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Impact of fly ash and banana fiber on mechanical performance of paver block concrete

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Original research paper

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Impact of fly ash and banana fiber on mechanical performance of paver block concrete

The use of concrete reinforced with natural fibres is globally considered a sustainable approach to infrastructure development. This study investigated the salient features of concrete paver blocks fabricated using fly ash, coal ash, superplasticiser, and banana fibres as fibre reinforcements. Banana fibres (15 mm in length) were prepared, followed by the fabrication and characterisation of concrete paver blocks. In the current study, banana fibre (0.5 %, 1 %, 1.5 %, 2 %, and 2.5 %) and admixture (0.5 % constantly) were used in different mix proportions in the fabrication of paver block to analyse the physicomechanical properties. The results demonstrated that the paver blocks containing 2 % modified banana fiber (with respect to weight of fly ash) show higher compressive strength (7.45 % for I-dumble and 17.12 % for zigzag paver blocks), flexural strength (14.99 % for I-dumble and 8.67 % for zigzag) and split tensile strength (12.182 % for I-dumble and 9.971 % for zigzag paver blocks), compared to other mix proportions. The use of modified banana fibres as reinforcement was found to be very effective in improving the mechanical properties and life span of paver blocks, which may lead to minimizing the preparation.

Key words:
natural fiber, compressive strength, split tensile strength, flexural strength

Izvorni znanstveni rad

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Utjecaj letećeg pepela i vlakana banane na mehaničke karakteristike betonskih opločnika

Primjena betona ojačanog prirodnim vlaknima općenito se smatra održivim pristupom razvoju infrastrukture. Ovaj je rad istraživao glavne karakteristike betonskih opločnika proizvedenih primjenom letećeg pepela, pepela od ugljena, superplastifikatora i vlakana banane kao ojačanja vlakana. Pripremljena su vlakna banane (dužine 15 mm), nakon čega je uslijedila izrada i karakterizacija betonskih opločnika. U ovome istraživanju utjecaj vlakna banane (0,5 %, 1 %, 1,5 %, 2 % i 2,5 %) i dodataka (0,5 % stalno) upotrijebljeni su u različitim omjerima mješavina za izradu blokova za popločavanje kako bi se analizirala fizikalno-mehanička svojstva. Prikazano je da opločnici koji imaju udio od 2 % modificiranih vlakana banane (u odnosu na težinu letećeg pepela) pokazuju veću tlačnu čvrstoću (7,45 % za dupli vezani opločnik i 17,12 % za cik-cak opločnike), savojnu čvrstoću (14,99 % za dupli vezani opločnik i 8,67 % za cik-cak) i vlačnu čvrstoću dobivenu cijepanjem (12,182 % za dupli vezani opločnik i 9,971 % za cik-cak opločnike) u usporedbi s ostalim omjerima smjese. Uporaba modificiranih vlakana banane kao vlakana za armiranje pokazala se vrlo učinkovitom u poboljšanju mehaničkih svojstava i životnog vijeka opločnika, što može dovesti do smanjenja izrade.

Ključne riječi:
prirodno vlakno, tlačna čvrstoća, vlačna čvrstoća dobivena cijepanjem, savojna čvrstoća

1. Introduction

Paver blocks are extensively used in landscaping and construction because they provide durability, strength, and a visually appealing finish to roads, pavements, and driveways. The use of natural fibres in the manufacturing of paver blocks has gained attention in recent years. The reason is that this is a sustainable alternative to traditional materials, which have significant environmental impacts during their production. Paver blocks, also known as concrete paving blocks, are a popular construction material used for various applications such as sidewalks, parking lots, and landscaping. Traditionally, paver blocks have been made using cement, sand, and aggregates; however, in recent years, there has been a growing interest in the use of natural waste fibres as a reinforcement material in paver block manufacturing. The utilisation of natural waste fibres, such as jute, coir, sisal, and hemp, can improve the mechanical properties and durability of paver blocks while also reducing the overall cost of production. Additionally, the use of waste fibres is an environmentally friendly approach because it reduces the amount of waste generated to end up in landfills. Testing the mechanical properties (BIS 15658) of paver blocks fabricated using natural waste fibres is important to ensure their structural integrity and longevity. Common tests such as compressive strength, flexural strength, abrasion resistance, and water absorption tests of banana fibre-reinforced pervious concrete provide valuable data on how this natural fibre influences the properties of pervious concrete. The feasibility and effectiveness of incorporating banana fibres to enhance the performance of pervious concrete could lead to sustainable solutions in construction practices [1]. The inclusion of marble dust and banana fibres in the asphalt mix is expected to reveal the impact of these additives on the durability and overall quality of the asphalt mix [2]. Through developing natural fibre reinforced concrete, the aim has been to shed light on properties, sustainability, applications, barriers, and opportunities. The findings of such studies represent the current state of knowledge in this field, identifying potential avenues for further research and applications in the construction industry [3]. An experimental investigation of the flexural behaviour of reinforced concrete beams using a hybrid combination of banana and steel fibres provided insights into the structural enhancements achieved through this innovative approach [4]. Agricultural waste materials suitable for use in the building industry have been identified and their diverse applications summarised, providing a basis for understanding sustainable alternatives derived from agricultural waste, and emphasizing their role in environmentally friendly construction practices [5]. The emerging need for environmentally friendly construction materials has led to extensive investigations into the feasibility and potential advantages of using natural fibres as reinforcements in concrete structures [6]. Impact of bacterial strain combinations in hybrid fibre-reinforced geopolymer concrete, specifically under heavy and very heavy traffic conditions, has been evaluated. Understanding the synergies between bacterial strains and fibres in enhancing the durability and performance of geopolymer concretes in high-traffic scenarios will contribute to sustainable infrastructure development [7]. Through investigations on the effects of incorporating banana fibres and lime on the mechanical and thermal properties of unburnt clay bricks, potential enhancements in the structural strength and insulation properties have been revealed, providing valuable insights into the development of sustainable building materials using agricultural waste and additives [8]. The viability of utilising natural fibres, including banana fibres, to enhance the stability and durability of compressed earth blocks has been established, contributing to the exploration of eco-friendly construction solutions [9]. Innovative approaches for processing banana fibres aim to improve their mechanical characteristics and expand their potential applications in various industries, including construction [10].

The studies on utilisation of coir (coconut fibre) in cementitious materials explore various applications of coir in enhancing the properties of cement-based materials, and shed light on its effectiveness, challenges, and potential contributions to sustainable construction [11]. The application of advanced computational techniques optimises production processes, thereby contributing to sustainable practices in the manufacturing of construction materials [12]. Fibre-reinforced concrete was fabricated using industrial hemp fibres to investigate the performance of hemp fibres as a reinforcement material in concrete, assessing their impact on strength, durability, and other relevant properties [13]. A broad spectrum of natural fibres has been explored for their application in construction materials, and their sustainability aspects have been evaluated throughout their life cycle [14]. There has been an increased focus on enhancing the properties of pervious concrete through the addition of supplementary materials and fibres. Specifically, the strength of pervious concrete is improved by incorporating rice husk ash and glass fibres, which provides insights into potential improvements in strength and durability [15]. The effect of natural fish-tail palm fibres on the workability and mechanical properties of fibre-reinforced concrete was explored to determine the potential of fish-tail palm fibres as reinforcement materials, assessing their impact on both the workability and mechanical strength of concrete [16]. A comprehensive overview of the use of jute fibres as reinforcement in concrete highlights their contribution to the mechanical properties of the material [17]. A mechanical characterisation study of hybrid fibre-reinforced eco-friendly geopolymer concrete made with waste wood ash investigated the synergies between the hybrid fibres and waste wood ash in geopolymer concrete, aiming to develop an environmentally sustainable construction material [18]. The flexural and fracture properties of polymer metal hybrid composite panels reinforced with natural fibres were investigated to reveal the mechanical behaviour of the hybrid composites, providing insights into their flexural strength and fracture characteristics [19]. With increased emphasis on sustainability, investigating the utilisation of hemp fibres in construction materials may provide insights into the early considerations and potential applications of hemp fibres in construction [20]. Bamboo fibre-reinforced polypropylene composites with melamine pyrophosphate and aluminium hypophosphite were explored to reveal the synergistic effects of flame-retardant additives on the mechanical behaviour of bamboo fibre-reinforced polypropylene composites, providing insights into both fire safety and material strength [21]. Desmarais explored the incorporation of waste fibres into unstable compressed earth blocks for sustainable construction in Ghana. This doctoral dissertation investigated the utilisation of waste fibres to enhance the properties of compressed earth blocks, contributing to sustainable construction practices in the region [22]. The combined use of sustainable aggregates and sisal fibres in composite blocks is an eco-friendly and durable construction material [23]. Application of nondegradable waste as a building material for low-cost housing has also been investigated, aiming to provide affordable and sustainable solutions for housing projects [24]. Research on reinforcement capabilities of bagasse and hemp fibres in cementitious composites has revealed valuable insights for the development of sustainable construction materials [25]. The flexural creep of self-compacting concrete reinforced with vegetable and synthetic fibres has been explored to reveal the influence of fibre reinforcement on the flexural creep behaviour of self-compacting concrete, providing insights into the long-term performance of such materials [26]. Incorporating sludge and agricultural waste improved the thermal properties of clay bricks, thereby contributing to sustainable brick manufacturing [27]. The properties of bamboo fibres and their composites offer insight into the potential applications and performance of these materials [28]. The impact of sisal fibre reinforcement on the strength and volume-related properties of concrete blocks has been investigated, providing insights into the utilisation of natural fibres in concrete manufacturing [29]. Galvanised iron wire reinforcement has been reported to influence the strength and ductile behaviour of concrete, enabling reinforced concrete applications [30].

The addition (wood biomass ash and recycled tire polymer fibres) of these alternative materials presents a potential solution for mitigating shrinkage in concrete. The findings of this study contribute to the understanding of sustainable additives for improving concrete performance, emphasising their positive impact on shrinkage reduction [31]. The economic aspects of using concrete containing blast-furnace slag for road pavements have been considered, revealing the cost-benefit relationship and highlighting the economic viability of incorporating blast furnace slag in concrete. In particular, the study emphasises the potential economic advantages of utilising alternative materials in road construction, providing a comprehensive view of its financial implications [32]. Superior mechanical properties of ultrahigh-strength concrete fabricated by incorporating glass fibres and silica fume underscore the positive impact on the concrete performance, providing valuable insights into the development of high-performance durable concrete [33]. An experimental study on the freezing resistance of permeable concrete modified with a vinyl acetate-ethylene copolymer emulsion and basalt fibre has attempted to address the challenges related to freezing conditions, providing insights into improving durability in harsh environments. The conclusion highlights the effectiveness of the proposed modifications in enhancing the freezing resistance of permeable concrete [34]. Representing further advancement in concrete reinforcement technology, the role of coated E-glass fibres in improving concrete performance has been examined and the positive impact of coated fibres on the strength properties of concrete has been revealed [35].

By exploring the potential for utilising sustainable materials (recycled and waste materials) for cement stabilisation, the study contributes to a deeper understanding of environmentally friendly alternatives. In addition, the positive effect of incorporating recycled and waste materials on the compressive strength of stabilised cement is revealed. Another study highlighted the promising mechanical properties of fly ash-based geopolymer mortars, supporting the development of eco-friendly construction materials [36, 37]. The feasibility of incorporating wood biomass ash as a sustainable alternative to traditional concrete components was investigated, underscoring the potential of wood biomass ash as a viable raw material that contributes to sustainable practices in the concrete industry [38]. The positive influence of incinerated paper sludge ash on the properties of fly ash-based geopolymer concrete has also been considered, which contributes to sustainable waste management practices [39].

The use of waste banana fiber in making paver blocks is a significant development in the field of construction and sustainable materials. Banana fiber is an abundant biodegradable resource in many countries, particularly in tropical regions. The use of banana fibres as reinforcement in concrete paver blocks can reduce the cost of construction and provide an eco-friendly alternative to traditional construction materials. This research is mainly focused on the performance and cost-effectiveness of making paver blocks using waste banana fibre. First, it can help reduce the cost of construction by replacing expensive materials such as steel and synthetic fibres. Second, the use of banana fibre can help reduce the carbon footprint of construction. Third, research in this area can help promote sustainable development and provide economic opportunities for communities with access to banana fibres.

Furthermore, the use of natural-waste banana fibres in paver blocks can lead to improvements in their mechanical properties, such as increased tensile strength and reduced cracking. These improvements can result in longer-lasting and more durable paver blocks that require less maintenance and replacement.

2. Characterization of materials

In the production of paver-block concrete, a detailed material characterisation is crucial for reproducibility. The cement used, specifically Ramco-OPC 53 grade, served as the binding agent and was produced by grinding clinker (limestone, clay, and other raw materials) at high temperatures in a kiln. Gypsum was added along with other additives to regulate the setting time. Specific details regarding the producer and type can be obtained from the product specifications provided by the manufacturer. Coal bottom ash and fly ash, which are by-products of coal-fired power plants (southern zone), are mineral residues resulting from coal combustion. Fly ash is a fine solid residue, whereas coal bottom ash is a heavier residue that settles at the bottom of furnaces. Both can be utilised in concrete production, offering an eco-friendly solution for coal waste disposal. For a comprehensive understanding, refer to the standard references for coal combustion by-products (Figure 1). The fly ash particles possess fineness ranging from 0.01 to 100 micrometres. This fine particle size distribution is desirable for concrete applications because it promotes better interaction with the cement paste and enhances the packing density of the mix. The fly ash has a specific gravity of 2.05, which is lower than that of Portland cement (approximately 3.15) and contributes to a reduction in the overall weight of the concrete paver blocks. The LOI of the fly ash is less than 6 %, which indicates the minimal presence of unburned organic matter that can hinder the strength development of concrete. The specific gravity of the coal bottom ash is 3.01, which is higher than that of fly ash, but lower than that of Portland cement. When converted from specific gravity, the density of the coal bottom ash is approximately 2.4 g/cm³. This higher density compared to that of fly ash can influence the overall weight and density of the resulting concrete paver blocks. The coal bottom ash exhibits a moderate water absorption capacity of 18 %. This water absorption characteristic must be considered during mix design to ensure proper workability and minimise potential issues related to moisture expansion or shrinkage in paver blocks. The content of SiO2 ranged from 40 % to 70 % in both fly ash and bottom ash. This oxide plays a crucial role in the pozzolanic activity of fly ash, where it reacts with calcium hydroxide in concrete to form an additional calcium silicate hydrate (C-S-H) gel, contributing to strength development. The proportion of Al_2O_3 was between 15 % and 30 % in both materials. Alumina (Al_2O_3) can contribute to the formation of additional cementitious phases and improve the long-term durability of concrete. The amount of CaO varied depending on the coal source used. In fly ash, the CaO content was likely lower than 10 %, whereas the bottom ash may have contained higher proportions, potentially up to 20 %. The presence of CaO in fly ash influences its pozzolanic activity. The concentration of Fe_2O_3 ranged from 5 % to 25 % in both fly ash and bottom ash. Iron oxide can influence the colour of the resulting concrete paver blocks, and M-sand, or manufactured sand, used as a fine aggregate in paver-block concrete, is a substitute for natural river sand. It is produced by crushing sandstone, granite, and basalt. The sand used in the experiment adhered to the production standards set for commercial M-sand. Coarse aggregates and larger particles of crushed stone, gravel, or slag were sourced from nearby quarries and ranged in size from 5 to 10 mm. These aggregates provide bulk material, reduce concrete costs, enhance structural integrity, and improve the tensile strength and resistance to cracking. The incorporation of coarse aggregates into concrete is also governed by established standards. The definitions and terms must align with these standards and must be appropriately referenced. Adherence to these regulations ensures precision and consistency in the terminology used within the context of concrete production, fostering clarity and conformity with industrial norms. Reference to the specific standards governing the application of coarse aggregates in concrete construction enhances the credibility and reliability of the information presented, and adherence to concrete aggregate standards ensures that proper definitions and terms are used.

Banana fibre, extracted from banana plant stems or leaves, is an innovative reinforcement for paver block concrete. To ensure reproducibility, the origin and production process of the banana fibres should be specified, including the main characteristics derived from this information. It is essential to note that banana fibres cannot be reused after incorporation into paver blocks. Superplasticisers such as Ceraplast 300 are high-range water reducers that enhance the workability and fluidity of concrete mixtures without compromising their strength and durability. They are widely used in paver block concrete manufacturing to improve flowability and overall product quality. We referred to the specific product specifications for Ceraplast 300 to ensure reproducibility.

Figure 1. Materials used

Paver block production using waste banana involves blending discarded banana fibres sourced from banana plant stems and leaves with cement or alternative binding agents, producing robust and environmentally friendly paving blocks.

Banana fibres have numerous advantageous properties, rendering them well-suited for integration into paver blocks. Their strength, flexibility, and light weight make them particularly suitable for construction applications. Furthermore, as a natural and renewable resource, banana fibre significantly reduces the environmental footprint associated with conventional construction materials. This innovative approach not only addresses waste concerns, but also aligns with the principles of sustainable construction, offering a promising avenue for eco-friendly building practices.

2.1. Preparation of waste banana into fiber

The initial stage involved decortication of the banana pseudostem. This was achieved by removing the outermost layer (exocarp) manually. Subsequently, the surface was abraded to ensure the complete elimination of any residual adhering tissue or contaminants. After decortication, the banana rachis (core) was mechanically pressed to extract the juice, which can be used in various downstream applications. The juiceless fibrous material (residue) was then dehydrated to reduce its moisture content to a predetermined level. Upon reaching the desired moisture content, the dehydrated residue underwent mechanical defibration, which involves shredding or rasping the material into narrow and elongated strands (fibres). These fibres were then collected for further processing, as shown in Fig. 2. The resulting fibres have multiple applications. This comprehensive process of collection, stripping, scratching, squeezing, drying, scraping, fibre cutting, and fibre collection allows for the effective utilisation of waste bananas, reducing overall waste generation.

The specific type of banana fibres used can be sourced from agricultural waste or produced in a laboratory. Agricultural waste banana fibres are typically obtained from discarded banana parts, whereas laboratory-produced fibres involve the controlled cultivation and processing of banana plants to yield fibres with the desired properties. The duration and temperature of the drying process can vary depending on the specific requirements. Banana fibres are dried at temperatures ranging from 60 degrees Celsius, and the duration is adjusted to remove excess moisture and achieve the desired fibre characteristics. Banana fibres are utilised in textiles, handicrafts, paper production, and other products because of their strength, flexibility, and eco-friendly nature. Banana fibres enhance the tensile strength and impact resistance of concrete, making it more durable. The decision to use banana fibres in concrete depends on the desired properties for construction applications, and in cases where tensile strength and sustainability are priorities, banana fibres can be a beneficial choice compared to other alternatives.

Figure 2. Preparation of banana fiber

2.2. Physical properties of materials

Ordinary Portland cement (grade 53) with a specific gravity of 3.05, determined through laboratory measurements, was used. The paver blocks incorporated M-sand, fly ash, and coal ash as filler materials. The specific gravities of the fillers measured in the laboratory setting were 2.76, 2.95, and 3.01, respectively. Waste banana fibres were employed to reinforce the paver block and prevent crack formation and voids. The specific gravity of the banana fibres, as measured in the laboratory, was 1.28. The specific gravity of an aggregate was determined by comparing its weight with that of an equal volume of water. This is an important parameter for several reasons. Typically, aggregates have a specific gravity ranging between 2.5 and 3.0 [5]. The ideal aggregate for optimal performance tends to have an average specific gravity of 2.60. This value is defined as the mass of a unit volume of aggregate divided by the mass of an equal volume of gas-free distilled water at a specified temperature, considering the weight of water within the voids filled by sinking the aggregate in water for approximately 15 h. Water absorption is a measure of the internal structure of aggregates. A standardised laboratory water absorption test was conducted to determine the water retention capacity of the coarse aggregates. The test yielded a value of 2.22 %. The acceptable water absorption limit for coarse aggregates varies depending on their intended application. For instance, drain layers can accommodate aggregates with a water absorption of approximately 4 %, whereas base courses generally restrict this to a maximum of 1 %. These permissible limits were established using standardised laboratory testing procedures.

The impact value of aggregates used in the wearing course should not exceed 30 %. The maximum percentage of bituminous macadam allowed was 35 %, according to IRC guidelines. For water-bound macadam base courses, the maximum allowable value was 40 %. Aggregate crushing value is a measure of the strength of the aggregate used in road construction, and represents the proportion by weight of the crushed or finer material obtained when the test aggregates are subjected to a specific load under standardised conditions. Bituminous macadam roads typically have a crushing values between 40 % and 45 %. The desired aggregate crushing value for road construction was 43 %, which can determine its suitability for various road layers. Table 1 (laboratory measurement) presents the physical properties of coarse aggregate. The water absorption test for coarse aggregates reveals the internal structure and porosity, which influence the amount of water retained and are vital for the concrete's performance. The impact value, percentage of bituminous macadam, and aggregate crushing value are relevant metrics for assessing the suitability of aggregates for road construction and providing insights into their strength and durability.

2.3. Sample preparation and moulding method

The mix proportions of the paver blocks (Table 2) were varied depending on the desired strength, texture, and durability of the final product. The manufacturing process (Figure 3) of the paver block involves several steps, starting with the mixing of various materials, such as cement, M-sand, coarse aggregate, fly ash, coal ash, banana fibre, and a superplasticiser (Ceraplast 300). Proper mixing of these materials is crucial to achieve the desired workability up to a true slump (85 mm).

Table 1. Physical properties of coarse aggregate

S. No.	Material	Type of test	Unit	Mean value
1	Coarse aggregate	Crushing strength	%	42.7
2		Impact strength	%	29.21
3		Water absorption	%	2.08
4		Specific gravity	g/cc	2.59

Table 2. Mix proportions of paver block per specimen

S. No.	Name of the materials	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
		[g]				
1	Fly ash	495	490	485	480	475
2	Coal ash	300	300	300	300	300
3	M-Sand	2000	2000	2000	2000	2000
4	Cement	200	200	200	200	200
5	Coarse aggregate	2500	2500	2500	2500	2500
6	Banana fiber	5	10	15	20	25
7	Super plasticizer (0.5 %) [ml]	5	5	5	5	5
8	Water [ml]	766	766	766	766	766

Figure 3. Manufacturing process of paver block

After the mixing process, the material was placed in moulds and compacted using a vibrator machine to remove any air pockets, thereby ensuring that the paver block was formed correctly. Once the compaction was complete, the moulds were demoulded to release the paver blocks. This process should be carefully performed to ensure that there is no damage to the paver blocks. Finally, the paver blocks were cured (at temperature 35 °C) for the recommended times (7, 14, and 28 d) to achieve the desired strength and durability. Curing helps prevent cracking and enhances the structural integrity of the blocks. This involved keeping the blocks moist and allowing them to set for a specific period.

Paver block making using waste banana fibres is not only an environmentally friendly solution to waste management but also presents an opportunity for income generation for local communities, particularly those situated in banana-growing regions.

3. Mechanical properties

3.1. Compressive strength test

The compressive strength is an important property of paver blocks that determines their load-bearing capacity. It represents the amount of force that a paver block can withstand before it begins to break or fail. In other words, the compressive strength is the maximum pressure or stress that a paver block can tolerate without cracking, crumbling, or crushing. This is a crucial factor in the design, manufacturing, and installation of paver blocks, because it affects their performance and longevity. The compressive strength of the paver blocks is determined through standardised tests and is usually measured in megapascals (MPa). A higher compressive strength indicates a stronger and more durable paver block that can withstand heavy loads and harsh weather conditions. Compressive strength test specifications (IS 15658:2006) are available in [46, 47]. Ninety specimens were tested (45 for I-dumble and 45 for Zig Zag paver blocks). The compressive strength of concrete is usually measured at 7, 14, and 28 days as the concrete attains its strength. After 28 days of curing, the concrete was anticipated to achieve its maximum strength. Table 3 presents the compressive strengths of the I-dumble and Zig Zag paver blocks.

Table 3. Compressive strength of paver block

Mix ID	**Compressive strength** [MPa] (I-dumble)			**Compressive strength** [MPa] (Zig Zag)		
	7 days	14 days	28 days	7 days	14 days	28 days
Mix 1.	9.96	16.53	23.57	9	15.09	22.46
Mix 2.	11.95	19.75	31.28	10.35	17.15	24.53
Mix 3.	14.37	23.68	34.58	11.53	19.1	30.54
Mix 4.	15.6	25.68	37.65	13.5	22.28	32.42
Mix 5.	10.41	17.23	33.64	9.92	16.43	23.42

The maximum compressive strength of the paver blocks was obtained using Mix 4 for both the I-dumble and Zig Zag paver blocks. In the I-dumble paver block, Mix 4 achieved a compressive strength of 37.65 MPa at 28 days of curing, using 480 g of fly ash and 1.5 % banana fibre. The compressive strength increased by approximately 7–10 MPa as curing time increased (Figure 4). Similarly, in the Zig Zag paver block, mix 4 exhibited a maximum compressive strength of 32.42 MPa after 28 days of curing, with the same proportion of fly ash and banana fibre (Figure 5). However, the compressive strength of the I-dumble paver block was higher than that of the Zig Zag block.

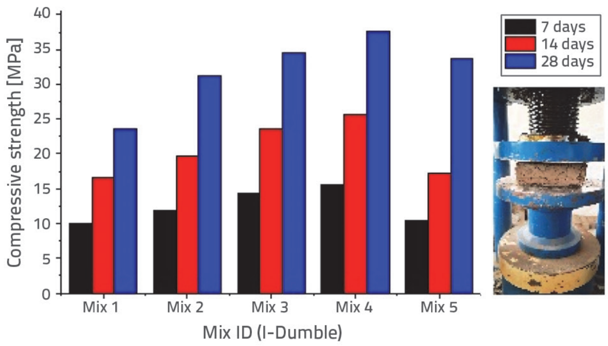

Figure 4. Compressive strength of I-dumble paver block

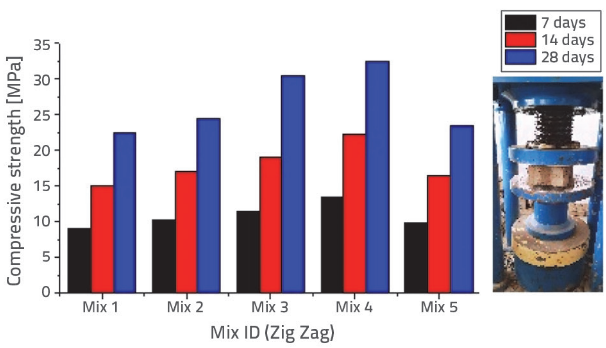

Figure 5. Compressive strength of Zig Zag paver block

Based on these results, it can be concluded that the I-dumble paver block is more suitable for areas with large live loads. The higher compressive strength of the I-dumble design suggests that it can withstand heavier loads and provide greater structural stability. It is important to note that the compressive strength cannot be the only consideration selecting a paver block design. Other properties such as flexural strength, water absorption, and split tensile strength should also be considered for a comprehensive evaluation of paver block performance in specific applications.

3.2. Split tensile strength

A split tensile strength test was performed on the paver block to determine its tensile strength. The test involved applying a tensile force to a cylindrical specimen of the paver block until it fractured. The split tensile strength (IS 15658:2006) of I-dumble-shaped and Zig Zag-shaped paver blocks depends on various factors such as the type of material used (Table 4), manufacturing process, dimensions and shape of the block, and curing period [38].

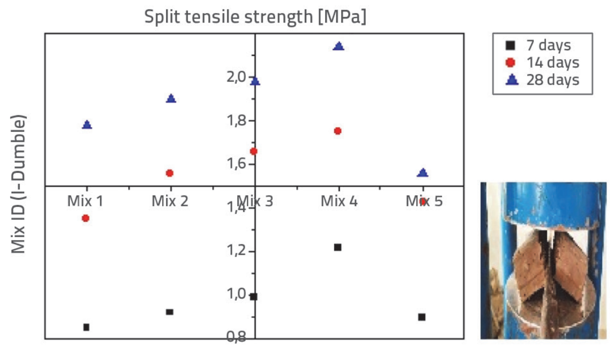

Figure 6. Split tensile strength of I-dumble paver block

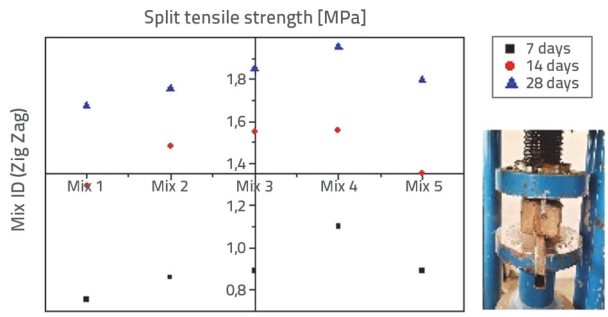

Figure 7. Split tensile strength of Zig Zag paver block

The split tensile strength of the Mix 4, which was 2 %, is considered to be the highest among all the other mixes. In I-dumble, the split tensile strength continues to increase from Mix 1 to Mix 3 and, reaches a maximum in Mix 4, i.e. 2 % of 2.140,

Table 4. Split tensile strength of paver block

Mix ID	**Split tensile strength** [MPa] (I-dumble)			**Split tensile strength** [MPa] (Zig Zag)		
	7 days	14 days	28 days	7 days	14 days	28 days
Mix 1.	0.85	1.35	1.78	0.75	1.3	1.67
Mix 2.	0.92	1.555	1.9	0.86	1.48	1.75
Mix 3.	0.99	1.655	1.98	0.89	1.55	1.85
Mix 4.	1.215	1.75	2.14	1.1	1.56	1.95
Mix 5.	0.895	1.42	1.56	0.89	1.35	1.8

and it is reduced in the very next Mix 5, i.e. 2.5 %. In I-dumble, the average difference between the three tests conducted on 7, 14 and 28 days of the split tensile strength obtained for the minimum split tensile strength was 45.35 % (Figure 6).In Zig Zag, the average difference between the three tests conducted on 7, 14 and 28 days of the split tensile strength obtained for the minimum split tensile strength was 34.82 %. By comparing the maximum value of split tensile strength obtained on the both I-dumble and Zig Zag (Figure 7), it was concluded that the split tensile strength of I-dumble is 9.03 % higher compared to that of the Zig Zag for 28 days. Thus, we can conclude that I-dumble is a better option to employ for high live load and dead load action areas.

3.3. Flexural strength test

The flexural strength of a paver block refers to its ability to withstand the bending stress without breaking or cracking. This property is important for paver blocks because they are commonly used in outdoor areas with regular feet and vehicular traffic. The ability of paver blocks to resist flexural stress ensures that they remain structurally intact and maintain their aesthetic appeal for a long period.

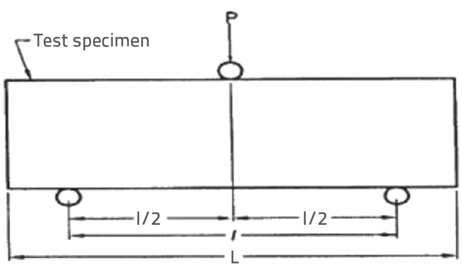

Figure 8. Schematic diagram of flexural strength test (IS 15658:2006)

The flexural strength of the paver blocks is determined through testing and is typically expressed in megapascals (MPa). Refer (IS 15658:2006) for the flexural strength test specifications (Figure 8). Table 5 lists the flexural strengths of the I-dumble and Zig Zag paver blocks.

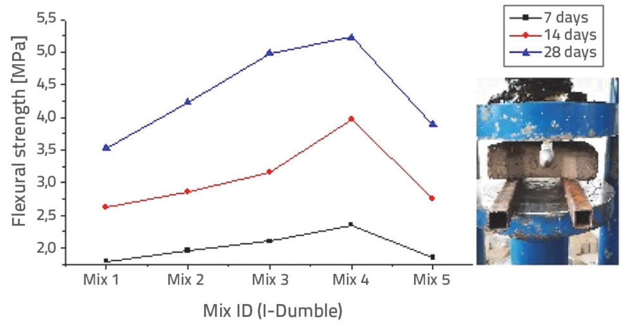

Figure 9. Flexural strength of I-dumble paver block

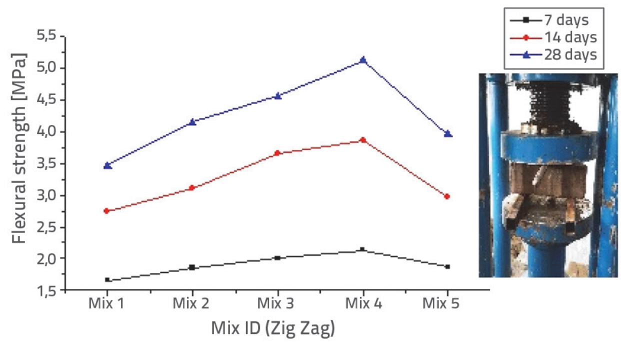

Figure 10. Flexural strength of Zig Zag paver blocks

The flexural strength results indicated that Mix 4, which contained 2 % banana fibres, achieved the highest flexural strength among all the tested mixes (Figure 9 and 10). In the case of the I-dumble paver block, the flexural strength gradually increased from Mix 1 to Mix 3 and reached its peak at Mix 4, with a value of 5.23 MPa. However, the flexural strength decreased in the subsequent Mix 5 (2.5 % banana fibres). The lowest flexural strength value was obtained for Mix 1 (0.5 % banana fibres), with a value of 3.52 MPa. For the Zig Zag paver block, the minimum and maximum flexural strength values obtained were 3.46 MPa and 5.12 MPa, respectively. The percentage difference between the two maximum flexural strengths of I-dumble and Zig Zag paver blocks, both containing 2 % banana fibre, was found to be 2.15 % for the 28-day testing period. Similarly, the percentage difference between the two minimum flexural strengths of I-dumble and Zig Zag paver blocks with 0.5 % banana fibre was 1.71 % for the 28-day testing period.

Table 5. Flexural strength of paver block

Mix ID	**Flexural strength** [MPa] (I-dumble)			**Flexural strength** [MPa] (Zig Zag)		
	7 days	14 days	28 days	7 days	14 days	28 days
Mix 1.	1.8	2.62	3.52	1.65	2.74	3.46
Mix 2.	1.96	2.86	4.23	1.85	3.1	4.15
Mix 3.	2.1	3.15	4.98	2	3.65	4.56
Mix 4.	2.35	3.98	5.23	2.13	3.86	5.12
Mix 5.	1.85	2.75	3.89	1.86	2.96	3.95

3.4. Water absorption

A water absorption test was performed on the paver blocks to determine their ability to absorb water. The test involved immersing the paver block in water for a specified period and measuring the increase in weight owing to water absorption. Refer (IS 15658:2006) for the water absorption test specifications.

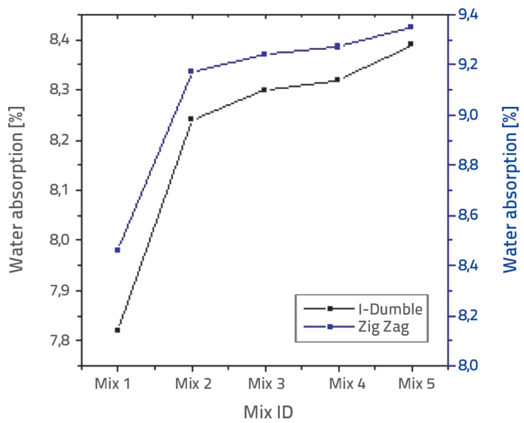

Figure 11. Water absorption of paver blocks

According to the test results (Figure 11), the water absorption values for all specimens exceeded 6 %, primarily attributed to the combination of the mix ratios and the inherent physical properties of the materials used. Mix 5, which contained 2.5 % banana fibre, demonstrated the highest water absorption in the I-dumble paver block. This implies that the paver block made with Mix 5 absorbed the most water when immersed in water for a specified duration.

By contrast, Mix 5 exhibited the lowest water absorption in the Zig Zag paver block. This suggests that the paver block made with Mix 5 showed the least amount of water absorption compared with the other mix proportions when subjected to the water immersion test. The variation in water absorption among different mix proportions can be attributed to several factors, including the interaction between the banana fibre and the concrete matrix, fibre distribution, and overall porosity of the paver block. The higher water absorption in the I-dumble paver block may be due to the presence of more voids or interconnected pores, allowing water to penetrate and be absorbed.

3.5. Failure pattern of paver blocks

Generally, the failure patterns of paver blocks can be classified into three types: shear, flexural, and compressive. Shear failure occurs when the paver block fails in a sliding manner owing to an applied load. Flexural failure occurs when the paver block bends and cracks owing to an applied load. Compressive failure occurs when the paver blocks are crushed by the applied load. The failure pattern (Figure 12) of paver blocks using waste natural banana fibre depends on various factors, such as the type of concrete mix used, the size and shape of the paver block, the percentage of banana fibre added, and the compaction method used during manufacturing.

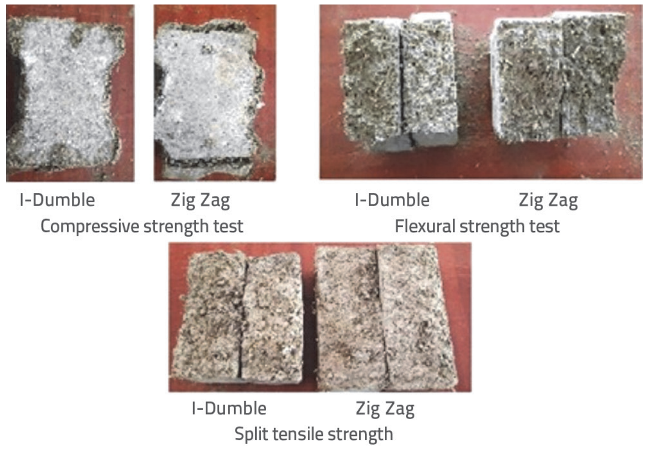

Figure 12. Failure patterns of paver blocks

The addition of banana fibre to the concrete mix can improve the mechanical properties of the paver block, including increased tensile strength, flexural strength, and impact resistance. The fibre-bridging effect of waste banana fibres is expected to mitigate crack propagation and improve the post-cracking behaviour of paver blocks, leading to a reduction in flexural failure and cracking under bending loads. Waste banana fibres can potentially improve the interfacial bond strength between the cement matrix and the aggregates. This improved bond can lead to a more effective stress transfer mechanism, thereby increasing the resistance of the paver block to shear deformation and failure. The mechanical properties and effectiveness of waste banana fibre reinforcement can be significantly affected by factors such as the fibre length, aspect ratio, and surface treatment. The curing regime employed during the paver block manufacturing process can affect the fibre–matrix bond development and consequently influence the overall mechanical behaviour. Variations in the mixing process, compaction techniques, and fibre dispersion methods can affect the distribution and effectiveness of waste banana fibre reinforcements in a paver block.

4. Cost analysis of paver blocks

The minimum pricing considerations include the material cost, fibre preparation expenses, and paver block manufacturing costs. The process of calculating potential earnings from a situation or project and subtracting the total cost associated with completing it. It predicts the profit gained from a project and compares the project cost with its estimated financial benefits.

The cost analysis in Table 6 shows that the market price [24] of I-dumble is higher than the price of Zig Zag. Owing to the inclusion of banana fibres, the compressive, flexural, and split tensile strengths were improved. The rate is decreased by

Table 6. Cost analysis of paver blocks

Mix ID	Current price [EUR]	I-dumble [EUR]	Current price [EUR]	Zig Zag [EUR]
Mix 1	0.19	0.122	0.17	0.122
Mix 2	0.19	0.121	0.17	0.121
Mix 3	0.19	10.0.121	0.17	0.121
Mix 4	0.19	0.121	0.17	0.121
Mix 5	0.19	0.121	0.17	0.121

35.56 % in the i-dumble paver block and 27.40 % in the Zig Zag paver block. Thus, when there is a bulk purchase of a banana fibre-reinforced paver block, it can be economically viable. The percentage differences between the market price and the estimated price were 43.261 % and 31.75 % for I-dumble and Zig Zag paver block.

5. Discussions and conclusion

This study investigated the potential of modified banana fibres (MBF) as reinforcement in concrete paver blocks to enhance their mechanical properties. The performance of paver blocks containing different MBF dosages (relative to fly ash weight) was compared with that of a control group. The results indicated a significant improvement in compressive strength, flexural strength, and split tensile strengths of paver blocks containing an optimal 2 % MBF content. This surpassed the typical 1.5 % MBF content reported in previous research, suggesting potential benefits of the specific MBF modification process used. This study acknowledges that several factors can influence the effectiveness of MBF reinforcement, including the inherent properties of the fibres themselves (length, aspect ratio, and surface treatment), overall mix design of the paver block concrete (cement content, aggregate type, and water-to-cement ratio), and curing regimen employed during production. All these factors play a role in the fibre–matrix interaction and stress transfer mechanisms within the composite material.

Overall, the research findings demonstrate the potential of MBF as a sustainable reinforcement material for paver blocks. The observed improvements in mechanical strength suggest that these paver blocks could offer superior, long-term durability and resistance to cracking under real-world loads. Additionally, this approach aligns with the growing emphasis on sustainable construction practices that utilise readily available agricultural by-products, such as banana fibres, potentially reducing reliance on resource-intensive conventional materials.

The experimental work of this project involved the conversion of banana stems into banana fibre and banana fibre-reinforced paver blocks, and their engineering properties were assessed in terms of water absorption, compressive strength, flexural strength, and split tensile strength.

- A maximum compressive strength of 37.650 N/mm^2 was obtained for Mix 4 of 37.650 N/mm^2 after 28 days of curing in the I-dumble paver block, while a maximum compressive strength of 32.420 N/mm^2 was obtained for Mix 4 of 32.420 N/mm^2 after 28 days of curing in the Zig Zag paver block. The compressive strength of the I-dumble was greater than that of the Zig Zag paver block, suggesting that it can be used in areas where a large live load is applied.
- The flexural strength of the Mix 4 (2 % of 5.230 N/mm^2) was the highest among all the other mixes. The minimum and maximum values obtained were 3.520 N/mm^2 and 5.230 N/mm^2 for I-dumble and Zig Zag, respectively. The percentage differences between the maximum and minimum flexural strengths were 2.156 % and 1.719 % for 28 days respectively.
- The split tensile strength of Mix 4 was the highest among all the mixes. In I-dumble, the split tensile strength increased from Mix 1 to 3 and reached its maximum in Mix 4. The average minimum difference of the tests conducted on 7, 14, and 28 days of the split tensile strength is 45.35 %. In the Zig Zag, the average minimum difference of the test conducted on 7, 14, and 28 days of the split tensile strength is 34.82 %. The I-dumble had a split tensile strength of 9.03 % compared with the Zig Zag for 28 days.
- Mix 5 (2.5 % banana fibre) had the highest water absorption in the I-dumble and the lowest water absorption in the Zig Zag paver block.
- The failure patterns of the paver blocks can be classified into three types: shear, flexural, and compressive. The addition of banana fibre to the concrete mix can improve the mechanical properties of the paver block, including increased tensile strength, flexural strength, and impact resistance. However, the failure pattern may still depend on factors such as the quality of the banana fibre used, the curing conditions, and the manufacturing process.
- It is demonstrated that the paver blocks containing 2 % modified banana fiber (with respect to weight of fly ash) show (7.45 % for I-dumble and 17.12 % for Zig Zag, 14.99 % for I-dumble and 8.67 % for Zig Zag, and 12.182 % for I-dumble and 9.971 % for Zig Zag) higher mechanical properties, respectively, as compared to that of the other mix proportions.

The banana fibres were uniformly dispersed throughout the mix by cutting and distributing them properly to prevent clustering. The fibres acted as void arrestors, mitigating cracks during testing and contributing to enhanced failure properties. From the mechanical properties, 2 % of banana fibre was the optimum mix proportion of the concrete banana reinforced paver block. As per IS 15658:2006, Table 1, 2 % banana reinforced I-dumble paver block can be used in light traffic areas with recommended thickness of 60 mm, whereas Zig Zag 2 % reinforced banana fibre can be used in non-traffic areas and with recommended thickness of 50 mm.

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