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DEVELOPMENT OF LOW-CARBON CONCRETE PAVER BLOCKS INCORPORATING RICE HUSK ASH AND SISAL FIBER FOR INFRASTRUCTURE APPLICATIONS

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KEY WORDS: Low-carbon concrete paver blocks, Rice Husk Ash (RHA), sisal fiber, light-traffic applications.

ABSTRACT:

Conventional concrete pavers depend largely on cement, resulting in high carbon emissions. Although there has been an extensive study on individual pozzolanic materials and natural fibres, there exists a gap regarding their combined effect on the performance of paver blocks. This study investigates the mechanical and durability properties of the low-carbon concrete paver block made up of Rice Husk Ash (RHA) and sisal fiber for sustainable infrastructure applications. The RHA was used as replacement level of 5%-20% by weight of cement with the inclusion of sisal fiber at 0.25%-1%. It was observed showed that 10% RHA combination with 0.75% fiber demonstrated enhanced mechanical properties. The developed paver blocks reached an average compressive strength of 35.83 MPa, meeting the IS 15658:2006 standards for light-traffic applications with average water absorption was 4.88%, which is under the limiting value 15658:2006 standards, signifying strong durability. The findings concluded that the synergistic use of RHA and sisal fiber improves strength, durability, and sustainability, offering a practical sustainable option for infrastructure pavement applications.

1. INTRODUCTION

Infrastructure construction, maintenance and repair significantly contribute to global CO2 emissions. Four major materials including steel, cement, iron and aluminium which contribute to 7.3% of yearly CO2 emissions (World Economic Forum, 2024). The infrastructure sector contributes almost 50% of cement-associated emissions and accounts for more than 25% of emissions arising from iron, steel and aluminum manufacturing. To mitigate these issues, the construction sector adopts more sustainable construction practices. The potential for using waste as a substitute for Portland cement-based construction material contributes in reducing the environmental effects. It imparts a convergent character to civil construction that aligns with global trends in sustainable development (He et al., 2019; Nidheesh & Kumar, 2019). A concept of replacing traditional material with low-carbon and recycled mineral composite material has gained significant attention in infrastructure projects. The recycling of non-metallic minerals has received growing interest lately. This form of recycling has fallen behind the recycling of metals, and the extraction and processing of non-metallic minerals continue to lead to changes in land use, deforestation, soil degradation, and water pollution (Yu et al., 2024). Low-carbon mineral composite materials are recognized for their cost-effectiveness, wate-derived and widely available mineral components. These composites depend on well-sourced raw materials that are energy-efficient, including municipal solid waste and by-products from industries. By incorporating recyclable materials and promoting reusable designs, these composites provide a more sustainable alternative to traditional and carbon-intensive materials.

Concrete paver blocks are commonly utilized in walkways, roads, patios, and low-traffic surfaces because of their simple construction, easy replaceability, and low maintenance needs. Paver blocks are employed for different categories of traffic in accordance with the specifications outlined in IS-15658: 2006). In infrastructure projects, paver blocks are favoured over conventional rigid pavements since they necessitate less skilled labour, enable local production, and provide cost-effective solutions. However, conventional paver blocks depend significantly on OPC, which limits their environmental sustainability. Concrete paver blocks are usually made using a mix of cement, fine aggregate, coarse aggregate, water, admixtures, etc. The overall performance of the concrete paver blocks is primarily governed by the properties of material used, water-cement ratio, mixing procedure and curing process. Conventional concrete paver blocks depend largely on cement and virgin aggregates, which contributes to the depletion of natural resources and adverse environmental impacts. In the

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production of cement paver block, raw materials are needed because the resources are available but in a scarce quantity. Conversely, there is imbalance of ecology and habitat in the complete manufacturing processes to process good quality paver block with required properties. The replacement of virgin raw material with other material up to 30% with the properties necessary for good quality paver block is possible (Uygunoglu et al., 2012; Kene & Patel, 2022). Many studies have been conducted to investigated the advantages of using different waste materials including granite dust, fly ash, marble dust, stone dust, glass powder, polypropylene fiber and sisal fiber to make paver blocks and hence improve the properties of the developed paver block.

The use of Rice Husk Ash (RHA) has developed as one of the promising additives in the cement-based products, providing numerous advantages that can promote sustainability and better performance of the construction materials. The global market for rice husk ash is projected to experience steady expansion between 2022 and 2029 as illustrated in Figure 1. According to Data Bridge Market Research, the market is anticipated to grow at a compound annual growth rate (CAGR) of 4.9% during this period, reaching an estimated value of USD 21,381.45 thousand by 2029. This growth is largely driven by the increasing demand for rice husk ash in the construction sector, where its high silica content makes it a valuable supplementary cementitious material. Its wide applicability in improving strength and durability of construction products has significantly enhanced its commercial potential, thereby contributing to the overall market growth.

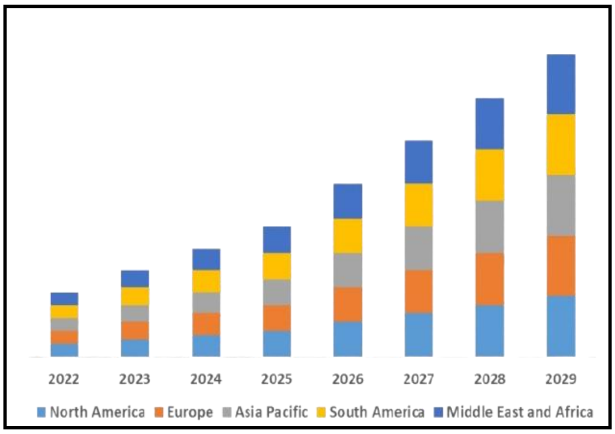


Figure 1. Global Rice Husk Ash Market – Industry Trends and Forecast to 2029

Over the past years, numerous studies (Ling et al., 2011; Liu et al., 2022; Kannur & Chore, 2023) have demonstrated that the addition of RHA in concrete has proven to be beneficial in terms of enhanced strength and durability, reduced impact on the environment within the construction industry. Furthermore, using RHA in cementitious matrices reinforced with natural fibres was initially explored in the 1980s (Gram & Nimityongskul, 1987; Shafiq et al., 1998). Among the many types of natural fibres available, sisal has gained global attention due to its widespread cultivation, which reduces transportation distances and lowers associated carbon emissions. Sisal is considered a promising sustainable fibre because of its notable strength and its ability to decompose naturally (Santana et al. 2021). A key benefit of incorporating sisal into cement-based composites is its capacity to bridge cracks both at the onset and after cracking occurs, thereby preserving stress transfer across the cracked sections (de Andrade Silva et al., 2009; Morton et al., 2010). Furthermore, the inclusion of sisal fibres has been shown to improve the toughness and resistance to impact loading of cementitious materials (Ferreira et al., 2024; Ardanuy et al., 2015). Guerra & Lopes (2024) investigated the effect of high RHA content in combination with sisal fiber at a rate of 4% and 6% by weight. It was reported that the composites containing 50% RHA exhibits higher compressive strength, multiple cracks, and toughness than the composite materials that contained metakaolin, fly ash and silica fume. Indeed, few studies explored the use of RHA as replacement of cement as well as use of sisal fiber as reinforcement in concrete composites. There is a lack of research on their combined effects specifically in paver blocks.

2. MATERIALS AND METHODOLOGY

2.1 Materials

Cement: OPC 53 grade cement was used as primary binder for the concrete mix.

Rice Husk Ash (RHA): The RHA was produced by controlled calcination at a temperature of 600 ± 50 °C to ensure the formation of reactive amorphous silica. After burning, the ash was finely ground and passed through a 75 µm sieve to obtain uniform particle size and improved pozzolanic activity. RHA was used as secondary binder for the concrete mix. The specific gravity of the RHA was approximately 2.1 g/cm^3. The RHA as shown in Figure 2 used at a replacement level of 0%, 5%, 10%, 15% and 20% by weight of cement.

Figure 2. Rice Husk Ash (RHA)

Sisal Fiber: The sisal fibre as shown in Figure 3 procured from the market. The fiber was cut into length of 50 mm and a diameter of 0.5, resulting in an aspect ratio of 100. The tensile strength of the fiber was measured as 500 MPa. The fibre was treated with 5% NaOH solution for 24 hours to enhance the roughness and bonding properties and then washed and dried thoroughly. The proportion of the fibre chosen for this study was 0%, 0.25%. 0.5%, 0.75% and 1% by volume of concrete as per IRC: SP: 46 guidelines.

Figure 3. Sisal Fiber

Aggregates: Fine aggregate (FA) was used in the study was M-Sand that met the requirements of IS: 383-2016 in zone- II. The well graded angular granite stone with the maximum size of 10mm was used as coarse aggregate (CA), which complies with the IS: 383-2016. Table 4 showed the properties of the M-sand and coarse aggregate.

Properties	Fine aggregate	Coarse aggregate
Bulk density (kg/m^3)	1646	1589
Specific gravity	2.6	2.65
Fineness modulus	2.75	6.71

Table 4. Properties of Fine aggregate and Coarse aggregate

Super plasticizer: A high range water reducing admixture, which is utilized as an admixture in the concrete. A polycarboxylate ether-based superplasticizer was used an admixture with low water to binder ratio workability as it complies with ASTM C 494-13. The specific gravity of superplasticizer was measured as 1.82. The superplasticizer was added at rate 0.8%-1.2% by weight of cement.

Water: This study used a portable tap water that was not contaminated with any particles such as oils, alkalies, acids, salt, sugar and organic substances. The water had a pH value of 7.0 ±1, meeting the IS: 456-2000 standards, for making the concrete. The superplasticizer was used as a rate of 0.8%, 1% and 1.2% by weight of cement.

2.2 Methodology

The primary objective of this study is to develop a low-carbon concrete paver blocks incorporating rice husk ash and sisal fiber. Figure 5 illustrates the methodology of the study

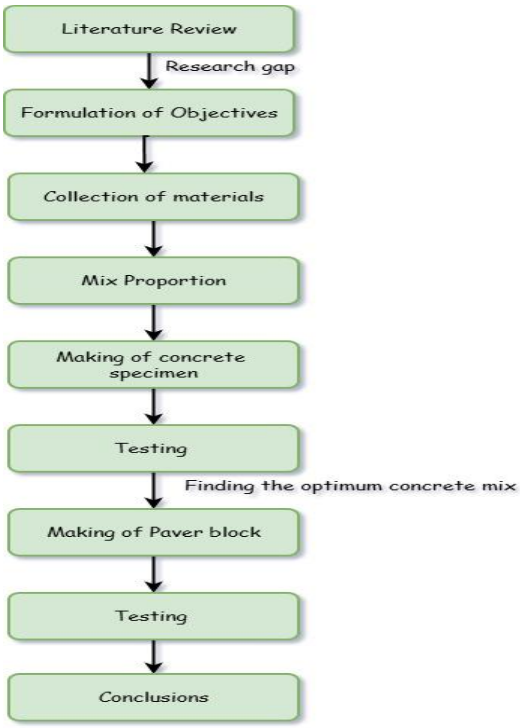


Figure 5. Methodology

2.2.1 Mix proportions: Having the above-considered materials, the concrete mix proportioning was done as per IS: 10262-2019 guidelines to obtain the target strength for M30 grade concrete. Approximately 10 concrete mix was proportioned with varying addition of RHA and sisal fibre as shown in Table 6.

Mix ID	RHA (%)	Sisal (%)	OPC	RHA	FA	CA	Water
R0S0	0	0	380	0	760	1520	171
R5S0.25	5	0.25	361	19	760	1520	171
R5S0.5	5	0.50	361	19	760	1520	171
R10S0.25	10	0.25	342	38	760	1520	171
R10S0.5	10	0.50	342	38	760	1520	171
R10S0.75	10	0.75	342	38	760	1520	171
R15S0.5	15	0.50	323	57	760	1520	171
R15S0.75	15	0.75	323	57	760	1520	171
R20S0.75	20	0.75	304	76	760	1520	171
R20S1	20	1.00	304	76	760	1520	171

Table 6. Mix Proportions

2.2.2 Mix of concrete: The cement, RHA, M-sand and coarse aggregate was measured as per their respective proportion were fed into the concrete mixer. Then, the ¼ of the water-superplasticizer was added into it and continue mixing, followed by the addition of sisal and then remaining amount of water-superplasticizer mixture was added into it and continued mixing to achieve required consistency. The fresh concrete filled into cube mould of 100 x 100 x 100mm, cylindrical mould of size 200m height with 100mm diameter and prism mould of size 100mm x100mm x 500mm to make cube, cylinder and prism specimen to determine the compressive strength, tensile strength and flexural strength of concrete. After 24 hours of moist curing, the sample was removed form mould and allowed to cuing for 7, 14 and 28 days.

2.2.3 Testing of concrete mix: The cube sample was tested for compressive strength by applying compression with the UTM of 100 kN and a least count of 1 kN as per IS: 516-2021 guidelines. The cylindrical sample was tested for split tensile strength by placing it horizontally at the centre of the loading surfaces of the UTM, and the load was applied until failure according to IS: 516-2021. The prism sample was tested for flexural strength (modulus of rupture) tests in accordance with the ASTM C78/C78M-21 standards subjected to four-point loading with a servo-controlled UTM that has a capacity of 1000 kN. The three samples were tested for each concrete mix to determine its average compressive strength, split tensile strength and flexural strength at 7, 14 and 28 days.

2.2.4 Making of paver block samples: Paver blocks were used in standard rectangular moulds to ensure that all dimensions and shape were similar as depicted in Figure 7. The sizes of the paver blocks were chosen to ensure ease of handling, straightforward compaction, and compatibility with equipment used for laboratory testing. Based on the mechanical properties results obtained from cube specimen testing at 7, 14 and 28 days of curing, the optimal mix proportion of RHA and sisal fibres were used as optimal mix proportion for manufacturing paver blocks. The manufacturing process began by dry mixing cement and RHA to achieve homogeneous distribution of the cementitious material. Then fine aggregates and coarse aggregates were added and mixed until. Following that sisal fibre was added slowly to the dry mix to avoid balling and fibre agglomeration. After achieving uniform fibre dispersion, water was added slowly while mixing continued. The mixing process was continued until a homogenous concrete mix that had a consistent texture and sufficient cohesiveness was obtained. The fresh concrete was then poured in the clean and oiled paver block moulds in layers. Manual compaction was done to get out the trapped air and to provide sufficient densification of the concrete as indicated in Figure 8. To minimise internal voids, increase surface finish as well as mechanical performance, proper compaction was necessary. Precautions were observed to fill the moulds uniformly and not to separate the materials when they were placed. The top surface of the moulds was finished smoothly to maintain dimensional uniformity as shown in Figure 7.3. After casting, the paver block moulds were kept undisturbed under ambient laboratory conditions to allow for initial setting of the concrete. Demoulding was done after 24 hours ensuring that the blocks had attained sufficient early strength to prevent damage during handling. After the demoulding, the paver blocks were water cured, which was continued for the specified curing period to facilitate hydration and pozzolanic reactions. The final paver block made was presented in Figure 9.

Figure 7. Paver block mould

Figure 8. Casting of Paver Blocks

Figure 9. Paver block

2.3 Testing of paver block samples

2.3.1 Compressive strength test: The compressive strength of concrete paver blocks was measured as per 15658:2006 standards. After 28 days of water curing, the block specimens were taken out of the curing tank and permitted to lose surface moisture. The blocks were visually inspected to confirm they were devoid of defects. Each block specimen was positioned centrally in a calibrated Compression Testing Machine (CTM) with the upper surface oriented upward to guarantee even load distribution. The load was applied axially without shock at a uniform rate until failure occurred. The maximum load at the point of failure was noted. The average compressive strength value was measured as the average strength value of three tested specimens. Figure 10 presents the compression testing of samples of paver blocks.

Figure 10. Compression testing of paver block

2.3.2 Water absorption test: The water absorption test was conducted as per IS 15658:2006 to assess the durability of paver blocks. The block samples were initially dried in a well-ventilated oven at 105 ± 5°C until a constant weight was reached, and the dry weight (W_1) was noted. The dried blocks were fully submerged in clean water at room temperature for 24 hours. After immersion, the samples were taken out, and surface moisture was gently wiped away with a damp cloth. The saturated weight (W_2) was subsequently assessed. Water absorption was calculated as the percentage increase in mass relative to the dry weight using the formula;

$$Water\ absoprtion\ (\%) = \frac{W_2 - W_1}{W_1}\ X\ 100$$

The average water absorption value was measured as the average water absorption value of three tested specimens. Figure 11 presents the water absorption testing of samples of paver blocks.

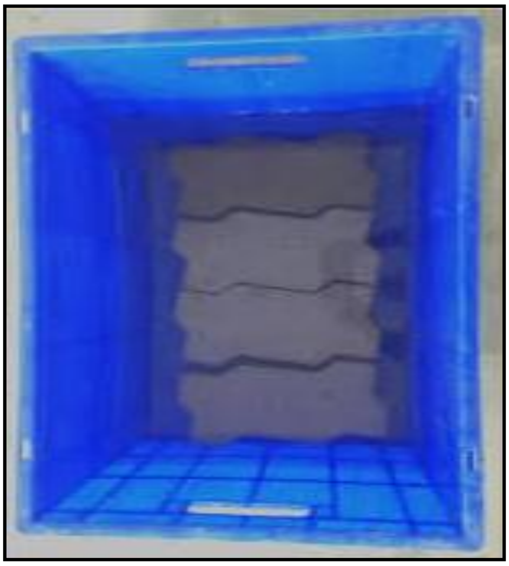
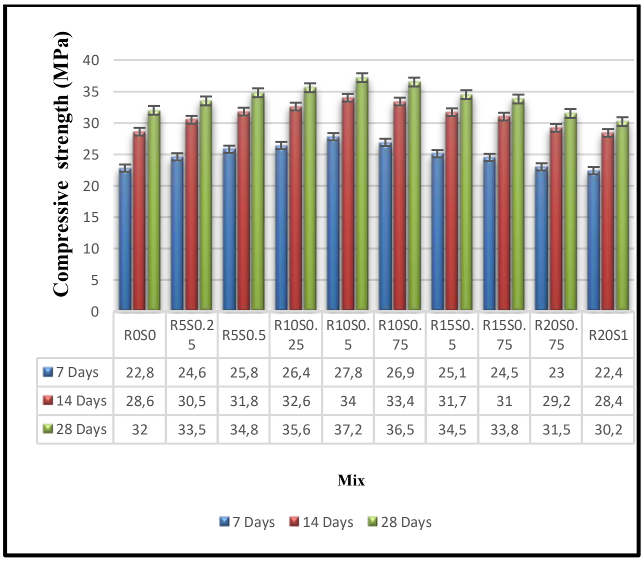


Figure 11. Water absorption testing of paver block

3. RESULTS AND DISCUSSIONS

3.1 Mechanical properties of concrete

3.1.1 Compressive strength: Figure 12 presents the compressive strength of concrete mixes clearly shows that RHA and sisal fiber has a significant effect on the mechanical properties of the concrete. It was observed that the inclusion of RHA and sisal fiber causes improvement in compressive strength as compared to control (R0S0) mix. However, incorporation of sisal fiber above 0.5% led to reduction in compressive strength due to the fiber agglomeration, lower workability, and higher void formation. Similarly, inclusion of RHA above 10% replacement level caused a progressive reduction of the strength due to the dilution of cement and the lack of calcium hydroxide to react with the pozzolana. All mixes containing RHA up to 10% replacement level exhibits better strength than the control (R0S0) mix at 7, 14, and 28 days. The maximum strength of 37.2 MPa was achieved for the R10S0.5 mix, which is about 16.25% higher than the control (R0S0) mix. This improvement in strength is due to the pozzolanic activity of RHA, where the amorphous silica reacts with the calcium hydroxide released during cement hydration to form additional Calcium-Silicate-Hydrate (C-S-H) gel, which enhances the matrix densification (Park et al., 2016; Ambrose et al., 2026). Moreover, fine particle size of RHA also provides a filler effect leading to the enhancement of the packing of particles and decreases pore spaces. Furthermore, the inclusion of sisal fibres also contributes in crack-bridging action, which restricts microcrack propagation and improves stress distribution within the concrete matrix. All mixes exhibited a uniform strength increase with age of curing, which showed that the mixes were continuing to hydrate and experience secondary pozzolanic reactions. The findings indicate that 10% RHA and 0.50% sisal fiber mixture offer the best combination of strength increase and material sustainability in the usage of paver blocks.



	R0S0	R5S0.25	R5S0.5	R10S0.25	R10S0.5	R10S0.75	R15S0.5	R15S0.75	R20S0.75	R20S1
7 Days	22,8	24,6	25,8	26,4	27,8	26,9	25,1	24,5	23	22,4
14 Days	28,6	30,5	31,8	32,6	34	33,4	31,7	31	29,2	28,4
28 Days	32	33,5	34,8	35,6	37,2	36,5	34,5	33,8	31,5	30,2

Figure 12. Compressive strength of concrete

3.1.2 Split tensile strength: Figure 13 presents the split tensile strength of concrete mixes clearly shows a consistent increase in split tensile strength with the inclusion of RHA and sisal fibre as compared to the control mix (R0S0). The control mix (R0S0) achieved the split tensile strength of 1.8 MPa, 2.2 MPa and 2.6 MPa at 7, 14 and 28 days; whereas the mix R5S0.25 mix containing 5% RHA AND 0.25% sisal fiber achieved the split tensile strength of 2 MPa, 2.45 MPa and 2.8 MPa at 7, 14 and 28 days. This indicates that the inclusion of RHA and sisal fiber enhanced tensile performance at all curing ages that results in better resistance of the cracks and bonding within the concrete matrix. The maximum split tensile strength of 2.55 MPa, 3.15 MPa and 3.6 MPa was achieved for the R10S0.75 mix, which is about 16.25% higher than the control (R0S0) mix at 7, 14 and 28 days. This is due to that the crack-bridging effect of sisal fibres mainly contributed to the improvement of the crack initiation and propagation, thus increasing post-cracking behaviour and tensile load carrying capacity (Senthilkumar et al., 2018; Zhang et al., 2025). The inclusion of RHA also further contributed to the microstructural densification and enhancement of interfacial transition zone (ITZ) properties due to secondary pozzolanic reactions. Also, as opposed to compressive strength, tensile strength kept on increasing even with increased fiber contents (0.75%), which indicates the dominant role of fibres in tensile stress resistant. However, at higher replacement levels of RHA (15 % and 20 %), tensile strength remained higher than the control mix, the rate of improvement slightly reduced. This could be due to cement dilution effect and possible losses of cohesion of the matrix at higher replacement level. The findings show that tensile strength is more sensitive to fiber dosage in comparison with compressive strength and a combination of 10% RHA 10% with 0.75% sisal 0.75 gives the best tensile performance.

3.1.3 Flexural strength: Figure 14 presents the flexural strength of concrete mixes clearly shows a significant improvement in flexural strength with the inclusion of RHA and sisal fiber as compared to the control (R0S0) mix. It was observed that all RHA and sisal fiber added concrete mixes exhibits improved flexural strength than the control (R0S0) mix, thus confirming the positive contribution of RHA and sisal fiber to the bending resistance. The highest flexural strength of 5.6 MPa was observed for R10S0.75 mix at then closely followed by the R10S0.5 with a flexural strength of 5.4 MPa. This improvement in flexural strength was attributed by two primary mechanisms: the pozzolanic and filler effect of RHA that refine the pore structure and enhances the interfacial transition zone; the crack-bridging effect of sisal fibres that can effectively control crack propagation under bending loads (Jr Savastano et al., 2006; Teixeira et al., 2022). As the flexural strength is very sensitized to tensile stress development at the bottom fiber of the specimen, the presence of fibres significantly enhances post-cracking behaviour and load carrying capacity. At higher RHA replacement levels (15% and 20%), flexural strength remained superior to the control mix but showed a slight reduction compared to the 10% replacement level. This reduction may be due to partial cement dilution and possible reductions in matrix cohesion at higher replacement percentages. The findings suggest that flexural strength is highly affected by the content of fiber and the combination of 10% RHA with 0.75% sisal fiber provides optimum flexural performance for sustainable paver block applications.

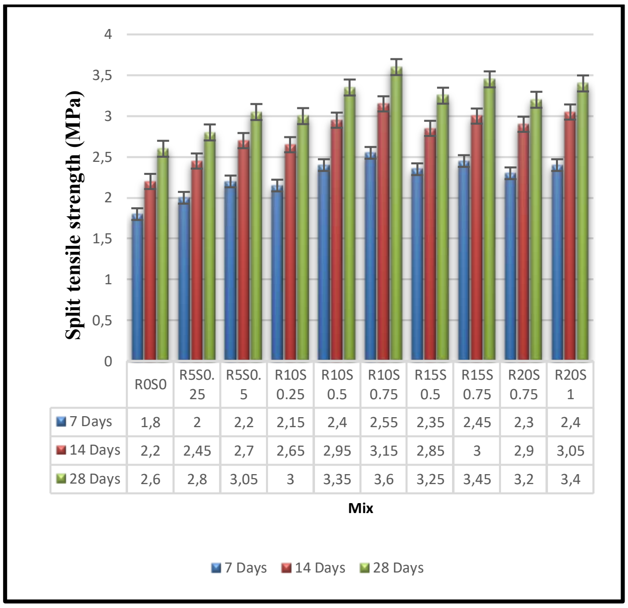


Figure 13. Split tensile strength of concrete

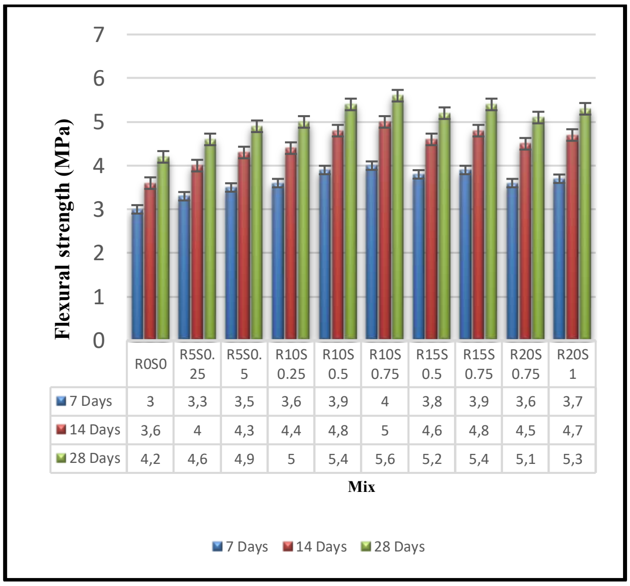


Figure 14. Flexural strength of concrete

3.2 Performance of the paver blocks

The R10S0.75 mix containing 10% rice husk ash (RHA) and 0.75% sisal fiber was found to offer superior flexural and tensile performance, which are critical parameters governing cracking resistance in paver blocks. Therefore, the R10S0.75 mix selected as optimum mix for the fabrication of paver block.

3.2.1 Compressive strength: The average compressive strength of the developed paver blocks was found to be 35.83 MPa with 35.60 MPa, 36.10 MPa and 35.83 MPa respectively as indicated in Table 15. The developed paver block achieved the average compressive strength of 35.83 MPa, which is appropriate for light-traffic applications. Therefore, the paver blocks produced using the optimized mix satisfy the compressive strength requirements of IS 15658:2006 and are suitable for use in light traffic applications.

Sample	Compressive strength (MPa)	Average Compressive strength (MPa)
1	35.60	35.83
2	36.10	
3	35.83	

Table 15. Compressive strength of paver block

3.2.2 Water absorption: The water absorption test conducted on three paver block samples yielded values of 4.80%, 5.10%, and 4.75%, resulting in an average water absorption of 4.88% as shown in Table 16. According to IS 15658:2006, the maximum permissible water absorption for concrete paver blocks is 6% by mass. The observed average of 4.88% is well within this limit, demonstrating a dense concrete matrix and indicating satisfactory durability. The relatively low water absorption can be attributed to the filler effect of sisal fiber and the pozzolanic activity of RHA, which contribute to a refined pore structure and enhanced concrete performance.

Sample	Water absorption (%)	Average Water absorption (%)
1	4.80	4.88
2	5.10	
3	4.75	

Table 16. Water absorption of paver block

3.3 Sustainability assessment of the paver blocks

The sustainability assessment in terms of Embodied Energy (EE) and Embodied Carbon (EC) for R0S0 and R10S0.75 mix was determined using the ICE v4.1 data. Embodied Energy (EE) and Embodied Carbon (EC) for R0S0 and R10S0.75 mix was presented in Figure 17. The EE of the R0S0 mix was measured as 2052.86 MJ/m^3, whereas the EE of the R10S0.75 mix was measured as 1980.19 MJ/m^3, indicating 3.5% a reduction of EE with the utilization of 10% RHA and 0.75% sisal fiber. Likewise, the EC of the R0S0 mix was measured as 373.06 $kgCO_2/m^3$, whereas the EE of the R10S0.75 mix was measured as 346.95 $kgCO_2/m^3$, indicating 7% a reduction of EC with the utilization of 10% RHA and 0.75% sisal fiber. The decrease is mainly due to the partial replacement of OPC, which has a high carbon footprint, with RHA that has a lower embodied carbon. Even though incorporating sisal fiber and a slightly elevated superplasticizer amount led to a slight increase in energy consumption, the overall environmental impact remained lower than the control mix. These results indicate that R10S0.75 provides enhanced mechanical capabilities with measurable environmental benefits.

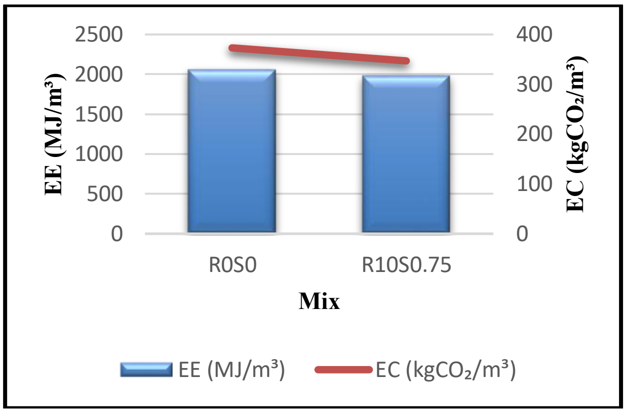


Figure 17. Embodied Energy (EE) and Embodied Carbon (EC)

4. CONCLUSIONS

The experimental results indicate that the developed paver blocks exhibit an average compressive strength of 35.83 MPa, which is suitable for application is light traffic pavement applications specified in IS 15658:2006. Water absorption tests results in an average of 4.88%, which is well below the maximum permissible limit of 6% as per IS 15658:2006. These results indicate a dense concrete matrix, satisfactory durability, and enhanced pore refinement due to the cracking bridging effect of sisal fiber and the pozzolanic activity of RHA. Collectively, the findings demonstrate that the paver blocks produced using the optimized mix satisfy the mechanical and durability requirements for pedestrian pathways, walkways, and other light-traffic applications. The findings confirmed that paver blocks incorporating RHA and sisal fibre can be successfully developed with acceptable mechanical performance while promoting sustainable construction and waste utilization.

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