P.; writing—review and editing, H.Y., C.L. and K.N.; supervision, K.N.; project administration, C.L.; funding acquisition, K.N. All authors have read and agreed to the published version of the manuscript.

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