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Potential of Trema Micrantha and Coconut Ash-Trees in Sustainable Innovation for the Repair of Rigid Pavements

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Abstract The premature deterioration of rigid pavements represents a serious road safety problem, affecting connectivity and causing human losses, while the production of Portland cement contributes significantly to CO_2 emissions. Therefore, this study proposes the use of natural materials, such as coconut shell ash (CSA) and Trema micrantha fibre (TMF), known as 'sachahuasca', to improve the durability and sustainability of pavements, offering alternatives that reduce dependence on cement and its environmental impact. The process began with the procurement and preparation of both materials: sachahuasca fibre was selected, washed, dried and cut, while coconut husk was collected, cleaned, washed and dried and then treated in a kiln, obtaining ashes that were incorporated into concrete in concentrations of CSA (0%, 0.5% and 1%) and TMF (0.5%, 1% and 1.5%) for the repair of rigid pavements. A total of 126 cylindrical and 21 prismatic samples were then manufactured and tested for compressive, tensile and flexural strength, with curing at 7, 14 and 28 days, for a total of 147 samples, in addition to slump, density and temperature tests. The results indicated that the mechanical and physical properties improved in the rigid pavement, highlighting an increase in strength during the first few days, which favours its durability. The low slump achieved is suitable for concrete in rigid pavements, promising not only to improve road infrastructure, but also to reduce CO_2 emissions.

Keywords Rigid Pavement, Coconut Shell Ash, Trema Micrantha Fibre, Sachahuasca

1. Introduction

In Peru, rigid pavements are widely used on roads connecting cities due to their durability, with an estimated service life between 10 and 20 years [1]. However, many of these roads show signs of deterioration before reaching this timeframe, which represents a challenge for road infrastructure. Despite the fact that 95% of the country's roads are paved, a large proportion are in poor condition, a situation that has contributed to the loss of 1,376 lives between January and July 2024 in accidents related to these defects [2] [3]. As if this were not enough, according to the National Institute of Statistics and Information (INEI), this problem is aggravated by the constant increase in traffic, as vehicle flow grew by 6.1% in the first four months of the year [4] [5]. In addition, infrastructure problems are compounded by the environmental impact of Portland cement production, a key material in rigid pavement construction, responsible for approximately 5% of the country's CO_2 emissions [6] [7]. This scenario highlights the urgent need to adopt more sustainable solutions. It is therefore imperative to develop alternatives that not only improve the durability of roads, but also reduce reliance on Portland cement and thus pollutant emissions, without compromising road safety. In this context, the use of natural materials such as coconut shell ash, basalt fibre and agave fibre has proven to be a promising option as these components have shown good performance in terms of compressive strength, flexural strength and reduced crack propagation, which extends the service life of rigid pavements [8] [9] [10] [11]. These advances support the feasibility of employing natural components to optimise both the structural properties and sustainability of pavements. Thus, our research focuses on evaluating the potential of Trema micrantha fibre, known as 'sachahuasca', combined with coconut husk ash, as an innovative combination to improve the performance of rigid pavements. This study is particularly relevant because of the paucity of previous research examining the use of these materials in pavements of this type, which represents a unique opportunity to investigate the benefits that these natural components can bring in terms of strength and durability. The incorporation of natural fibres such as these could contribute to the creation of stronger and more durable pavements. In this sense, this approach responds to the current need to adopt practices that minimise environmental impact, promoting the creation of infrastructures that are not only efficient and durable, but also aligned with green building trends and carbon footprint reduction.

1.1. Literature Review

Although there is not much previous research on the use of coconut shell ash in rigid pavements, studies have been carried out with other ashes applied in this type of structures. One example is the use of olive ash as a partial replacement of cement in percentages from 0 to 12.5%, where a reduction in slump and an improvement in compressive strength were observed. The mixture with 7.5% olive ash achieved a strength of up to 36 MPa, compared to 31 MPa for conventional concrete (Portland cement) [12]. In addition, the Department of Civil Engineering in India evaluated the use of coconut shell ash in rigid pavements at 1, 5, 10, 15, 20 and 25% proportions, and found that an addition of 10% improved the durability properties compared to conventional concrete, showing lower water absorption, lower weight loss in acidic conditions, lower chloride ion penetration and controlled expansion against sulphate attack [13].

Despite limited research on combining coconut ash with sachahuasca (Trema micrantha) fiber in rigid pavements, previous studies highlight the potential of coconut ash and natural fibers in concrete. In India, the Civil Engineering Department investigated coconut ash as a partial cement replacement mixed with seawater, addressing environmental concerns of cement production. Tensile, compression, and flexural tests on mixtures with 15%, 20%, and 30% coconut ash revealed that at 28 days, compressive strength increased to 34.87 N/mm^2 (vs. 22.3 N/mm^2 for conventional concrete), though flexural strength decreased to 5.33 N/mm^2 (vs. 6.73 N/mm^2), and tensile strength showed minimal difference (1.368 N/mm^2 vs. 1.28 N/mm^2) [14]. Another Indian study using coconut fibers as coarse aggregate (CSCA) and coconut ash as cement replacement (CSA) found flexural strength improved by 11% with 15% CSCA and 12% CSA, while compressive strength increased with 10% CSA and 15% CSCA [15]. Conversely, a study using coconut shell waste as aggregate observed a 62.6% compressive strength reduction at 7 days, reducing to 21.5% at 18 days [16]. Differences stemmed from using coconut shells instead of fibers. Another Indian study combining coconut shells as aggregate with 10% fly ash showed a 16% compressive strength increase [17] [18].

In Pakistan, coconut ash replaced cement in proportions up to 25%, with 10% addition achieving maximum compressive strength of 42.73 N/mm^2 (vs. 39.54 N/mm^2 without ash) and flexural strength improving to 4.22 N/mm^2 (vs. 3.89 N/mm^2). Exceeding 10% decreased mechanical properties [19] [20]. In Canada, 0%-20% coconut ash was tested as cement replacement, with 10% yielding the best results: 12% compressive strength increase, 9% flexural strength increase, 10% tensile strength increase, 20% higher modulus of elasticity, and 15% embodied energy reduction, enhancing both mechanical properties and sustainability [21]. In the Philippines, studies using 0%-40% coconut shell ash classified it as class N pozzolan. A 10% addition increased compressive strength by 92.10%, though it was more prone to sulfate attack [22].

These studies indicate that coconut ash and fibers can enhance concrete properties, with material type and proportions being critical to performance, promoting sustainable construction methods.

On the other hand, Trema micrantha has not yet been investigated in the field of civil engineering, specifically in applications such as concrete or other construction materials. However, this plant has some outstanding characteristics that could make it relevant in this context. Trema micrantha belongs to the family Ulmaceae, being known as 'dogwood' or 'pinewood'. It is a tree that can reach heights of 10 to 15 metres [23], characterised by a straight trunk, spreading branches and light grey or brown bark. Its leaves are simple and alternate, with serrated margins, being bright green on the upper side and paler on the underside. The tree produces small white to yellowish flowers arranged in inflorescences and fruits in the form of drupes containing a single seed [24]. It is found compound in tropical and subtropical areas, being used in reforestation and ecosystem restoration projects due to its rapid growth rate and ability to adapt to diverse soil conditions [25] [26]. Although parts of the plant have been used in some cultures for medicinal purposes, more research is needed to validate these applications [27].

Based on the benefits documented in the literature review on coconut husk ash, this research focused on its application combined with an innovative material: Trema micrantha ('sachahuasca') fibre. Although coconut husk ashes have shown favourable properties in other applications, their use in rigid pavement rehabilitation has not been explored, nor has the synergistic combination of sachahuasca fibres and coconut ashes been investigated. To evaluate the impact of these natural fibres, concrete samples were manufactured in which both materials were incorporated in different proportions with respect to the total weight of cement. These samples were tested at 7, 14 and 28 days, analysing their physical and mechanical properties, in order to determine the contribution of these materials in improving the structural properties of concrete used in the repair of rigid pavements.

2. Materials and Method

In this section, tests were carried out to evaluate the physical and mechanical properties of concrete modified with additions of sachahuasca fibre and coconut shell ash, applied to rigid pavement repair. A mix design was also developed detailing the quantities of each material used per cubic metre, optimising the composition of the concrete for better results in strength and durability.

2.1. Rigid Pavement

Rigid pavement is a type of road surface characterised by high strength and durability. It is mainly composed of concrete, which may include admixtures to improve its performance [28]. Its characteristics include low deformation under load, high compressive strength and long service life, making it an ideal choice for areas with heavy traffic [29]. However, in Huancayo these conditions are not always met, as various parts of the city have experienced road infrastructure problems, especially in high traffic areas. Figure 1 shows the deterioration of the rigid pavement in several main streets, where cracks and subsidence are visible at critical points. In Item A, Avenida Mariscal Castilla, located in the district of El Tambo (475422.45 W, 8668635.89 S), shows cracks in one of the busiest connecting roads into the city. In Item B, the intersection of Calle 2 de Mayo with the main road to Huancayo, in the district of Huancayo (477479.00 W, 8666396.03 S), shows considerable wear and tear affecting vehicular flow. Finally, in Item C, Avenida Huancavelica, in the district of Chilca (477353.97 W, 8663901.58 S), close to commercial centres such as Metro, the pavement has subsided, compromising both safety and accessibility. This situation highlights the urgent need for rigid pavement improvements in these key areas to ensure the integrity of the road infrastructure.

2.2. Trema Micrantha Fibre

Trema micrantha, or sachahuasca, is a tree native to the Amazon that can reach up to 30 metres in height [30]. Renowned for its smooth bark and large, shiny leaves, it grows mainly in moist, well-drained soils of high and secondary rainforest [31]. In addition to its ecological relevance, its fibre is valued for its excellent mechanical properties and its potential in the manufacture of biocomposites and sustainable textiles [32].

a) Av. Mariscal Castilla-El Tambo

b) 2 de Mayo-Huancayo

c) Ovalo Parque de los Héroes-Chilca

Figure 1. Deterioration of rigid pavement in Huancayo

Table 1 highlights the physical and mechanical properties of Trema micrantha fiber, which was obtained from the literature review conducted by researchers M. Sfiligoj Smole, et al [32], showing an interesting profile for structural applications. The tensile strength of 85 MPa stands out, suggesting a potential to improve the durability and strength of composite materials without compromising lightness.

Table 1. Properties of the Micrantha trema [32]

Density	0.48 g/cm³
Tensile strength	85 MPa
Modulus of elasticity	2.5 GPa
Water absorption	12-14%
Tenacity	0.5 J/cm²
Impact resistance	3 KJ/cm²

2.3. Coconut Shell Ash

Coconut fibre, from the Cocos nucifera tree, is a durable material that grows in tropical climates. In addition to its uses in cooking for its high content of healthy fats and fibre, it is used in the cosmetics industry for its moisturising properties. In construction, its shell is used to make ropes, carpets and insulation materials due to its strength and durability [33] [34] [35].

In our research, coconut shell ash stands out as a promising replacement for cement due to its physical and chemical properties. The specific gravity of 1.152 and an absorption capacity of 4.80% are indicators of its suitability in concrete mixes. In addition, the sodium oxide (Na_2O) content of 0.256% is crucial, as this compound contributes to the activation of the chemical reaction that strengthens concrete, similar to the role it plays in Portland cement. These characteristics as seen in Table 2 suggest that coconut shell ash is not only viable, but could also improve the sustainability and performance of concrete in structural applications.

Table 2. Properties of coconut shell ash [35]

Specific gravity (gr/cm³)	1.152
Absorption (%)	4.80
Humidity (%)	8.89
Al_2O_3%	0.0022
Fe_2O_3%	0.562
Na_2O %	0.256
SiO_2 %	0.005
SO_3 %	0.128

2.4. Flowchart of Fibre Procurement

Figure 2 shows the flow diagram for obtaining the coconut husk ash and Trema micrantha fibres, used as additives in the concrete in proportions of coconut husk ash (0.5% and 1%) and Trema micrantha fibre (0.5%, 1% and 1.5%). The process started with the collection of both raw materials, followed by a cleaning stage to remove residues and a thorough washing, ending with controlled drying. In the case of Trema micrantha fibre, after drying, a uniform fibre with a length of 5 cm was obtained. In parallel, the coconut husk underwent a calcination process in an oven at 400 °C, followed by sieving through a No. 200 mesh to ensure fine and homogeneous particles. With these procedures, both additions were ready to be incorporated into the concrete mixes, ensuring uniformity and quality in the final material.

Figure 3 shows, in item a, the coconut shell in its natural state, as obtained at the beginning of the process described in the flow diagram in Figure 2, and in item b, the final product transformed into ash. Similarly, in item c, the sachahuasca raw material is shown, and in item d, the final result after processing.

2.5. Mix Design

Table 3 presents the mix design, detailing the quantities of each component, expressed in Kg/m³, used in the study, including water, cement, coarse and fine aggregates, as well as coconut shell ash (CSA) and Trema micrantha fibre (TMF), also known as sachahuasca. In this design, constant amounts were maintained for all dosages, from 0% of both fibres to 1% coconut shell ash and 1.5% Trema micrantha fibre. The amount of coconut husk ash and Trema micrantha fibre was added in relation to the cement, ensuring adequate integration of these materials into the mix.

Table 4 presents the optimised dosage and updated mix design with adjustments for water absorption of the materials. In this process, a water absorption of 4.80% was considered for coconut shell ash (CSA) (Table 2) and 13% for Trema micrantha fibre (TMF), a value obtained as an average between 12% and 14% (Table 1). Water absorption is calculated using the formula: 'Water absorbed (L) = Mass of material (Kg) × (Absorption percentage / 100)'. Subsequently, the dry weight of the materials is adjusted using the formula: 'Adjusted dry weight = Initial wet weight / (1 + (Absorption / 100))'. For example, in sample C1 (0.50% CSA + 0.50% TMF), the amount of water was adjusted to 185.45 L and the dry weight of the absorbent materials to 3.733 kg. This resulted in a reduction of the cement content from 413.53 kg to 409.797 kg, thus optimising the final dosage. This adjustment ensures a proper balance in the mix design by considering the absorption capacity of the materials and their impact on the water content, allowing for a more efficient and controlled batching.

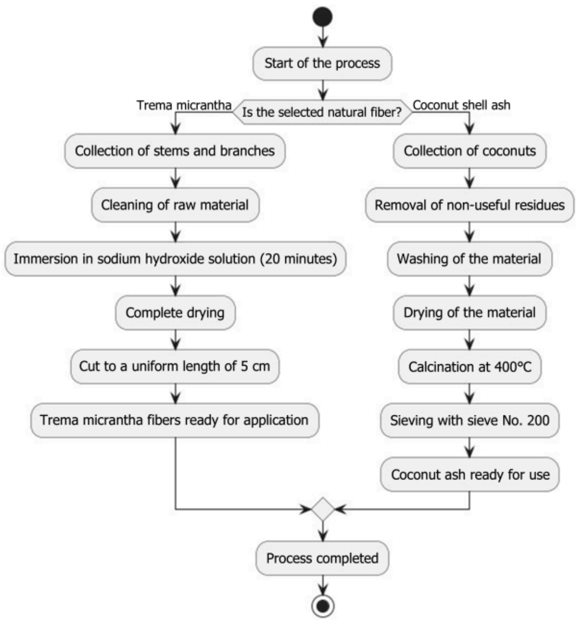


Figure 2. Fibre Procurement Diagram

Figure 3. Coconut ash and fibre from Trema micrantha

Table 3. Quantity of materials for the concrete mixture

MIX DESIGN						
Samples	Water	Cement	Coarse Aggregate	Fine Aggregate	Coconut Shell Ash	Trema Micrantha fibre
	L	Kg	Kg	Kg	Kg	Kg
0%	185.00	413.53	900	768	0.00	0.00
0.50%CSA + 0.50%TMF	185.00	413.53	900	768	2.07	2.07
0.50%CSA + 1.00%TMF	185.00	413.53	900	768	2.07	4.14
0.50%CSA + 1.50%TMF	185.00	413.53	900	768	2.07	6.20
1.00%CSA + 0.50%TMF	185.00	413.53	900	768	4.14	2.07
1.00%CSA + 1.00%TMF	185.00	413.53	900	768	4.14	4.14
1.00%CSA + 1.50%TMF	185.00	413.53	900	768	4.14	6.20

Table 4. Optimised dosage

MIX DESIGN							
Samples	Water	Cement	Coarse Aggregate	Fine Aggregate	Coconut Shell Ash	Trema Micrantha fibre	Ratio of water to cement
	L	Kg	Kg	Kg	Kg	Kg	a/c
0%	185.00	413.53	900	768	0	0	0.45
0.50%CSA + 0.50%TMF	185.45	409.797	900	768	2.07	2.07	0.45
0.50%CSA + 1.00%TMF	185.72	407.965	900	768	2.07	4.14	0.46
0.50%CSA + 1.50%TMF	185.99	406.142	900	768	2.07	6.2	0.46
1.00%CSA + 0.50%TMF	185.64	407.896	900	768	4.14	2.07	0.46
1.00%CSA + 1.00%TMF	185.91	406.064	900	768	4.14	4.14	0.46
1.00%CSA + 1.50%TMF	186.17	404.241	900	768	4.14	6.2	0.46

We used the dosage of Table 3 because we kept the amounts of water, cement and aggregates constant, with the objective of evaluating only the effect of the addition of CSA and TMF on the mechanical behavior of the concrete. Applying the adjusted dosage of Table 4 would have generated uncertainty in the results, since the modifications in the water-cement ratio, derived from the water absorption by coconut shell ash and Trema micrantha fiber, would have introduced additional variables that are difficult to control. Such changes would have interfered with the direct interpretation of the effect of the admixtures, since it could not be certain whether the variations in strength were due to dosage or absorption. Therefore, we opted for Table 3, which allowed us to isolate the impact of CSA and TMF. Table 4 was considered only as a theoretical and explanatory approach, useful for understanding how these materials affect water demand, but not suitable for direct comparative experimental purposes.

2.6. Experimental Preparation

Once the dosages for each addition were established, as shown in Table 3, tests were performed, including slump, temperature and density, as well as mechanical compression, physical tensile and flexural tests, in order to evaluate the behaviour of the concrete according to the additions indicated in the table. The slump test, essential in this research, was carried out in accordance with the MTC E 705 standard [36] using the Abrams cone; after obtaining a homogeneous mix with the same dosages of additives, which included coconut shell ash (0.5% and 1%) and Trema micrantha fibre (0.5%, 1% and 1.5%), the mould was moistened, placed on a flat surface, filled in three compacted layers with 25 rod strokes and the slump was measured after removing the mould vertically. For the density test, performed according to MTC E 714 [36], the Washington pot was used; after wetting the materials, the container was filled in three compacted layers with 25 strokes of rod, the outside was tapped with a rubber mallet 10 to 15 times, and the container was weighed with the concrete at the end. For the temperature test, in accordance with MTC E 704 [36], a thermometer accurate to ±0.5 °C was used by inserting it 75 mm into the mix, allowing the temperature to stabilise for 2 minutes before recording the reading, This test evaluates the temperature of the fresh concrete to ensure proper hydration conditions, as well as to identify potential issues related to workability, setting time, or early-age strength development influenced by ambient and material temperatures. For the mechanical tests, which include compression, tensile and flexural tests, standardised procedures were followed according to MTC E 704, MTC E 708 and MTC E 711, respectively [36]. In the compression test, cylindrical specimens of 15 cm diameter and 30 cm height were used, cured for 7, 14 and 28 days. The specimens were placed in the equipment with neoprene bases, and a controlled load of 35 ± 7 psi/s was applied up to the failure point. In the tensile test, cylindrical specimens of the same dimensions (15 cm diameter and 30 cm height), also cured for 7, 14 and 28 days, were used. These specimens were placed in the machine, secured along the centre of the bottom plate, and a force varying between 50 and 1000 kN/min was applied. In the bending test, 15 cm x 15 cm x 50 cm prismatic specimens were used, cured for 28 days. After centring the specimen in the rig and placing a top bar, a load of 0.9 MPa/min and 1.2 MPa/min was applied until the failure point was reached. All tests were performed at the same dosages as indicated in Table 3 and were supervised by laboratory technicians, ensuring the use of personal protective equipment (PPE) for the safety of the participants.

Figure 4 presents a flow diagram that synthesises what has been described above and includes graphical representations of the tests carried out. This diagram facilitated the understanding of the procedures carried out in the laboratory, providing a clearer view of how they were executed. It also highlights the importance of including the most representative images of each test, allowing a better visual interpretation of the key stages of the experimental process.

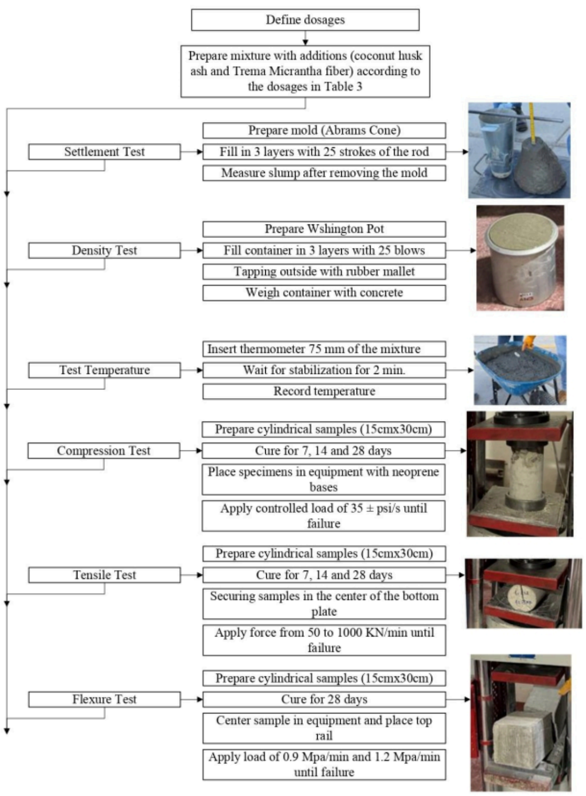


Figure 4. Diagram of laboratory tests

3. Results

The performance of the concrete used for rigid pavement repair is presented below, evaluated through both cylindrical and prismatic samples, with a total of 147 samples. These were cured for 7, 14 and 28 days, respectively. In addition, a cost analysis related to rigid pavement repair was carried out to determine the economic viability of the process.

3.1. Slump Test

Table 5 shows the results of the slump test, considering dosages ranging from 0% (without fibres) to values with additions of coconut husk ash and Trema micrantha fibre, which vary between 0.5 % and 1.5 %.

Table 5. Slump results

DOSAGE	SLUMP (Inches)
0 %(CSA)+ 0 % (TMF)	4.38
0.5 %(CSA)+ 0.5 %(TMF)	4.15
0.5 %(CSA)+ 1 %(TMF)	3.89
0.5 %(CSA)+ 1.5 %(TMF)	3.64
1 %(CSA)+ 0.5 %(TMF)	3.36
1 %(CSA)+ 1 %(TMF)	3.25
1 %(CSA)+ 1.5 %(TMF)	3.01

Figure 5 presents the slump test, showing a progressive reduction in slump as the additions of coconut shell ash (CSA) and Trema micrantha fibre (TMF) are increased. Initially, with no additions of CSA and TMF, a slump of 4.38 inches was obtained. With an addition of 0.5% of both components, the slump dropped to 4.15 inches. By increasing the CSA and TMF ratio, a steady decrease in slump was recorded: with 0.5% CSA and 1% TMF, 3.89 inches; with 0.5% CSA and 1.5% TMF, 3.64 inches; with 1% CSA and 0.5% TMF, 3.36 inches; and with 1% CSA and 1% TMF, 3.25 inches. Finally, the combination of 1% CSA and 1.5% TMF resulted in a drop of 3.01 inches. These results indicate that the mixes with lower slump values, corresponding to the higher CSA and TMF additions, are more suitable for rigid pavements due to their low workability, while the initial mixes, with higher slump, may require composition adjustments to achieve optimum consistency.

3.2. Density

Table 6 shows the results obtained from the density test, which is fundamental for evaluating the quality and performance of concrete in rigid pavement applications. This test incorporated different dosages of coconut shell ash (0%, 0.5% and 1%) and Trema micrantha fibre (0%, 0.5%, 1% and 1.5%), allowing to analyse how these additions affect the properties of the concrete and contribute to its strength and durability under service conditions.

Figure 6 presents the density results as a function of the additions of coconut shell ash (CSA) and Trema micrantha fibre (TMF). The standard sample, without additions of CSA and TMF, reached a density of 2312.05 kg/m³. With an addition of 0.5% CSA and 0.5% TMF, the density increased to 2328.09 kg/m³. As the proportion of CSA and TMF increased, successive increases in density were observed: with 0.5% CSA and 1% TMF, the density was 2332. 81 kg/m³; with 0.5% CSA and 1.5% TMF, the density reached 2339.34 kg/m³; with 1% CSA and 0.5% TMF, the density reached 2346.71 kg/m³; with 1% CSA and 1% TMF, the density reached 2350.52 kg/m³; and finally, with 1% CSA and 1.5% TMF, the density reached 2357.80 kg/m³. These results reflect a trend of increasing density as the proportions of CSA and TMF increase, suggesting that these additions strengthen the compactness of the material.

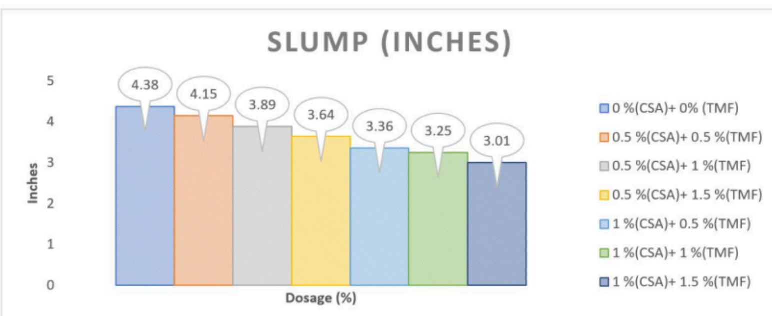


Figure 5. Slump with addition of CSA and TMF

Table 6. Density results

DOSAGE	DENSITY (Kg/m³)
0 %(CSA)+ 0 %(TMF)	2312.05
0.5 %(CSA)+ 0.5 %(TMF)	2328.09
0.5 %(CSA)+ 1 %(TMF)	2332.81
0.5 %(CSA)+ 1.5 %(TMF)	2339.34
1 %(CSA)+ 0.5 %(TMF)	2346.71
1 %(CSA)+ 1 %(TMF)	2350.52
1 %(CSA)+ 1.5 %(TMF)	2357.80

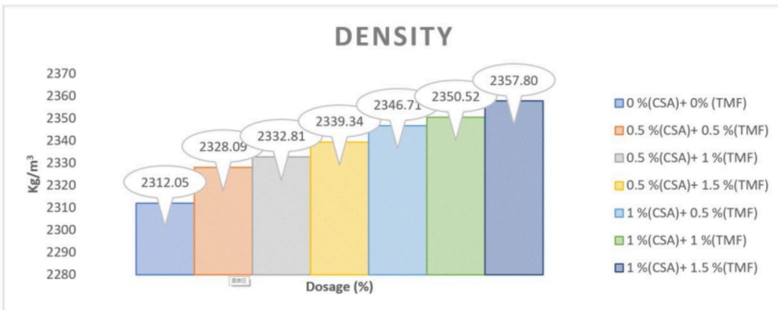


Figure 6. Density with addition of CSA and TMF

3.3. Temperature

Table 7 presents the results of the temperature test with different fibre dosages, as detailed in the table above. This test, focused on rigid pavements, includes additions of coconut shell ash and sachahuasca fibre, and the results are key to evaluating the feasibility and thermal behaviour of the concrete in real service conditions.

Table 7. Temperature results

DOSAGE	TEMPERATURE (°C)
0 %(CSA)+ 0 %(TMF)	22.34
0.5 %(CSA)+ 0.5 %(TMF)	22.67
0.5 %(CSA)+ 1 %(TMF)	22.98
0.5 %(CSA)+ 1.5 %(TMF)	23.21
1 %(CSA)+ 0.5 %(TMF)	23.59
1 %(CSA)+ 1 %(TMF)	24.12
1 %(CSA)+ 1.5 %(TMF)	24.87

Figure 7 shows the temperature results as a function of coconut shell ash (CSA) and Trema micrantha fibre (TMF) additions. Initially, without addition of CSA and TMF, a temperature of 22.34°C was recorded. With the addition of 0.5% CSA and 0.5% TMF, the temperature increased to 22.67°C. As the proportions of CSA and TMF are increased, gradual increases in temperature are observed: with 0.5% CSA and 1% TMF, a temperature of 22.98°C is obtained; with 0.5% CSA and 1.5% TMF, the temperature reached 23.21°C; with 1% CSA and 1.5% TMF, the temperature reached 23.21°C; with 0.5% CSA and 1.5% TMF, a temperature of 22.34°C is obtained. 21°C; with 1% CSA and 0.5% TMF, the temperature rose to 23.59°C; with 1% CSA and 1% TMF, it reached 24.12°C; and finally, with 1% CSA and 1.5% TMF, the maximum recorded temperature of 24.87°C was reached. These results indicate that the addition of CSA and TMF contributes to a gradual increase in the temperature of the material, possibly related to the thermal interaction of the components. For cold climates, it is beneficial for the concrete temperature to increase slightly to ensure proper setting and to avoid strength problems associated with low thermal conditions.

3.4. Compressive Strength

Table 8 presents the results of the compressive strength test. Although measurements were made at 7 and 14 days, the most significant values for rigid pavements are at 28 days. Each test included three measurements, of which the averages are reported.

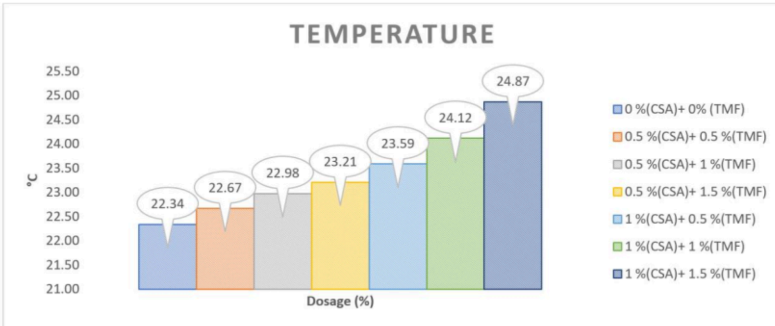


Figure 7. Temperature with addition of CSA and TMF

Table 8. Compressive strength results

DOSAGE	Compressive strength Kg/cm² 28 days	
0 %(CSA)+ 0 %(TMF)	248.02	238.59
	227.98	
	239.76	
0.5 %(CSA)+ 0.5 %(TMF)	235.43	250.59
	267.17	
	249.16	
0.5 %(CSA)+ 1 %(TMF)	264.95	266.59
	277.99	
	256.83	
0.5 %(CSA)+ 1.5 %(TMF)	295.63	287.32
	278.45	
	287.87	
1 %(CSA)+ 0.5 %(TMF)	257.34	267.01
	278.16	
	265.53	
1 %(CSA)+ 1 %(TMF)	249.24	259.37
	267.74	
	261.14	
1 %(CSA)+ 1.5 %(TMF)	256.49	246.77
	235.96	
	247.87	

Figure 8 shows the results of the compressive strength of concrete at 7, 14, and 28 days, revealing the impact of coconut shell ash (CSA) and Trema micrantha fiber (TMF) additions. At 7 days, without any additions, the initial strength was 167.29 Kg/cm², which increased to 176.69 Kg/cm² with the addition of 0.5% CSA and 0.5% TMF, and further rose to 183.89 Kg/cm² with 0.5% CSA and 1% TMF. The maximum strength at 7 days, 197.54 Kg/cm², equivalent to an 18.08% increase, was achieved with the addition of 0.5% CSA and 1.5% TMF. Beyond this proportion, strength began to decrease as CSA and TMF content increased. At 14 days, without additions, the strength was 209.59 Kg/cm², and the best result was again obtained with 0.5% CSA and 1.5% TMF, reaching a strength of 267.56 Kg/cm², representing a 27.66% increase. However, with fiber content exceeding this proportion, strength began to decline. At 28 days, the strength without additions reached 238.59 Kg/cm², while the highest strength, 287.32 Kg/cm² (a 20.42% increase), was recorded with 0.5% CSA and 1.5% TMF. These results indicate that an optimal proportion of 0.5% CSA and 1.5% TMF significantly improves compressive strength during the early curing stages, although increasing fiber content beyond this level tends to reduce the concrete's strength.

Table 9 presents a table with the images of the failures obtained during the compression tests carried out on the machine, together with the descriptions corresponding to each type of coconut husk ash and sachahuasca fibre dosage. The images show the different failure modes that occurred under load, where it is highlighted that the most frequent failures were crushing and diagonal failures in compressive strength, indicating how the variation in dosages influences the behaviour of the material.

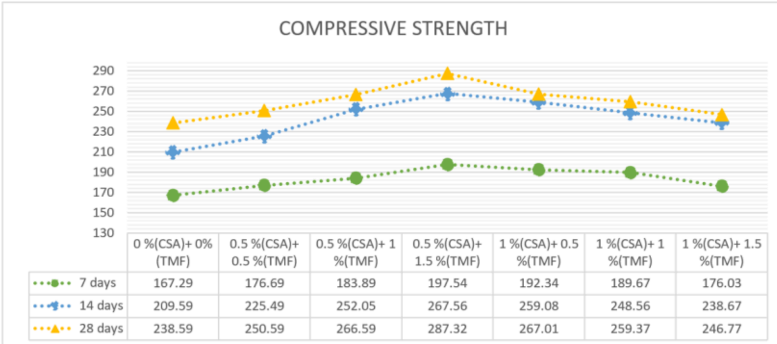


Figure 8. Compressive strength with addition of CSA and TMF

Table 9. Compressive Strength Failure Types

Dosages	Cylindrical samples	Type of failure	Description
0%CSA+0%TMF		Conical fault (partial diagonal)	The specimen exhibited inclined or diagonal cracks that propagated rapidly from the base to the top edges of the specimen. This failure reflects the fact that unreinforced concrete has a lower capacity to resist short stresses, resulting in abrupt fracture.
0.5%CSA+0.5%TMF		Crushing failure	It was the concrete disintegration at the base or contact area of the test machine. The addition of small proportions of CSA and TMF slightly increased the compressive strength, but did not significantly affect the ductility.
0.5%CSA+1%TMF		Local crush failure	In this failure, the concrete disintegrated mainly at the base of the specimen, where excessive stress concentration occurs. Increasing TMF improved the localised strength, but still allows stress concentration, which limits the homogeneity of the failure.
0.5%CSA+1.5%TMF		Shear or diagonal failure	In this failure, the specimen showed inclined or diagonal cracks due to the action of shear forces. Therefore, this dosage provided an excellent balance between strength and ductility. The high addition of TMF optimised stress distribution and delayed failure initiation.

Table 9 continued

1%CSA+0.5%TMF		Crush failure of the upper end	In this failure, the concrete disintegrated and crushed near the top of the specimen. The higher proportion of CSA without sufficient TMF caused uneven stress distribution, limiting the improvement in performance.
1%CSA+1%TMF		Failure by conification	At this failure, the specimen developed a cone-shaped material release at the top. This ratio provided more ductile behaviour, but did not exceed the performance observed at 0.5%CSA + 1.5%TMF.
1%CSA+1.5%TMF		Combined shear failure (cone and shear)	On this fault, a combination of cone-shaped detachments was observed along with inclined linear fractures indicating shear stresses, due to the increased stress concentration.

Table 10. Tensile strength results

DOSAGE	**Tensile strength (Kg/cm²)**	
	28 days	
0 %(CSA)+ 0 %(TMF)	22.08	22.29
	24.19	
	20.61	
0.5 %(CSA)+ 0.5 %(TMF)	28.11	25.54
	23.14	
	25.37	
0.5 %(CSA)+ 1 %(TMF)	29.81	28.69
	31.11	
	25.15	
0.5 %(CSA)+ 1.5 %(TMF)	34.98	32.45
	29.39	
	32.99	
1 %(CSA)+ 0.5 %(TMF)	35.11	30.07
	26.10	
	29.01	
1 %(CSA)+ 1 %(TMF)	32.59	29.08
	26.96	
	27.68	
1 %(CSA)+ 1.5 %(TMF)	28.11	25.43
	23.13	
	25.04	

3.5. Tensile Strength

Table 10 presents the tensile strength test results obtained with different dosages of CSA and TMF, highlighting the average values at 28 days of curing, calculated from three measurements per dosage. As in the compressive strength test, measurements were also taken at 7 and 14 days. Tensile strength is a key parameter, as it improves the ability of concrete to resist tensile stresses, increases its durability and reduces cracking in applications such as rigid pavements.

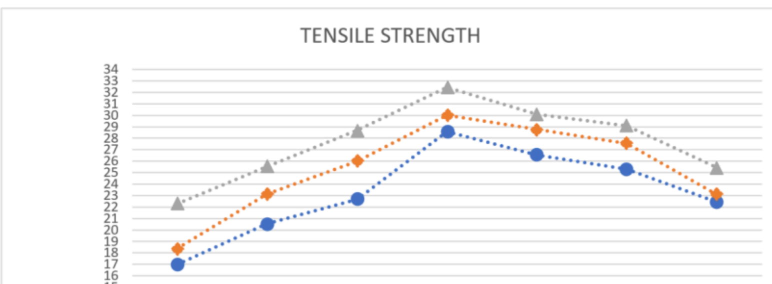
Figure 9 shows the tensile strength results of the concrete at 7, 14 and 28 days, showing a positive impact with the incorporation of coconut shell ash (CSA) and Trema micrantha fibre (TMF) admixtures. At 7 days, the initial strength without additions was 16.99 kg/cm^2, which progressively increased to reach a maximum of 28.59 kg/cm^2 with a dosage of 0.5% CSA and 1.5% TMF, representing an increase of 68.28%. At 14 days, the pattern was maintained, with an initial strength of 18.39 Kg/cm^2 and an optimum value of 30.01 Kg/cm^2 with the same dosage of 0.5% CSA and 1.5% TMF, registering an increase of 63.19%. At 28 days, without additives, the strength was 22.29 Kg/cm^2, and the maximum value of 32.45 Kg/cm^2, representing an increase of 45.58%, was also obtained with 0.5% CSA and 1.5% TMF. These results suggest that the dosage of 0.5% CSA and 1.5% TMF optimises the strength of the concrete in its early stages of curing, while further increases in CSA and TMF tend to reduce the achieved strength.

Table 11 presents the dosages of coconut shell ash, ranging from 0.5% to 1%, and of sachahuasca fibre, ranging from 0.5% to 1. 5%, accompanied by images illustrating the different types of failure observed, from diametral tensile failure to inclined fractures; especially highlighting diametral failure, which is characterised by a clean rupture along the plane, which highlights its relevance in the analysis of the tensile strength of these natural materials, providing valuable information on their behaviour under load and their potential application in sustainable engineering.

3.6. Bending Strength

Table 12 presents the results of the flexural strength test, performed exclusively at 28 days of curing, as opposed to the tensile and flexural tests. For each dosage, three measurements were obtained, and the final result corresponds to the average of these.

Figure 10 shows the results of the flexural strength of concrete at 28 days showing the impact of coconut shell ash (CSA) and Trema micrantha fibre (TMF) additions. Without additions, the initial strength was 41.39 kg/cm^2, which increased to 46.67 kg/cm^2 with an addition of 0.5% CSA and 0.5% TMF, continuing to increase to 49.86 kg/cm^2 with 0.5% CSA and 1% TMF. The maximum strength of 51.32 Kg/cm^2, equivalent to an increase of 23.99%, was reached with a dosage of 0.5% CSA and 1.5% TMF. From this ratio, the strength started to decrease with higher additions of CSA and TMF. With 1% CSA and 0.5% TMF, the strength was 48.02 kg/cm^2, while with 1% CSA and 1% TMF a reduction to 44.87 kg/cm^2 was recorded, and 42.56 kg/cm^2 with 1% CSA and 1.5% TMF. These results suggest that the optimum ratio of 0.5% CSA and 1.5% TMF maximises the 28-day flexural strength, while further increases in additives tend to reduce the strength obtained.



	0 %(CSA)+ 0% (TMF)	0.5 %(CSA)+ 0.5 %(TMF)	0.5 %(CSA)+ 1 %(TMF)	0.5 %(CSA)+ 1.5 %(TMF)	1 %(CSA)+ 0.5 %(TMF)	1 %(CSA)+ 1 %(TMF)	1 %(CSA)+ 1.5 %(TMF)
7 days	16.99	20.54	22.65	28.59	26.54	25.31	22.43
14 days	18.39	23.12	25.99	30.01	28.76	27.54	23.11
28 days	22.29	25.54	28.69	32.45	30.07	29.08	25.43

Figure 9. Tensile strength with addition of CSA and TMF

Table 11. Tensile strength failure types

Dosages	Cylindrical samples	Type of failure	Description
0%CSA+0%TMF		Diametrical tensile failure	In this failure, the concrete developed a small longitudinal fracture along the diametral plane. Without fibres, the tensile stresses are concentrated in a single plane, causing a direct and rapid fracture.
0.5%CSA+0.5%TMF		Diametrical fracture failure in the indirect tensile test	The concrete broke cleanly along the plane, generating a longitudinal crack that divided it into two halves. The combination of fibres did not significantly alter the fracture behaviour.
0.5%CSA+1%TMF		Inclined or eccentric fracture failure	In this failure, the concrete broke out of the diametral plane, showing an inclined fracture. The fibres increased ductility, but the non-uniform stress distribution caused inclined failures.
0.5%CSA+1.5%TMF		Inclined or eccentric fracture failure	In this failure, the concrete broke out of the diametral plane, showing an inclined fracture. The higher proportions of TMF reinforced the ductility, being the optimum dosage.
1%CSA+0.5%TMF		Combined fracture failure (diametral and end failure)	It is a fault with a main fracture along the diametral plane, accompanied by secondary fractures. This combination provided a balance between strength and ductility due to the unbalanced addition of CSA and TMF.
1%CSA+1%TMF		Inclined or eccentric fracture failure	The concrete broke out of the diametral plane, showing an inclined fracture. The high proportions of CSA and TMF increased the deformation capacity of the concrete, but also generated unbalanced internal stresses that caused failure in inclined planes.
1%CSA+1.5%TMF		Inclined or eccentric fracture failure	In this type of failure, the fracture occurred in a plane inclined or deviated from the diametral axis of the specimen. The higher dosage of TMF provides greater energy absorption, but introduces greater irregularities in the fracture pattern.

Table 12. Flexural strength results

DOSAGE	Flexural strength Kg/cm²	
	28 days	
0 %(CSA)+ 0 %(TMF)	47.12	41.39
	40.05	
	37.01	
0.5 %(CSA)+ 0.5 %(TMF)	52.99	46.67
	39.12	
	47.91	
0.5 %(CSA)+ 1 %(TMF)	42.91	49.86
	55.25	
	51.43	
0.5 %(CSA)+ 1.5 %(TMF)	58.32	51.32
	44.12	
	51.53	
1 %(CSA)+ 0.5 %(TMF)	56.02	48.02
	39.63	
	48.41	
1 %(CSA)+ 1 %(TMF)	43.97	44.87
	51.83	
	38.81	
1 %(CSA)+ 1.5 %(TMF)	49.87	42.56
	34.99	
	42.81	

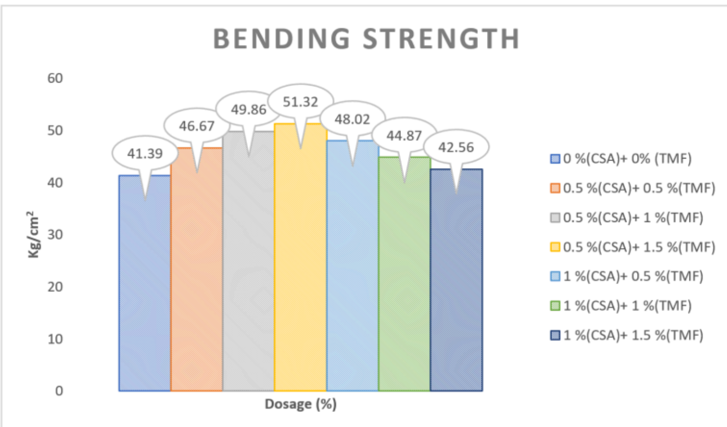


Figure 10. Flexural strength with addition of CSA and TMF

Table 13 presents the failures generated by the bending machine, where each dosage specified in Table 3 shows variations in the types of failures observed. These range from pure bending failures to eccentric diagonal cuts. Of particular note is the pure bending failure, which is characterised by a clean break in the middle of the material, this type of failure being very common in strength testing. This analysis provides a clear view of how different dosages affect the mechanical behaviour of materials under load, which is fundamental for its application in rigid pavements.

3.7. Unit Cost Analysis

According to the results obtained in the mechanical properties, it is observed that the addition of different percentages of sachahuasca fibres and coconut shell ash to the concrete improved its characteristics, especially highlighting the dose of 0.50% of coconut shell ash (CSA) and 1.5% of Trema micrantha fibre (TMF) as optimal, which demonstrates the feasibility of its application. Based on these results, a unit cost per cubic metre analysis was performed, comparing conventional concrete with modified concrete. Table 14 shows the cost of conventional concrete for the repair of rigid pavements, with a total of 506.57 soles, broken down into labour, materials and equipment. In addition, a sub-item for cleaning is included, since the repair of rigid pavements requires prior preparation of the surface, which increases the unit cost per cubic metre. It should be noted that the use of hand tools represents 3% of the total cost.

Table 15 presents the unit cost analysis for the rigid pavement repair illustrated in Figure 11. In contrast to the analysis in Table 14, the labour cost was increased due to the need for additional personnel to obtain coconut shell ash (CSA) and sachahuasca fibre (TMF). This analysis was carried out using the optimum dosage of 0.50% CSA and 1.5% TMF, considering both the cost of the inputs and the labour required for collection and preparation. It should be noted that no costs were incurred for the sachahuasca or coconut fibres, but the cost of transport (land freight) of the sachahuasca fibre was considered, given that it comes from tropical areas of the rainforest, as well as the freight of the coconut husk. The total estimated cost was 543.41 Peruvian soles, with a minimum difference of S/. 36.84 soles with respect to conventional concrete, which represents a viable investment that improves the mechanical properties of concrete for the repair of rigid pavements.

Table 13. Flexural Strength Failure Types

Dosages	Prismatic samples	Type of failure	Description
0%CSA+0%TMF		Pure bending failure	The beam broke in half along the central axis due to excessive loading which generated tensile stresses in the zone of maximum bending.
0.5%CSA+0.5%TMF		Pure bending failure	Similar to the dosage without fibres, fracture occurred along the central axis. The fibres slightly improved the load-bearing capacity before fracture.
0.5%CSA+1%TMF		Diagonal shear failure (near supports)	The beam showed a diagonal fracture near the supports due to high shear forces. The higher proportion of TMF delayed the onset of this failure.
0.5%CSA+1.5%TMF		Slight bending failure (mini cracks)	With the dosage of 0.5% CSA and 1.5% TMF, a mini-crack failure was observed. This dosage optimised the stress distribution, improving the strength and ductility of the concrete, which delayed crack propagation. The fibres contributed to crack control, preventing catastrophic fracture.

Table 13 continued

1%CSA+0.5%TMF		Eccentric bending failure	The failure occurred outside the central axis. The higher proportion of CSA did not significantly improve performance.
1%CSA+1%TMF		Diagonal shear failure (near supports)	Similar to the case of 0.5% CSA + 1% TMF, but with higher stiffness. Fibres did not achieve uniform stress distribution, limiting ductility.
1%CSA+1.5%TMF		Partial failure	With 1% CSA and 1.5% TMF, partial flexural cracking occurred, where the cracking stopped at the middle of the beam. This dosage is not optimal, as it does not adequately distribute the stresses and does not sufficiently improve the ductility, limiting the strength of the concrete. The crack indicates insufficient load carrying capacity to resist high stresses.

Table 14. Unit Cost Analysis for the Repair of Rigid Pavement

RIGID PAVEMENT					
Performance:	15		Direct unit cost m^3		506.57
Description	Unit	Cuadrilla	Quantity	U.P	P.Partial
Labour					
Officer	HH	1.00	0.53	66.45	35.44
Operator	HH	1.00	0.53	84.70	45.17
Pawn	HH	1.00	0.53	59.80	31.89
					112.51
Materials					
Crushed stone 1/2‘’-3/4‘’	m^3		0.590	53.390	31.50
Coarse sand	m^3		0.460	38.140	17.54
Water	m^3		0.185	1.500	0.28
Portland Cement Type I (42.5 kg)	UND		9.730	25.420	247.34
Accelerant	m^3		0.007	43.140	0.31
					296.97
Equipment and Tools					
Hand tools	%		0.030	112.51	3.38
Concrete Vibrator 3/4‘’-2‘’’	HM	1.00	0.53	76.27	40.68
Concrete mixer 9-11 P3	HM	1.00	0.53	6.78	3.62
					47.67
SUB ITEM					
Cleaning	m^3		1.00	49.42	49.42
					49.42

Table 15. Unit Cost Analysis for Repair of Rigid Pavement with CSA and TMF Additions

RIGID PAVEMENT					
Performance:	15		Direct unit cost m^3		543.41
Description	Unit	Cuadrilla	Quantity	U.P	P.Partial
Labour					
Officer	HH	1.00	0.53	66.45	35.44
Operator	HH	1.00	0.53	84.70	45.17
Pawn	HH	2.00	1.07	59.80	63.79
					144.40
Materials					
Crushed stone 1/2‘’-3/4‘’	m^3		0.600	53.390	31.50
Coarse sand	m^3		0.480	38.140	17.54
Water	m^3		0.185	1.500	0.28
Portland Cement Type I (42.5 kg)	UND		9.730	25.420	247.34
					296.66
Equipment and Tools					
Hand tools	%		0.030	144.40	4.33
Concrete Vibrator 3/4‘’-2‘’'	HM	1.00	0.53	76.27	40.68
Concrete mixer 9-11 P3	HM	1.00	0.53	6.78	3.62
					48.63
SUB ITEM					
Cleaning	m^3		1.00	49.42	49.42
TMF Inland Freight	Kg		6.20	0.52	3.23
CSA Inland Freight	Kg		2.07	0.52	1.08
					53.72

Figure 11. Repair of rigid pavement

3.8. Comparative Cost of Materials

The analysis in Table 16 focuses on the main materials used in the manufacture of concrete, such as cement, water, coarse aggregate, fine aggregate, natural fiber (or Trema micrantha fiber in the case of fiber concrete), and accelerant. In the case of non-fiber concrete, material costs are relatively high due to the greater amount of cement and coarse aggregate required to achieve the desired strength. On the other hand, by incorporating fiber (specifically Trema micrantha fiber and coconut shell ash), a slight reduction in the use of cement and coarse aggregate is observed, which contributes to a decrease in the total cost. Thus, the cost per cubic meter of concrete without fiber is S/ 296.69, while concrete with fiber, using the optimized dosage indicated in Table 15 (which corresponds to 0.50% CSA and 1.5% TMF, since this mixture has shown the best results in tests), and has a cost of S/ 273.00. This difference of S/ 23.68 between both types of concrete translates into an economic benefit of S/ 23.68, which represents a reduction of 7.98% in the total cost of concrete with fiber compared to conventional concrete without fiber. This saving reinforces the economic viability of incorporating natural fibers in the mix, which not only improves the mechanical properties of the concrete, but also reduces its economic impact.

Table 16. Unit costs of materials for the repair of rigid pavements without additions and with additions of CSA and TMF

Fiber-free concrete			Unit Cost	TOTAL	Fiber concrete			Unit Cost	TOTAL
Materials	Unit	Quantity			Materials	Unit	Quantity		
Cement	Bags	9.73	S/ 25.42	S/ 247.34	Cement	Bags	8.76	S/ 25.42	S/ 222.68
Water	L	0.19	S/ 1.50	S/ 0.28	Water	L	0.20	S/ 1.50	S/ 0.31
Coarse aggregate	kg	0.59	S/ 53.39	S/ 31.39	Coarse aggregate	kg	0.56	S/ 53.39	S/ 29.64
Fine aggregate	kg	0.46	S/ 38.14	S/ 17.38	Fine aggregate	kg	0.42	S/ 38.14	S/ 16.07
Natural fiber	kg	0.00	S/ 0.00	S/ -	Trema micrantha fiber (TMF)	kg	6.20	S/ 0.52	S/ 3.23
Accelerant	m^3	0.01	S/ 43.14	S/ 0.30	Coconut shell ash (CSA)	m^3	2.07	S/ 0.52	S/1.08
Total cost per m^3				S/ 296.69	Total cost per m^3				S/ 273.01

4. Discussion

This section presents articles related individually to coconut ash and sachahuasca fiber, because there are not many studies that address both fibers in the same article. It should be noted that sachahuasca fiber is a new material and, to date, there has been no research specifically applied to rigid pavement using these fibers.

In Ranatunga, Castillo and Toma's research on the use of coconut shell ash (CSA) as a supplementary material to cement, they observed a progressive decrease in concrete slump as ash was increased. With an addition of 20% CSA, the slump was reduced by 50%; by increasing the amount to 25%, the decrease reached 72.9%; and with 30% ash, the slump was reduced by 85.7%, from 140 mm in the control mix to only 20 mm [37]. These results coincided with those of our research, in which we observed a settlement reduction of 31.28% when incorporating 1% CSA and 1.5% Trema micrantha fiber (TMF).

According to authors Arunabh and Brind, in their research on the use of coconut straw ash in rigid pavements, they observed an increase in compressive strength of 10.02%, 14.63%, 18.09% and 21.56% with additions of 2.5%, 5%, 7.5% and 10% ash, respectively [38]. Similarly, Hyndman, Ahmed, Kamau and Fitriani employed coconut shell ash in rigid pavements, achieving that with an addition of 20%, a strength higher than 32.5 N will be reached, meeting the requirements of CEM II/A. -LLL [39]. We agree with these investigations, although in our case we used coconut ash and Trema micrantha fiber (TMF), which are also natural materials and which, in rigid pavements, obtained favorable results in the increase of compressive strength. In our research, we achieved a 21.67% increase in strength at 14 days with an addition of 0.5% CSA and 1.5% TMF.

According to the study conducted by Lejano, Elevado, Fandiño, Andrew, Datinguinoo and Oliveros, the use of coconut in different forms, such as ash and husk as coarse aggregate, was not beneficial in terms of tensile strength. In conventional concrete, they achieved a strength of 4.10 MPa, whereas, by incorporating these coconut fibers, the strength was reduced to 2 MPa [40]. In contrast, in our study, by using coconut ash (CSA) as a partial replacement of cement along with sachahuasca fibers (TMF), we obtained positive results. At 28 days of curing, we achieved a maximum tensile strength of 32.45 kg/cm², compared to the standard of 22.29 kg/cm², using an addition of 0.5% CSA and 1.5% TMF.

Due to the lack of research on sachahuasca fiber, a discussion will be made in relation to fibers having similar characteristics. According to the authors Beskopylny, Stel'makh, Shcherban, Mailyan, Meskhi, Shilov, Beskopylny and Chenil'nik, in their study on the addition of sisal fiber in concrete, favorable results were obtained in flexural strength, reaching a 33% increase with only a 1% addition of such fiber [41]. We agree with these findings, since by using both sachahuasca fibers and coconut ash, we achieved good results in terms of flexural strength. At 28 days of curing, we achieved a maximum strength of 51.32 kg/cm², compared to the strength of 41.39 kg/cm² without addition, using a 0.5% proportion of coconut ash (CSA).

In general, the incorporation of coconut shell ash and natural fibers has been shown to improve the properties of concrete, contributing to its increased performance and durability. These natural materials offer a sustainable and effective alternative to optimize the performance of concrete in structural applications such as rigid pavements.

5. Conclusions

The incorporation of coconut shell ash (CSA) and Trema micrantha fiber (TMF) significantly improved the mechanical properties of the concrete, being favorable for its use in rigid pavements. The optimum dosage was 0.5 % CSA and 1.5 % TMF, with maximum increases in compressive (20.42 %), tensile (68.28 %) and flexural (23.99 %) strength at 7, 14 and 28 days. Exceeding these proportions generated a decrease in strength, indicating a saturation effect that compromises the concrete structure.

In addition, the mix showed a reduction in slump and an increase in density, factors that favor compactness, reduce the penetration of external agents and improve the behavior of the concrete against early loads. Although the unit cost increased by S/ 36.84 per m³, it is compensated by a 7.98 % reduction in the total cost of materials, by reducing the use of cement and coarse aggregate, representing a saving of S/ 23.68 per m³. Overall, the use of CSA and TMF represents an efficient, economical and sustainable solution to improve the performance of rigid pavements, provided that the dosage is controlled to avoid adverse effects.

This study was conducted under laboratory conditions, which limits direct extrapolation to real scenarios. No variations in admixture quality were considered, nor were properties such as long-term durability, fire resistance or freeze-thaw cycles evaluated.

It is recommended to perform tests in field conditions, analyze the behavior of the concrete against chemical agents, abrasion, extreme temperatures and explore synergies with other admixtures or fibers. It is also pertinent to study the environmental impact of concrete with CSA and TMF, especially in relation to the reduction of CO_2 emissions.

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