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Evaluation of the Impact of Natural Fiber Incorporation into Bituminous Coating: The Case of Banana Fibers

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Abstract

This study was conducted with the aim of improving the service life of road wearing courses by incorporating banana plant fibers into bituminous mixtures. Fibers extracted from the banana trunk were characterized through tests measuring water absorption, tensile strength, Young's modulus, and elongation before being incorporated in one or two layers into the bituminous mixtures. Three types of samples (Marshall, Duriez, and Prismatic) were prepared and subjected to various tests, including compressibility index, creep, compactness, Marshall stability, as well as compressive and flexural strengths (three-point and four-point bending). The experimental results indicate that samples containing a single fiber mat layer, whether treated or untreated, exhibit lower mechanical performance compared to those containing two layers. Moreover, the incorporation of untreated fibers significantly improves Marshall stability, creep behavior, compressibility, and compressive and flexural strengths. These findings lead to the conclusion that it is possible to enhance the service life of pavement wearing courses by integrating banana plant fibers without any prior treatment.

Keywords

Sustainability, Wearing Course, Bituminous Coating, Incorporation, Vegetable Fibers

1. Introduction

Population mobility and the transport of their goods create a significant need for road infrastructure that must be sustainable over the long time. Indeed, road transport is one of the main levers of socio-economic development and sub-regional integration with 80% to 90% of traffic and has an impact of 35% on the cost price of products [1]. The issue of the service life of roadway is therefore becoming a key concern for the sector. It is accepted that the underlying structural layers of roadway can achieve the set longevity objectives. However, damage such as potholes, corrugated iron, and Upward migration of fine [2] requires early repairs which generally take place on the wearing courses. So, a question arises about the possibility of improving the durability of this layer with Eco materials. Thus, to address this concern, a study was initiated to improve the durability of the wearing course of a road. It will therefore be a question of carrying out a study which will make it possible to extend the lifespan of roads while acting on the surface layer by integrating vegetable fibers.

2. Materials and Methods

2.1. Raw Materials

2.1.1. Banana Fibers

Banana fibers are natural fibers from the false trunk of the banana tree. The false trunks are cut into small parts and then split to obtain banana stem lamella. Each lamella thus obtained is combed manually until a heap of wet fibers is obtained. Finally, the fibers are separated manually and dried in the sun (**Figure 1**).

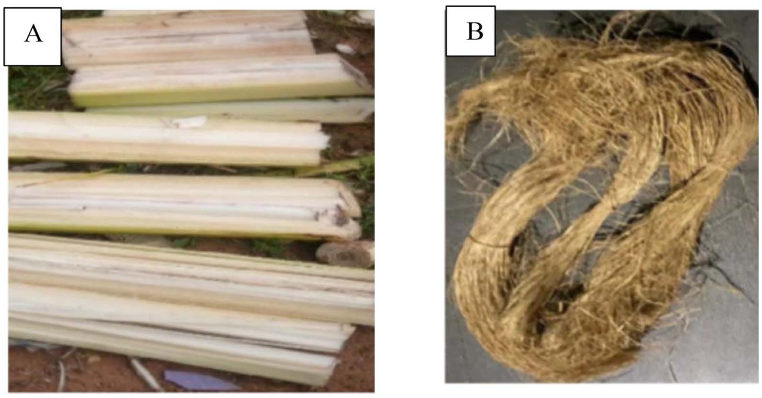

Figure 1. Fiber's extraction process: (A) banana stem lamella; (B) banana fibers maintaining the Integrity of the Specifications.

Banana fibers have been woven to take full advantage of their mechanical performance. A weaving device was created for this purpose (**Figure 2(A)**). With this device, we obtain mats of banana fibers (**Figure 2(B)**). The mats thus obtained will be used for further research work.

The fibers used for the fabrication of the mats exhibit a water absorption capacity of 280%, an elongation at break of 4.68%, a tensile strength of 64.37 MPa and Young's modulus of 1585.26 MPa.

2.1.2. Bitumen

The bitumen is used by the COLAS COTE D'IVOIRE company in ABIDJAN. The tests carried out on the bitumen gave a penetrability value of 42 and a softening point value of 50. According to the standards EN 1426 [3] and EN 1427 [4], the bitumen thus used is class 35/50.

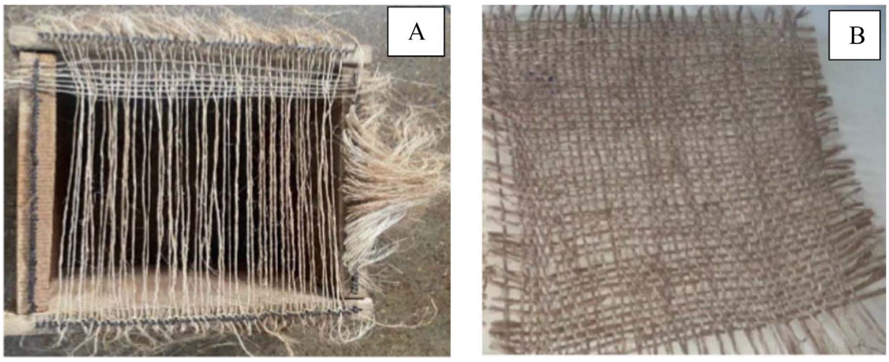

Figure 2. Weaving of banana fibers: (A) Weaving device; (B) Banana fiber mat.

2.1.3. Aggregate

The combination of different aggregate sizes must result in a granulometric curve as close as possible to the reference curve. The aggregates used for this study are crushed granite, also used by the COLAS COTE D'IVOIRE company with a granular class of 0/9. The aggregate has a spread-out granulometry and is poorly graded with a predominance of granular class 0/4.

2.2. Formulation and Preparation Method

2.2.1. Formulation

All samples used were processed at the COLAS COTE D'IVOIRE laboratory in ABIDJAN. The mats were used in one (1) or two (2) layers in bituminous coatings. Three (3) types of samples were made, namely Prismatic samples, Marshall samples and Duriez samples (Figure 3).

Figure 3. Shaping molds: (A) Marshall mold, (B) Duriez mold, (C) Prismatic specimen shaping device.

For the Marshall and Duriez samples, the fiber mats were cut into cylindrical shapes of 6 cm and 5 cm diameter, respectively. The Marshall molds have an inside diameter of 106 mm and the Duriez molds have an inside diameter of 80 mm. The fiber mats will be weighed before being incorporated into the material. Some of them will be soaked in a bitumen emulsion before being incorporated and others will be used without prior treatment (Figure 4).

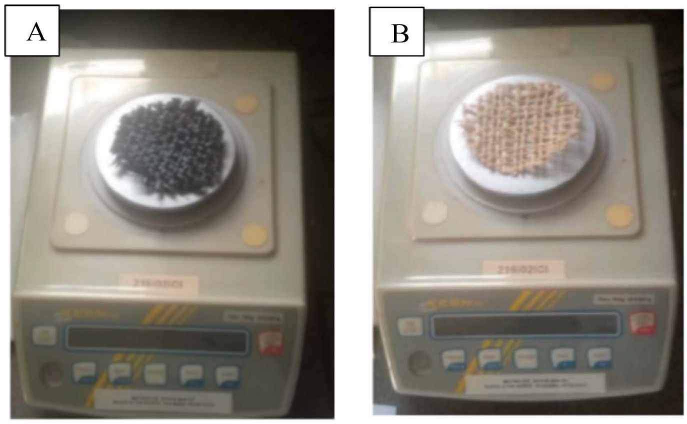

Figure 4. Weighing the mats ((A): Soaked in emulsion; (B): Untreated).

The pre-treatment of the fibers is intended to improve the adhesion between the fiber and the binder.

2.2.2. Formatting Samples

Bituminous concrete (BC) is produced in a coating plant at 180˚C. Once produced, the BB is spread on a tray in order to carry out quartering, the objective of which is to have all the representative elements of the sample in all the shots (Figure 5). Each quarter is then weighed and returned to the oven in order to raise the temperature of the BC to 160˚C.

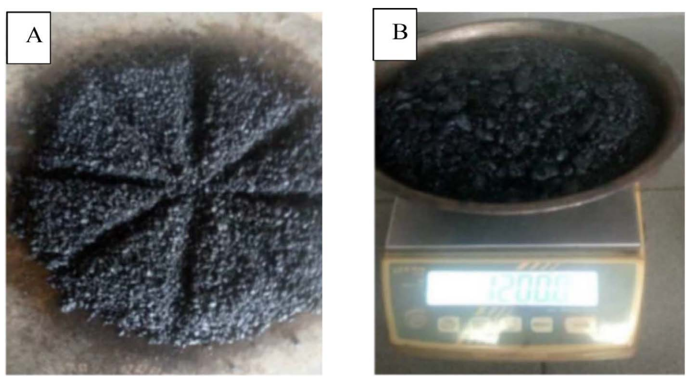

Figure 5. Sampling: ((A): Quartering; (B): Weighed).

1) Duriez sample

The samples were manufactured in accordance with the NF EN 12697-30 standard [5]. The Duriez molds are prepared in the same method as the Marshall molds.

A sample of 1000 g of BC is first taken. Then, the preparation of the fiber mats (cut into small circles of 50 mm diameter and soak some in a bitumen emulsion and others not). A precut paper is first placed at the bottom of the mold. Then, 500 g of BC (for samples with 1 layer of fibers) or 300 g (for samples with 2 layers of fibers) are poured into the mold. The fiber mat layer is then placed in the mold.

Another quantity of BC is poured into the mold. Finally, the whole thing is covered with a second paper, followed by compaction and automatic demolding.

2) Marshall sample

The samples were manufactured in accordance with the European standard: NF EN 12 697-30 [5]. The quantity of bituminous concrete required to make a Marshall sample is 1200 g. The samples are compacted manually using a Marshall hammer (4500 g) at a rate of 50 strokes per side according to standard FN EN 12697-31 [6]. The samples were made according to a specific methodology. First, a pre-cut paper is placed at the bottom of the mold. Then, 600 g (for samples with 1 layer of fibers) or 400 g (for samples with 2 layers of fibers) are poured into the mold. The fiber layer is then placed in the mold, followed by filling the mold with another quantity of BC. Finally, the whole thing is covered with a second paper, followed by manual compaction and demolding.

Following this operation, the samples (**Figure 6**) are left at room temperature to cool. Four (4) hours after sample preparation, the Marshall test is carried out because the road can be opened to traffic four (4) hours after laying the wearing course.

Figure 6. Samples for the Marshall test.

The sample elaboration methodology is summarized in **Figure 7**.

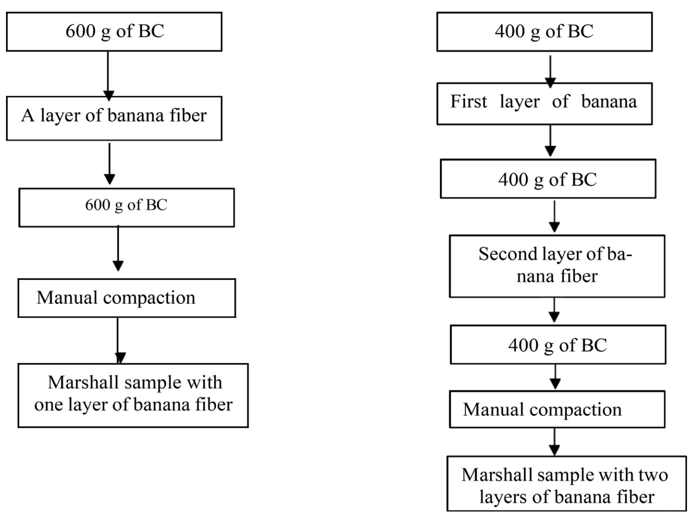

Figure 7. Illustrative diagram of the procedure for making Marshall samples.

3) Prismatic Samples

To shape Prismatic samples, a quantity of BC is poured to a height of 35 mm for samples containing one layer of fiber mat and 25 mm for those containing two layers of fibers into the device designed for this purpose.

Compaction is then carried out using the VIALIT tamper (2500 g) at a rate of 400 pass. After this first compaction phase, the banana fiber mat is placed on the compacted layer followed by another layer of BC at a height of 35 mm or 25 mm. The whole is compacted again with the same number of passes (400). Another fiber cloth is placed on the first two (2) layers of 25 mm compacted with another quantity of bituminous coating of 25 mm height, and then a third (3rd) compaction for the samples of two layers of banana fibers. The thickness of each sample after compaction is 60 mm in accordance with the regulations in force in Côte d'Ivoire, which stipulate that the bituminous wearing course is 60 mm.

2.3. Characterization of Samples

2.3.1. Duriez Test

The Duriez test is used to determine the water sensitivity of bituminous aggregates. It is carried out in accordance with the standard NF EN 12697-12 [7]. After demolding, the heights, diameters and masses of the samples are determined. After this step, the samples are separated into two batches: one batch completely immersed in water and the other exposed to the open air. After seven days, the submerged samples are removed and dried. The samples are weighed again, first in the open air and then in water. Following the weighing, the samples are placed on the Duriez device (Figure 8) to be crushed and the data thus collected are used for calculations to determine the compressibility index.

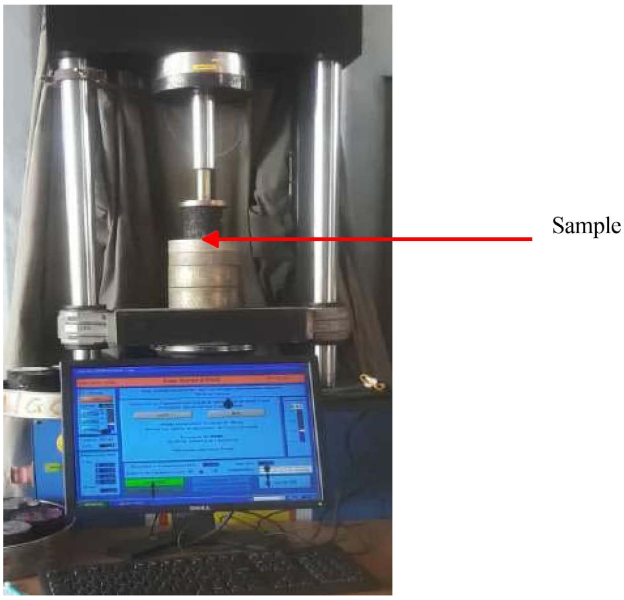

Figure 8. Duriez divice with sample to be crushed.

2.3.2. Marshall Test

The Marshall test is a mechanical test designed to determine the compactness, creep, and Marshall stability of a hot coated for given temperature and compaction energy. It is produced according to standard NF EN 12 697-34 [8]. After the various weighings and the calculation of density, the test pieces and the crushing jaw are immersed in a thermostatic bath at a temperature of 60˚C ± 1˚C for 40 min. After this operation, the specimen is subjected to the compression test. The operation is automated and the values (stability and creep) are read simultaneously. The values obtained allow to determine the different parameters. Thus, Marshall stability is the value of the maximum load at failure of the sample [9]. Creep is the value of the sample's subsidence, along a vertical diameter, at the moment of rupture (or at the moment when the maximum load is reached) [9].

Marshall compactness indicates the percentage of fullness in a bituminous coated after compaction. The percentage of compactness is determined by the ratio of the apparent density (AD) of the sample by the real density (RD). The formula for the compactness of the sample expressed as a percentage is as follows:

$$\text{Compactness} = (\text{AD}/\text{RD})*100 \tag{1}$$

The compactness value must be between 92% and 97% according to the standard NF EN 12697-34 [8] [10].

2.3.3. Compressive Test (Prismatic Samples)

The compressive test is a mechanical and destructive test performed on samples to determine the compressive strength (Cs). The compressive strength is the ratio of the applied force to the surface area(section) of the half-prism (formula 2).

$$\text{Cs} = \text{F}/(\text{b} \times \text{d}) \tag{2}$$

With:

Cs (MPa): Compressive strength.

F (N): Load applied to the sample surface b (mm): Sample width.

d (mm): Sample thickness.

2.3.4. Three-Point and Four-Point Bending Tests

Three-point and four-point bending tests are mechanical tests performed to determine ultimate strength (σ) and ultimate strain (ε). The test was conducted in accordance with Afnor standard NF B51-008 [11].

The breaking strength is calculated using the following formulas (3 and 4):

$$\text{Three-point bending } \sigma = (3*F*d)/(2*b*h^2) \tag{3}$$

and

$$\text{four-point bending } \sigma = (3*F*(L-d))/(2*b*h^2) \tag{4}$$

With:

σ: Bending strength (MPa).

F: Bending load (N).

h: Height of the specimen (mm).

L: Length of the stressed sample (mm).

b: Width of the sample (mm).

d: Distance between supports (mm).

2.3.5. Permeability Test

Permeability is a fundamental parameter that determines the durability of materials. Previously cut tubes are glued to the samples using strong glue. A sheet of graph paper is then glued to each tube using transparent tape. A quantity of water (h_0) taken with a syringe is then injected into the tubes. Once this quantity of water has been injected, the time taken for the liquid to infiltrate the sample is recorded using a stopwatch (Figure 9).

Figure 9. Permeability test device.

At the end of the test, the permeability is determined using Darcy's formula (5) [12]:

$$K = \frac{S \cdot L \cdot Ln\left(\frac{h_0}{h_t}\right)}{S \cdot (t_1 - t_0)} \quad (5)$$

With:

K: Permeability coefficient (m·s^{-1}); S: Tube section (m^2).

L: Sample height (m).

S: Sample surface area in contact with water(m^2); h_0: Head difference at time t_0.

h_t: Head difference at time tt.

t_0: Time taken to read the waer height in the tube.

t_1: Time taken to read the head difference in the tube.

3. Results and Discussions

3.1. Influence of Banana Fibers on the Duriez Test

Figure 10 summarizes the compressibility index obtained from the Duriez test.

The histograms show that most of the samples containing banana fiber layers have higher compressibility values than the control sample. According to the standard, the compressibility index must be greater than 0.75, or 75% [13]. It can therefore be concluded that the fibers have significantly improved the compressibility of the bituminous coating. Indeed, the samples containing one or two layers of fibers, whether treated or not, have compressibility values ranging between 78% and 100.64%. It is also observed that the compressibility of the samples decreases when moving from one to two layers of fibers (treated or untreated). This decrease is likely due to the amount of water absorbed by the fibers during storage,

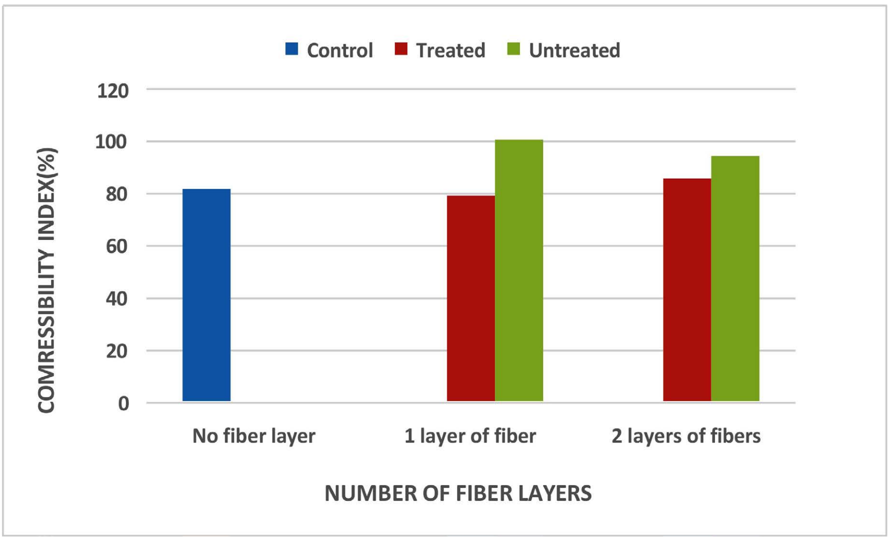

Figure 10. Variation of the compressibility index as a function of the number of fiber layer.

a phenomenon that promotes debonding between the aggregates and the binder. The value (100.64%) can be explained by the fact that when there are fewer plant fibers in the materials, there is less water absorption, leading to less stripping between the particles and the binder, thus resulting in higher compressibility. These results are consistent with those of [10]. The compressibility index values of the samples with two fiber layers and those with one untreated fiber layer are all higher than that of [14], which is 0.76% or 76%.

3.2. Influence of Banana Fibers on Marshall Properties

The results obtained allowed study of the Marshall parameters.

3.2.1. Creep

The creep results from the Marshall test are presented as a histogram in Figure 11.

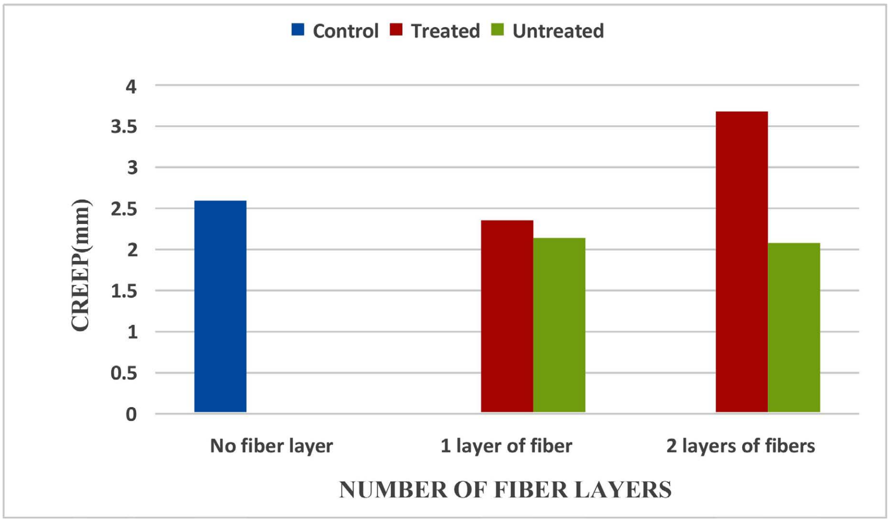

Figure 11. Creep variation as a function of the number of fiber layers.

The samples tested all gave results between 2 and 4 mm. It is noted that the samples containing plant fibers treated with a bitumen emulsion before use have higher creep rates than those containing untreated fibers. The control samples (not containing fibers) have a higher value (2.8 mm) than those containing a layer of fiber, whether the fibers are treated or not. However, the samples containing two layers of treated fibers have higher values (4 mm) than all other types of samples. Fibers treated with bitumen emulsion increase the amount of bitumen in the material.

Thus, bitumen, being a viscoplastic material, an increase in temperature then causes the bituminous coating to behave like a viscoelastic solid [10] [15]. This causes an increase in creep. According to the European standard NF EN 12 697-34 [8], a sample has good creep when its value is between 2 and 4 mm. But it is advisable to have a value closer to 2. Thus, the good creep is obtained with the value 2.08 mm obtained on the samples containing two layers of untreated fibers. This value is lower than those reported by [16] and [17], which are respectively 3.616 mm and 4 mm in their studies on the incorporation of natural fibers into bituminous coatings. Therefore, appropriate to say that the incorporation of banana fibers without treatment with a bitumen emulsion and in two layers considerably improves the creep value of the Marshall samples. This improvement is due to the fibers, which absorb part of the bitumen, thereby reducing the deformation of the sample.

3.2.2. Compactness

Figure 12 summarizes the compactness results from the Marshall test.

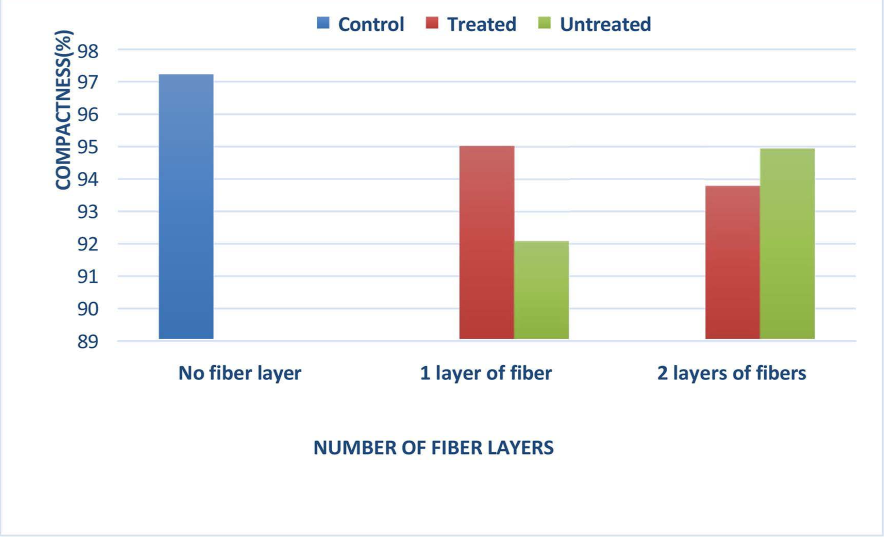

Figure 12. Variation of compactness as a function of the number of fiber layers.

The histograms show that the samples containing fibers treated with a bitumen emulsion have higher compactness than those with untreated fibers. However, the compactness of the control samples (97%) is significantly higher than that of the samples containing either treated or untreated fibers. It is also noted that the compactness of the samples containing fibers ranges between 92% and 97%, which complies with the NF EN 12697-34 standard [8] and the SETRA-LCPC guidelines [18], both of which specify a compactness requirement between 92% and 96% for bituminous coated. The reduction in compactness observed in the fiber-containing samples, compared to the control samples, is attributed to the presence of fibers within the sample. Indeed, the load applied to the surface layer during compaction is partially transmitted to the underlying layer containing the fibers, thereby reducing the compaction. These results are lower than those of [19], which is 96.5%. This variation is due to the presence of fiber mats that are sandwiched within the samples. However, the control value is consistent with that of [16].

3.2.3. Marshall Stability

Figure 13 shows the Marshall stability results.

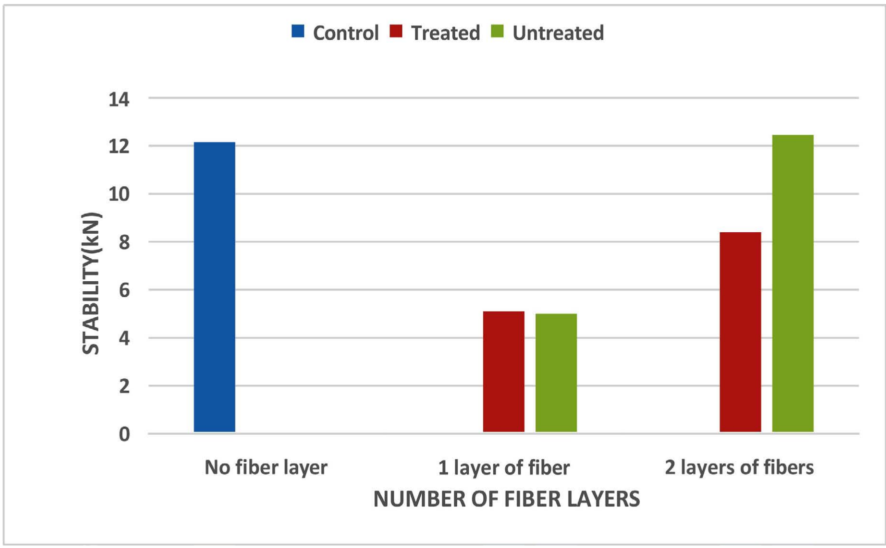

Figure 13. Variation of Marshall stability as a function of the number of layers.

The samples containing a fiber layer (treated or untreated) have results below the minimum value (10 kN) set by the NF EN 12 696-34. Moreover, the stability value (12.45 kN) of the samples containing two layers of untreated fibers is higher than that of the samples containing two layers of treated fibers (8.4 kN). We also observe that the stability of the samples with two layers of untreated fibers (12.45 KN) is higher than that of the control samples (12.15 KN). Indeed, the fibers incorporated into the samples create a zone where load transmission is inhibited within them. These areas will allow the sample to better withstand loads before breaking. It should be noted that samples containing two layers of untreated banana fibers delay the failure of the bituminous coated because the fibers prevent the propagation of cracks. The stability of the samples with two layers of untreated fibers is higher than that obtained by [10], which is approximately 11 kN when polymer was incorporated into the bitumen and by [20], obtained a strength of 11 kN by using palm oil fibers in asphalt mixture. However, the value of 12.45 kN remains lower than those obtained by [19], which is 21.63 kN, and by [14], which is 18.23 kN. Indeed, the incorporated fiber mats constitute areas where cracks propagate with difficulty because the fibers have high tensile strength (64.3 MPa) and Young's modulus (1585.26 MPa). These areas allow the sample to better resist loads before breaking.

It should therefore be noted that samples containing two layers of untreated banana fibers delay the failure of the bituminous coating, as the fibers prevent the propagation of cracks. For the next steps of the work, the samples will be made using untreated fibers.

3.3. Compressive Strength

The results from the compression test are shown in **Figure 14**. The fibers used for this test were not treated with a bitumen emulsion.

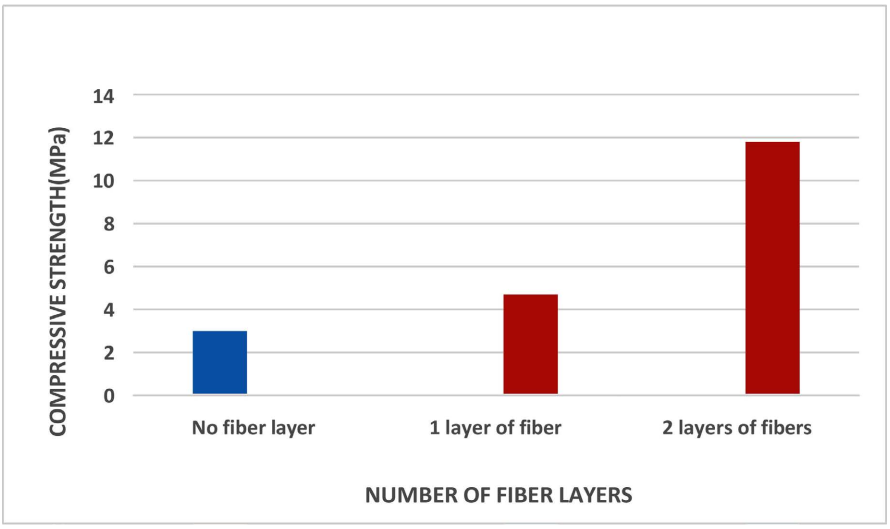

Figure 14. Variation of compressive strength as a function of the number of fiber layers.

The compressive test results on Prismatic specimens show a progressive increase in strength (from 3 to 11.80 MPa) with the increasing number of fiber layers. This increase is due to the presence of fibers, which absorb part of the stress before transmitting it to the underlying layers. Thus, the fiber mats redistribute the stress among themselves [21] [22]. This redistribution helps to increase the compressive strength of the samples according to the number of fiber layers.

3.4. Three and Four-Point Bending Strength

Figure 15 shows the results of the 3-point and 4-point tests conducted on the Prismatic samples containing only untreated fibers.

The results show an increase in strength with the number of fiber layers in both 3-point and 4-point bending. The three-point bending strength values range from

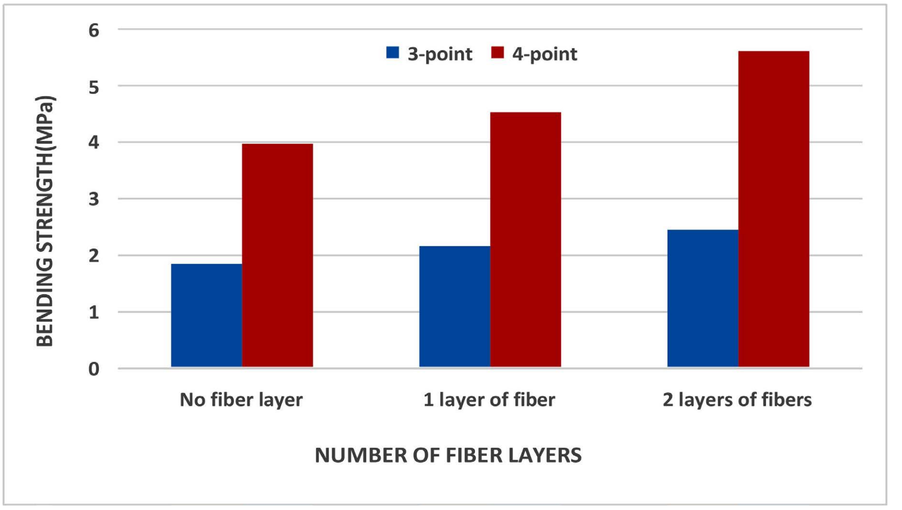

Figure 15. Variation of bending strength as a function of the number of fiber layers.

1.85 MPa for the control samples to 2.17 MPa for one fiber layer, and then to 2.45 MPa for two layers. These values reflect the predominant role that the fibers play in slowing down crack propagation. As for the four-point bending, the values range from 3.97 MPa for the control samples to 4.45 MPa for one layer, and then to 5.61 MPa for two layers of fibers. The progression of these results demonstrates not only the good cohesion between the particles in the samples but also the role of the fibers in delaying crack propagation [21]. These results are consistent with those obtained by some authors [23]-[27], who demonstrated that it is possible to improve the bending strength of composites incorporating plant fibers at a certain proportion However, the bending results obtained in this study are lower than those of some authors [28], which range from 36.26 MPa for 5% fiber content to 39.66 MPa for 20% fiber content in the material. This difference in values is due to the higher fiber proportion, as well as the treatments undergone by the fibers prior to their use in the material.

3.5. Permeability

Permeability was measured using the variable head permeameter method on Prismatic samples (**Figure 16**).

We observe an increase in the permeability coefficient with the number of fiber layers. This increase is due to the number of mat layers present in the bituminous coating. Indeed, the greater the number of mat layers, the more the mixture will absorb water because the fibers are hydrophilic. A sample containing one layer will be less permeable than one containing two. Similarly, since bitumen is an impermeable binder, a significant amount of it leads to a decrease in the water permeability of the material. These results are consistent with those of some authors [29]-[33].

These researchers found in their studies that it is possible to reduce the permeability of materials by increasing the quantity of the impermeable binder within them.

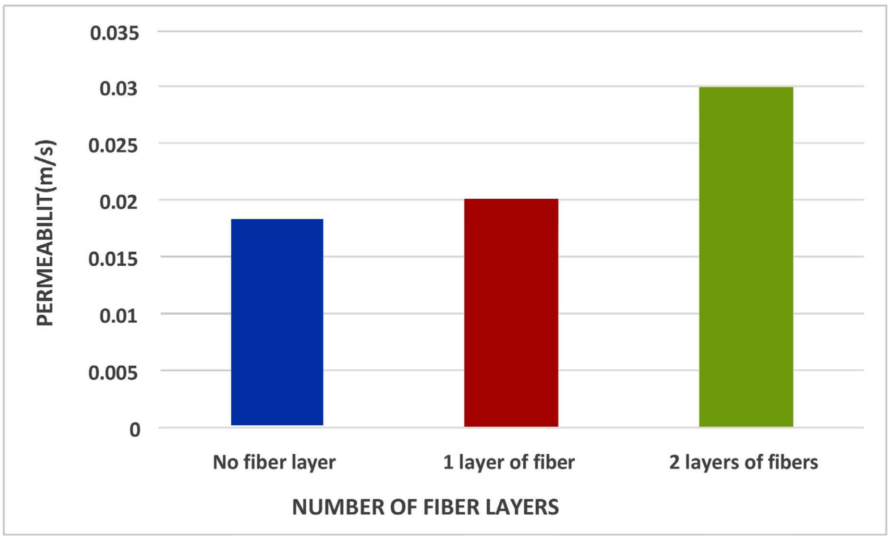

Figure 16. Variation of permeability as a function of the number of fiber layers.

In this study, it would therefore be essential to impregnate the banana fibers more thoroughly with bitumen. This would reduce the contact between water and the fibers, thereby decreasing water absorption.

4. Conclusions

With the aim of extending the service life of the wearing course, this study was conducted by incorporating plant fibers (treated or untreated banana fibers). The samples obtained subsequently underwent various characterization tests. The results obtained led to the following conclusions:

- The resulting samples subsequently underwent various characterization tests. The results obtained allowed the following conclusions to be drawn: The Marshall test revealed a decrease in creep (from 3.33 to 2.08 mm), an increase in stability (from 12.15 to 12.45 kN), and a slightly lower compaction (from 97% to 95%) compared to the control sample. These improvements are more significant with samples containing two layers of untreated fiber mats;
- The Duriez test showed a higher compressibility index (from 94.33% to 100.64%) in samples with two layers of fibers inside and without prior treatment than in the control sample;
- In compression, the samples containing two layers of mats reached 11.82 MPa, compared to 3.05 MPa for the control;
- The 3-point and 4-point bending strengths are higher than those of the controls;
- Additionally, plant fibers, which have a good affinity for water, when incorporated into bituminous mix, promote high permeability (3×10^{-2} m/s) of the latter to water.

The overall results of all the tests conducted revealed that plant fibers (banana fibers) incorporated in two layers and without prior treatment improve the mechanical performance of the road's wearing course.

Acknowledgements

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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