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Analysis of Flexural Strength in Asphalt Concrete Specimens Using a Net-Shaped Inclusion of Waste Coffee Capsules

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Abstract: Asphalt mixtures can include various recycled materials, which often replace some of the coarse and fine aggregate components. In some cases, a percentage of material called mineral filler, made up of particles that pass through a No. 200-sieve, is also admitted in the preparation of the mixture. With the increasing amount of packaging used as containers for various products, many of which need to be disposed of properly and become an environmental burden in warehouses without proper reuse, there is potential for including these elements in the sustainable modification of asphalt mixtures. This research suggests reusing plastic and aluminum coffee capsules, which are difficult to recycle. While most studies crush recycled materials to sizes smaller than 0.075 mm for use in mixes, this research focuses on assembling the waste capsules into a network of cells inside specimens subjected to bending to observe the mechanical behavior of the asphalt mixture. The findings indicate that incorporating capsule networks can lead to a significant enhancement in the flexural strength of the examined beams, with an increase of up to 200%. Moreover, the deformation is reduced by an average of 66% upon the emergence of the initial crack in the specimen.

Keywords: coffee capsules; asphalt mixtures; flexural modified test

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1. Introduction

Worldwide concern for the environment has made the study of the mechanical and hydraulic performance of asphalt mixes made from recycled materials a virtual necessity. This preoccupation is due to the overexploitation of virgin resources and the pollution caused by waste that is neither properly managed nor recycled for new use.

The incorporation of foreign materials into asphalt mixes aims to enhance specific properties typically associated with mechanical performance, e.g., reducing permanent deformation and improving fatigue resistance. However, additives or modifications can also enhance aspects such as durability, drainage, and aggregate–bitumen adhesion.

Plastics, widely utilized due to their cost-effectiveness, lightness, durability, and performance, have become an integral part of various applications [1–3]. Nevertheless, concerns have arisen regarding the excessive utilization of single-use plastics, which are projected to represent approximately 50% of global plastic production by 2022 [4], with only a quarter dedicated to durable plastics such as pipes, coatings, and structural applications [1].

In the realm of asphalt modification, polymers have shown potential for improving durability, particularly in terms of high-temperature stability [5], stiffness [6,7], fatigue resistance [8,9], and viscosity [10]. This modulating effect extends to compatibility and low-temperature bending. It is noteworthy that many studies emphasize the environmental benefits of these advancements, particularly in mitigating potential contamination [11–13].

The issue surrounding coffee capsules lies in the proper disposal and recycling process required by consumers. Research indicates that a substantial portion of coffee pod consumers in Spain dispose of them in regular trash, unaware that this leads to their ultimate destination in sanitary landfills, thereby imposing significant negative impacts on the environment. Moreover, the current regulations do not categorize these capsules as containers and therefore, do not indicate that they should not be discarded in the yellow container. Even attempting to separate the aluminum and organic components for disposal remains ineffective due to organic residue persisting within the capsules.

Another significant challenge in regards to coffee capsules is their composition, as they contain a small amount of aluminum along with plastic, which hinders their recyclability. This characteristic complicates the separation process, thereby leading to less efficient disposal methods, such as incineration or landfill deposition, as their ultimate fate [14,15].

Regarding environmental impact, Refs. [16,17] have conducted a comparative study of coffee capsules employing different packaging materials, including plastic, aluminum, and biodegradable options. Their findings underscore the substantial environmental impact of both plastic and aluminum production, primarily driven by the energy-intensive nature of the production and usage phases. Similarly, Marinello et al. (2021) [18] also explored the environmental impact of these capsules and highlighted the significant role of energy consumption in contributing to environmental harm, echoing the sentiments of other researchers. Their study emphasizes the urgent need to discover alternatives enabling the separation of all capsule components to enhance recyclability.

The current state of research regarding the incorporation of plastics in asphalt mixtures clearly demonstrates that plastics are commonly utilized in pulverized form or as strips to modify the mixtures themselves or the asphalt cement. However, the use of waste plastic material in reticulated form, capitalizing on the shape of the capsules, has not been explored. The initial phase of the study was proposed to assess the flexural strength of asphalt mixtures. Subsequent stages will evaluate additional tests, including dynamic modulus, fatigue, phase angle, and CBR.

The thesis presented in this study is based on using plastic coffee capsules embedded in prismatic samples of asphalt mix in a cell-like network to enhance the material's flexural strength. The study utilized a hot dense mix (MDC_19), with aggregates and bitumen from local sources that were characterized according to INVIAS standards. When applying the flexural load, the specimens were supported with a free spacing at least three times their height, with a 2% tolerance.

Background

Recently, there has been growing concern in the field of plastics recycling regarding the discovery of a new type of sedimentary rock. This rock comprises a natural parent rock fused with plastic components, and is being referred to by some scientists as "plastistones". Defined by Santos et al. (2022) [19] as rocks with plastic residues exhibiting a smooth texture and shiny appearance typical of molten plastic, plastistones are characterized by a homogeneous plastic material with a wide range of porosity, along with the presence of vesicles, flow structures, molten plastic mass, and in some cases, intercalations of lithic fragments (Figure 1).

These rocks are formed from plastic debris that has entered the environment, thus becoming part of the geological cycle of rocks and transported by environmental agents such as water and wind [20–24]. The majority of these rocks originate from microplastics that have weathered over time, resulting in residues of polyethylene (PE), polypropylene (PP), polyethylene terephthalate (PET), and polyvinyl chloride (PVC) [25–27] (Ward and Reddy, 2020; Stubbins et al., 2021; Fei et al., 2022).

Figure 1. Debris plastic melted into a natural rock.

In the domain of hot asphalt mix applications, plastic is widely employed as a modifying agent. This versatile material can exist in various forms and with several origins, impacting its incorporation into the mix. It has been observed in the form of pellets, flakes, microparticles, shreds, fibers, and even powder (refer to Figure 2 for a visual representation).

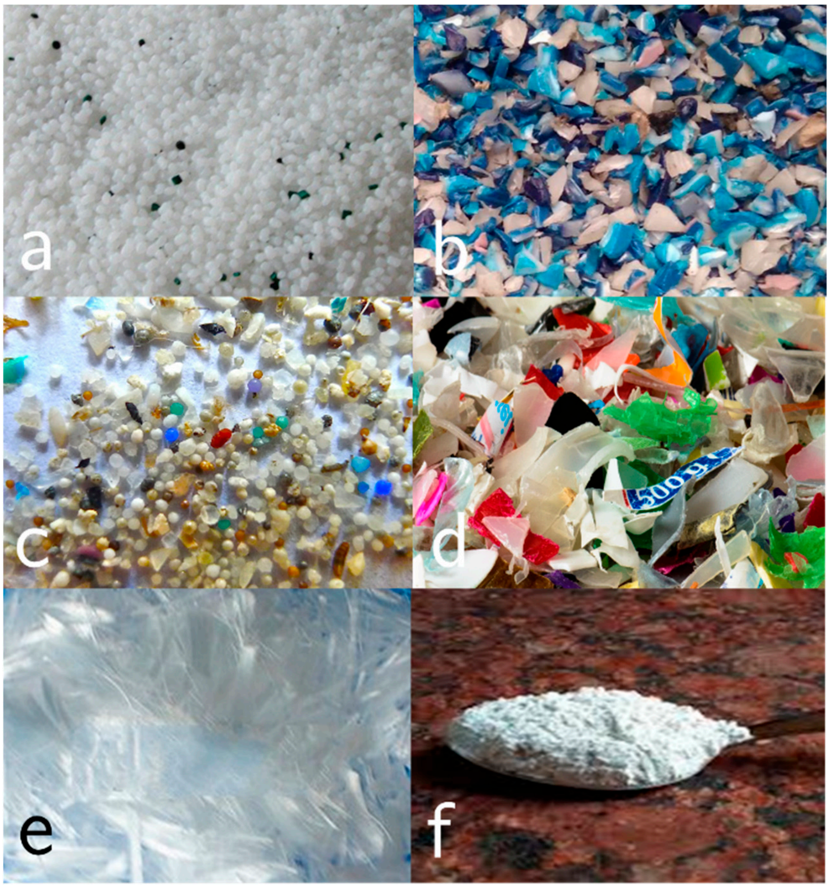

Figure 2. Waste plastics: (**a**). pellets; (**b**). shreds; (**c**). microplastic; (**d**). flakes; (**e**). fibers; (**f**). powder.

Pellets, for instance, are industrially processed small plastic spheres, with a maximum size of 0.5 mm, designed to be directly integrated into the material being modified, such as asphalt or asphalt mix (refer to Figure 2a) [28–32]. Conversely, flakes are typically derived from cuttings, e.g., from PET bottles and other containers, and are reduced to small square pieces (Figure 2b) [33,34].

In the context of microplastics, these are exceedingly small particles, measuring less than 5 mm, which may be inhaled by living organisms. In certain cases, they are artificially created through the abrasion of tires or other plastic components intended for use in hot asphalt mixes [35–38] (Lv et al., 2021; Campanale et al., 2020; Enfirn et al., 2022; Boom et al., 2023).

Shreddings, obtained through cutting, typically with scissors in a laboratory setting, can assume a slenderer form compared to that of flakes, often appearing as strips [39,40]. Notably, the use of nylon strips from army camouflage in other geomaterial applications has exhibited potential implications for their utilization in asphalt mixtures (Castilla, 2023) [41] (*vide* Figure 2d).

The application of plastic fibers in the asphalt mix serves two primary functions: as an asphalt stabilizer, mitigating the drain-down effect, and as a reinforcing additive, enhancing mechanical performance [42–47] (Tpakin, 2008; Slebi et al., 2020, Slebi et al., 2022; Guo et al., 2023; Jia et al., 2023, Alnadish et al., 2023). Furthermore, when plastic is crushed and reduced to sizes smaller than 0.075 mm, it is commonly utilized as a filler in the asphalt mix [48,49].

Refs. [50,51] provide a broader background that can furnish more details on the state-of-the-art practices in the use of plastics in asphalt mixtures and asphalt binders, particularly regarding human health, end-of-life options, legislation, and policies/concepts.

The following points underscore the rationale for utilizing coffee capsules of this kind, notwithstanding the fact that the capsules are not produced in a manner that involves cutting them into flakes, shreds, fibers, or crushing them into powder. This alternative is appealing due to its lack of need for any prior processing before employing it as a reinforcement, particularly in the case of an asphaltic concrete beam. This assertion implies that, despite being an additive, it does not undergo chemical interaction with the asphalt or the hot asphalt mix. Its usage is intended for reinforcement in the lower third, where the fibers of the specimen exhibit trajectories subjected to tension. Further elaboration on this topic will be provided subsequently.

In the process of this investigation, antecedents dating back to 1980 have been identified. For example, the utilization of plastic geogrids for reinforcing geomaterials such as pavements or soils has been documented. Komatsu et al. (1998) [52] conducted a study involving the implementation of geogrids composed of polyoxymethylene fibers, a thermoplastic material known for its high strength, toughness, and modulus stiffness. The experiments demonstrated improvements in durability, viscosity, and crack resistance when compared to the results for the control specimens that did not incorporate geogrids. The findings indicated an overall increase in stiffness in the specimens as a result of the application of geogrids.

Other studies have examined the impact of plastic geogrids on the durability of asphalt pavements, as well as the effect of initial strain and geogrid placement within the pavement layer to enhance resistance to fatigue caused by dynamic loading. A significant finding from this research is that according to Widodo et al. (2013) [53], placing a geogrid at 2/5 of the pavement layer thickness yields a better response compared to that obtained by placing the geogrid at the center of the layer.

The results of the research by Chazallon et al. (2021) [54] also concur with those from the majority of studies stating that the presence of a plastic geogrid significantly affects tensile strength and modulus of elasticity. Additionally, they discovered that despite potential damage during compaction, the geogrid's residual strength can still uphold the fatigue limit of asphalt concrete.

Numerous studies have investigated various waste products and their potential to improve the characteristics of asphalt mixtures, although these studies are not directly related to the specific focus of our investigation. For instance, research on reclaimed asphalt pavement (RAP) has demonstrated that the use of recycled mixtures does not significantly differ in regards to properties compared to those of conventional hot mix asphalt (HMA) [55,56]. Furthermore, polymer additions, particularly involving linear low-density polyethylene (LLDPE), low-density polyethylene (LDPE), and high-density polyethylene (HDPE), have gained popularity for enhancing asphalt cement performance in recent decades [57–59]. Additionally, the application of substances of biological or chemical origin, such as vegetable oils, volcanic ashes, rice husk ashes, waste soils (expansives), and blast furnace slag, has shown potential to improve the properties of asphalt mixtures or cement [60–66].

2. Materials and Methods

A total of 72 samples of asphalt mixes containing 3 cm and 4.5 cm diameter coffee capsules were prepared using a constant compaction of 75 blows. A factorial experiment was carried out in which one factor, the asphalt content, was varied by 0.5% for each mix, with the same particle-size distribution range. This was performed in order to discover the working methodology for the test, followed by the compaction procedure, and ultimately, the results for the analysis of the flexural strength were obtained.

The test molds are prepared in such a way as to ensure a constant percentage of bitumen. This bitumen percentage is defined by the previous testing of the aggregates in the mix. The laboratory tests provide a starting point for determining the final mix's working formula or optimum bitumen content, using a variable asphalt content of 5% and 5.5%. Similarly, the proportions of the mixes are formulated from the results of the granulometric analysis. MDC-19 was chosen as the hot asphalt mix because it has a finer particle size, and its aggregates can more easily penetrate the capsules.

2.1. Material Characterization

Table 1 shows the index characterization studies performed on the natural aggregate. In some cases, the local INVIAS standard was used; in other cases, the AASHTO and ASTM standards were employed.

Table 1. Index characterization of the natural aggregate.

Test	Standard	Value
Specific Gravity/Absorption (3/4″)	AASHTO T 85 [67]	2.52/1.67%
Specific Gravity/Absorption (3/8″)	AASHTO T 85 [67]	2.50/1.71%
Specific Gravity/Absorption (#4)	AASHTO T 85 [67]	
Specific Gravity/Absorption (#40)	AASHTO T 84 [68]	
Specific Gravity/Absorption (#80)	AASHTO T 84 [68]	
Specific Gravity/Absorption (#200)	AASHTO T 84 [68]	
Specific Gravity/Absorption of fines	AASHTO T 84 [68]	2.51/1.51%
Los Angeles Machine Abrasion, 500 revs.	AASHTO T 96 [69]	24.7%
Micro-Deval	AASHTO T327-05 [70]	22.4%
10% fines (dry strength)	DNER-ME 096-98 [71]	116 kN
Fractured particles, 1 face	ASTM D 5821-01 [72]	88%
Fractured particles, 2 faces	ASTM D 5821-01 [72]	81%
Plasticity index (IP)	ASTM D 4318-00 [73]	NP
Flattening index	NLT 354-91 [74]	9.6%
Elongation index	NLT 354-91 [74]	9.6%
Sand equivalent	AASHTO T 176–02 [75]	76%

The presence of larger grain sizes, such as 3/4″ and 3/8″, is correlated with an increase in absorption, as the specific gravity experiences a slight decrease. This phenomenon can be attributed to the differences in specific surface area between smaller and larger aggregates. As a result, smaller aggregates exhibit a greater overall specific surface area, thereby promoting easier adhesion of asphalt cement due to the increased available area. Moreover, the material demonstrates abrasion resistance that aligns with acceptable standards, as evidenced in AASHTO T 96 [69]. The recommended value, in accordance with the regulation, is 25% abrasion in the Los Angeles machine. Notably, there is no evidence of clay minerals or organic matter that may compromise the adhesion between the aggregate, asphalt cement, and, ultimately, the coffee pods.

Figure 3 shows the particle size distribution of virgin aggregate in the asphalt cement contents corresponding to 5 and 5.5%. It is of utmost importance to mention that although the percentage passing is the same for both samples, what is relevant is the calculation of the volumes in the asphalt, aggregates, and voids of the test specimens, since these may vary, depending on the asphalt content. It is essential to highlight that, although the coffee capsules occupy a volume in the specimen, this was calculated and occupies approximately 1% of the total volume. This value was disregarded for the estimations.

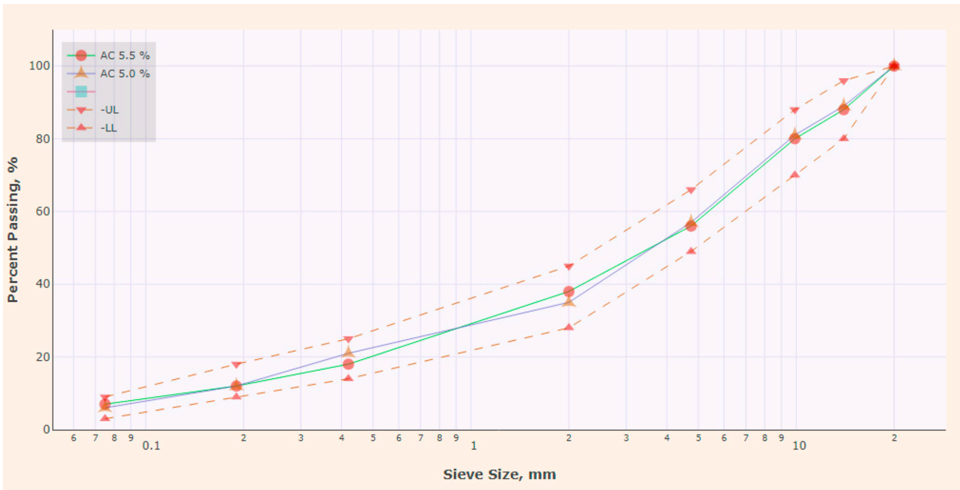

Figure 3. Particle size distribution of samples with AC 5.0 y 5.5% vs particle size range, according to INV-E-123 (2013) [76].

Likewise, the CA 60-70 asphalt cement was characterized. Table 2 shows the bitumen results that will function as an asphalt binder between aggregates. The optimum asphalt content was obtained by compacting ten Marshall samples with 75 blows per face, increasing the asphalt percentages from 4.5% to 6.0%. For mixing temperatures and subsequent compaction, the procedure outlined in ASTM D6925 [77] was followed, which adopts hot dense mix temperatures of 85 ± 15 SSF (170 cP) and 140 ± 15 SSF (280 cP).

Table 2. AC 60-70 Characterization.

Test	Standard	Unit	Material
Original AC			
Penetration (25 °C-100 g-5 s)	ASTM D-5 [78]	0.1 mm	62.5
Penetration index	NLT 181/88 [79]	-	−0.7
Softening point	ASTM D36-95 [80]	°C	52.5
Absolute viscosity (60 °C)	ASTM D4402 [81]	Poises	1750
Specific gravity	AASHTO T 228-04 [82]	-	1.012
Viscosity 135 °C	AASHTO T-316 [83]	Pa-s	0.36
Ductility (25 °C, 5cm/min)	ASTM D-113 [84]	cm	>105
After RTFOT			
Loss of mass	ASTM D-2872 [85]	%	0.47
Penetration (25 °C-100 g-5 s)% original	ASTM D-5 [78]	%	72
Increased softening point	ASTM D36-95 [81]	°C	5

2.2. Sample Preparation

Once the characterization of the different materials was explicit, we proceeded to prepare the samples. Since the beams will include a component not part of an ordinary asphalt mixture, this component must be carefully inserted into the sample. The coffee capsules are manually placed in the form of a net, and the capsules must be adhered to each other with silicone to ensure several points of contact between each capsule and to confirm that they can function as a joint fabric (Figures 4 and 5). It is important to mention that there is no bonding by an external agent between the cross-linked capsule layer and the asphalt mixture. The beams used two types of configurations; the first option included 52 coffee capsules, 3 cm in diameter, and the second employed 14 coffee capsules, 4.5 cm in diameter, from which the lid and the organic material (coffee) were previously removed. This procedure is imperative to ensure the penetration of the asphalt mixture into each element to avoid fewer voids in the sample.

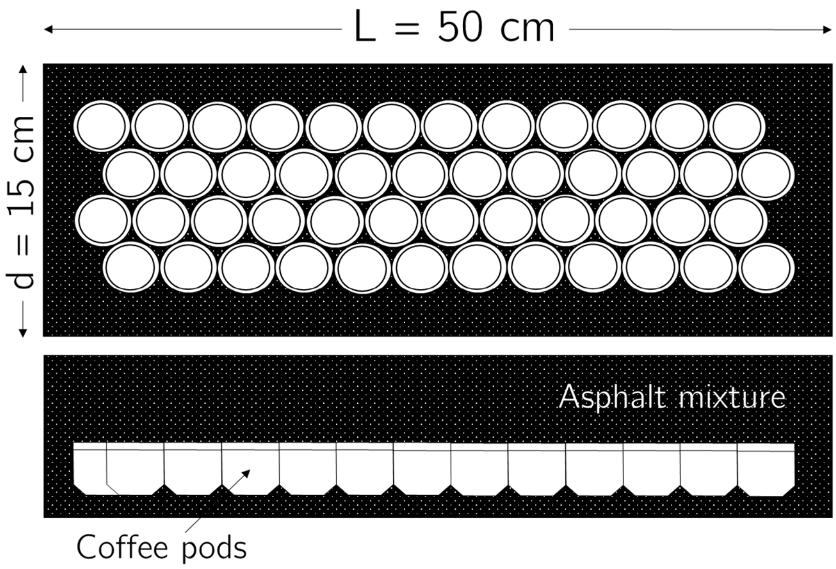

Figure 4. Configuration of 3 cm diameter coffee capsules embedded in the hot asphalt mix beam.

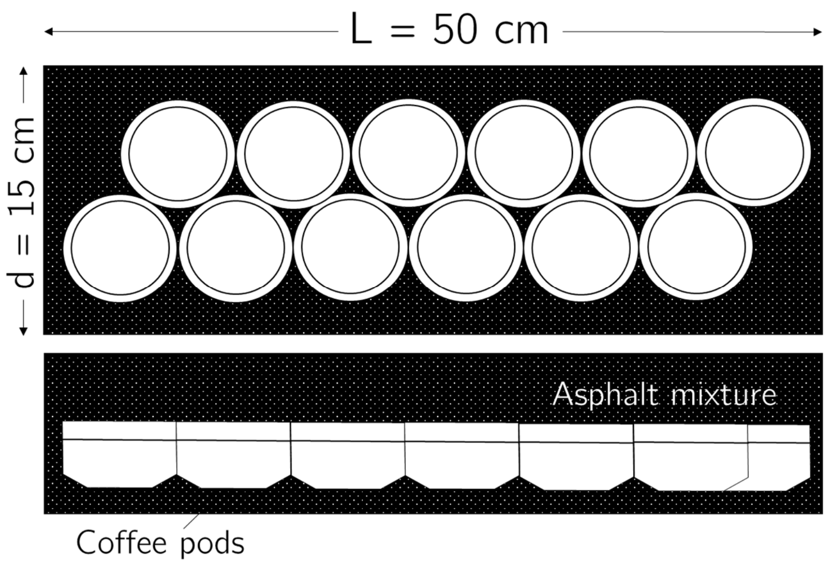

Figure 5. Configuration of 5.4 cm diameter coffee capsules embedded in the hot asphalt mix beam.

A bed of initial asphalt mix is placed under the capsule network so that the pods are not in direct contact with the mold, as shown in Figure 6. The coffee capsules are uncovered to remove the organic material and ensure they are filled with asphalt mix.

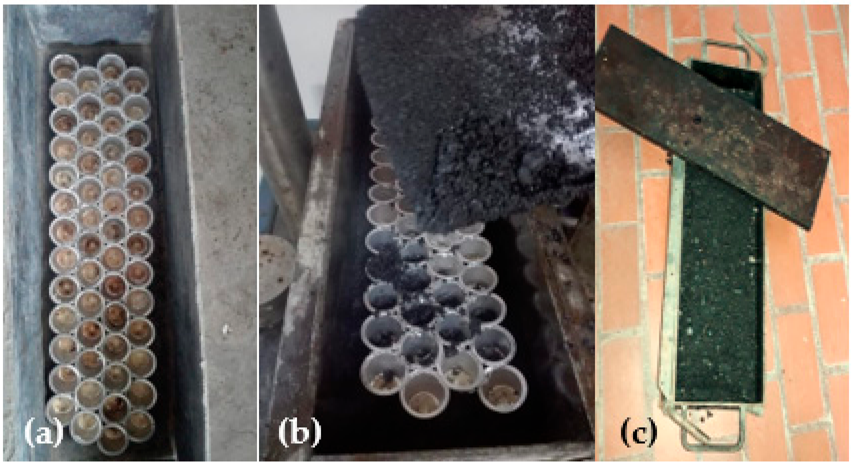

Figure 6. (**a**) Configuration of 5.4 cm diameter coffee capsules; (**b**) moment before the asphalt is poured; (**c**) after compaction.

The samples were compacted by applying a constant and uniformly distributed load, with the help of a platen on top, in three layers until a 15 cm thickness was reached, according to the configuration of each beam. The first layer, which will embed the network of coffee capsule cells, will cause some initial deformation in these elements. However, in later photographs, it can be seen that this deformation is minimal when observing a specimen after testing (Figure 7).

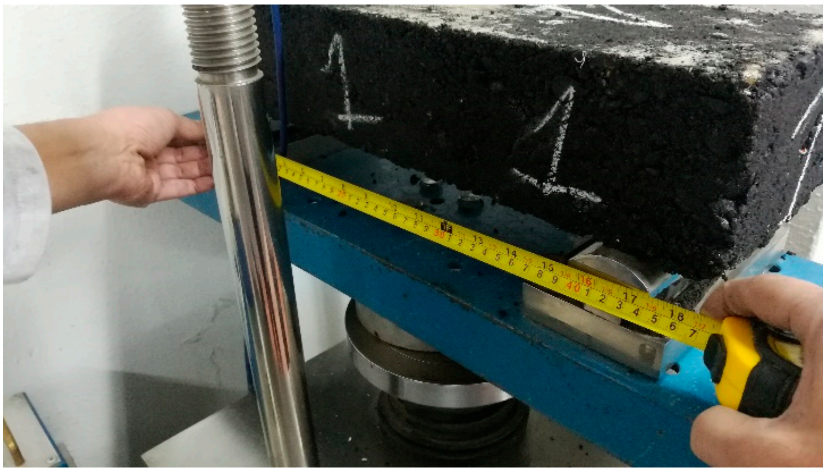

Figure 7. Assembling the sample for testing.

The optimum asphalt content was obtained by compacting five Marshall samples using 75 blows per face, gradually increasing the asphalt percentages from 4.5% to 6.0%. The chosen particle size distribution and typical phase volumes for AC 5.0% and 5.5% are shown in Figure 5 and Table 2. In the same way, Table 3 summarizes the Marshall test results for the optimum asphalt content of MDC-19. The optimum content obtained was 5.0% for samples with pods, and 5.5% for the non-pods option. However, it was determined to use both CA percentages for all configuration alternatives.

Table 3. Results of Marshall test MDC-19.

AC (%)	Stability-S (kN)	Flow-F (mm)	S/F	Voids (%)
4.5	11.82	3.87	3.05	6.14
5.0	12.52	3.72	3.37	4.09
5.5	11.59	3.89	2.98	2.75
6.0	11.66	4.13	2.82	1.53

The one-third loading method is used for flexure tests, using load blocks that ensure that the forces applied to the beam are perpendicular to the face of the specimen and without eccentricity. The specimens meet the requirements of INV E-402 [86]. The samples display a free distance between supports of at least three times their height, with a tolerance of 2% (Figure 7).

A total of 72 specimens were meticulously prepared and subjected to bending using a monotonic load and a fixture positioned at the top of the specimen to ensure pure bending in the beam. The deflection at the center of each specimen was precisely measured at the moment of the first crack, which coincided with the point when the monotonic load in the fixture ceased to increase.

Table 4 provides an overview of the tests conducted and presents the key characteristics of the specimens utilized. Additionally, conventional control specimens lacking a capsule network were employed to analyze the behavior and establish a reference point for comparisons.

Table 4. Test program.

Sample	AC-5.0% (with Pods)	AC-5.5% (with Pods)	AC-5.0% (no Pods)	AC-5.5% (no Pods)
MDC-19, 3.0 cm MDC-19, 4.5 cm	12 specimens 12 specimens	12 specimens 12 specimens	12 specimens	12 specimens

Figure 8 shows the specimens after failure, displaying the presence of the coffee capsules in the lower third of the beam. It can be seen that the failure process creates a compressibility in the capsules that does not affect the bending results. This physical expression was an expected response in the results. It is also clear that beam failure rarely occurs through any of the capsules but usually between two coffee capsules.

Figure 8. Position of the capsules in the lower third of the specimen after failure.

2.3. Load Application

The applied load should be steadily and smoothly increased at a rate between 0.9 MPa/min and 1.2 MPa/min, leading to a progressive rise in extreme fiber stress until the point of failure, as shown in Figure 9. Subsequently, three measurements of each dimension, located at the edges and center, are recorded to the nearest 1.3 mm (0.05″). These measurements are used to calculate the average width and the average height and to pinpoint the location of the fracture line within the failure area of the specimen.

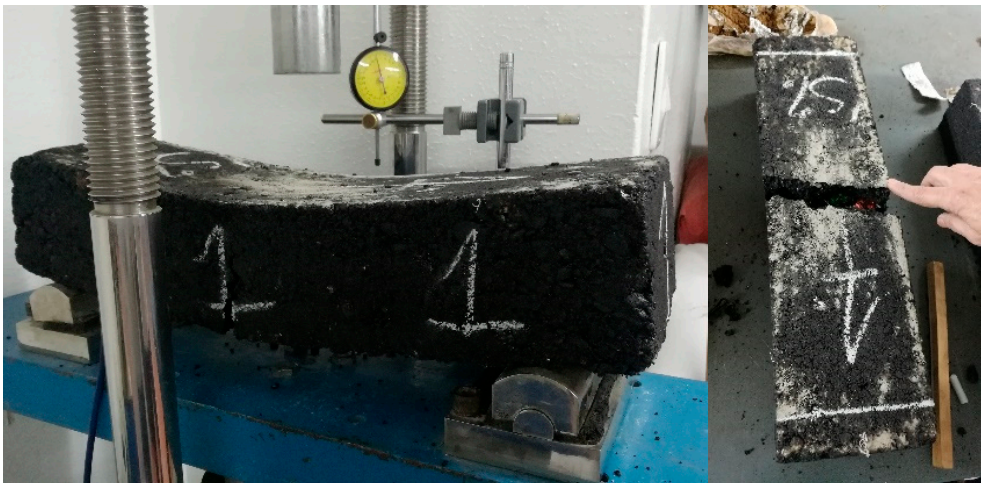

Figure 9. Deformation of the beam at the end of the test.

3. Results

In this section, the flexural strength and deformation results are presented, examining the variations in asphalt content in relation to the presence of capsules in the samples. As outlined earlier, a total of 72 samples were generated, representing the three replicates of each test for 24 different combinations of asphalt and capsule content in the specimens. The average of the three replicates was then calculated, and this value was incorporated into Figures 10–14. Additionally, the specimens are evaluated in comparison to the control samples that do not contain capsules.

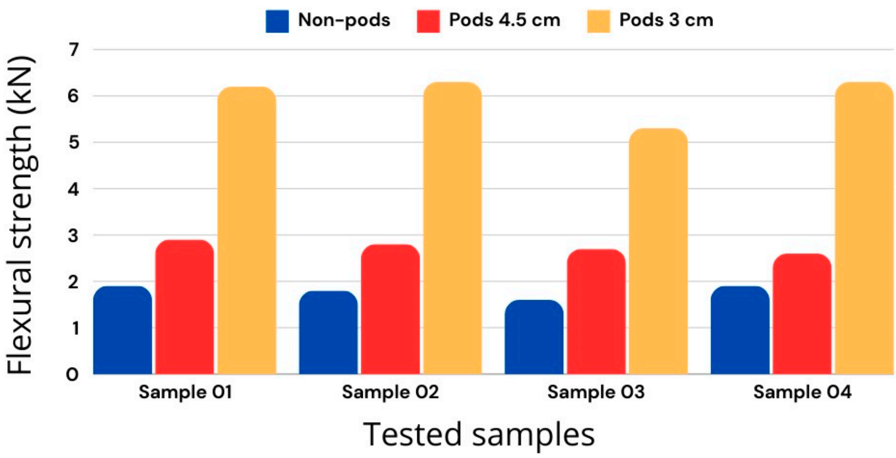

Figure 10. Behavior of the samples, without the addition and with the addition of coffee capsules, for 5.0% asphalt.

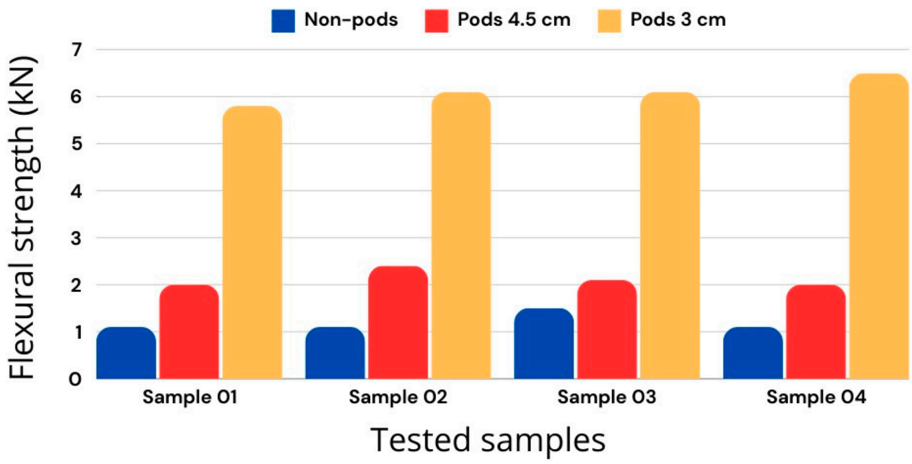

Figure 11. Behavior of the samples, without the addition and with the addition of coffee capsules, for 5.5% asphalt.

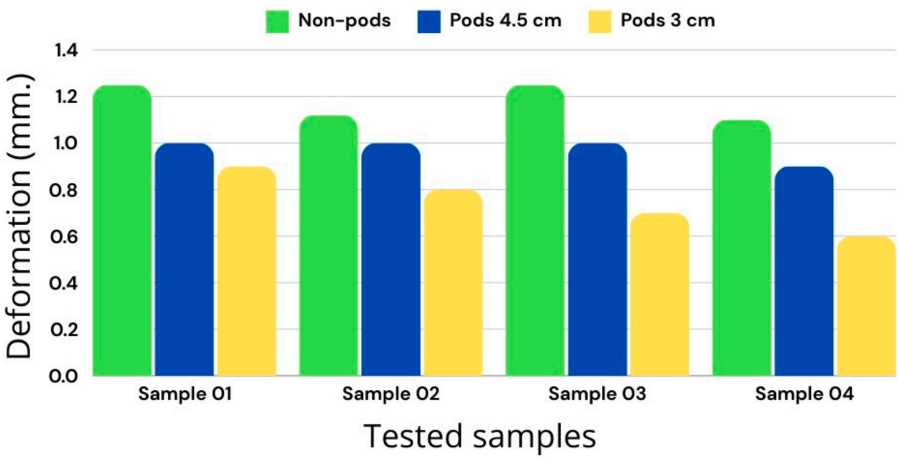

Figure 12. Deformation in the samples at the center of the beam before the appearance of the first crack (AC 5.0%).

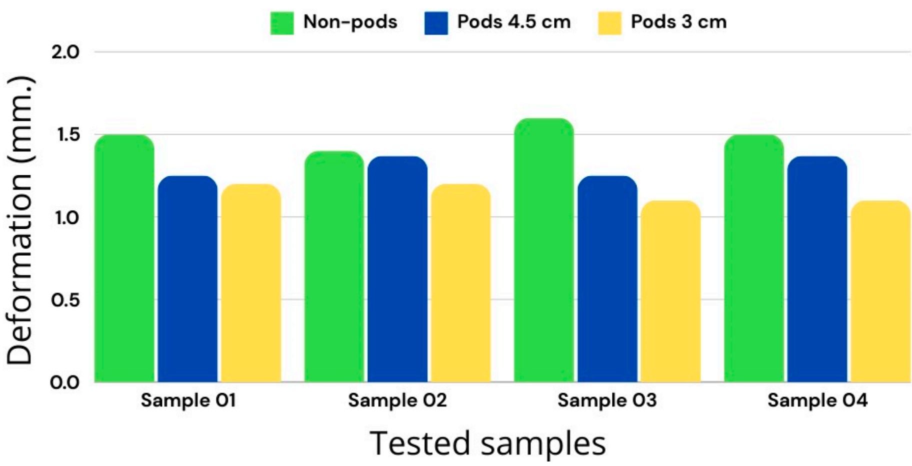

Figure 13. Deformation in the samples at the center of the beam before the appearance of the first crack (AC 5.5%).

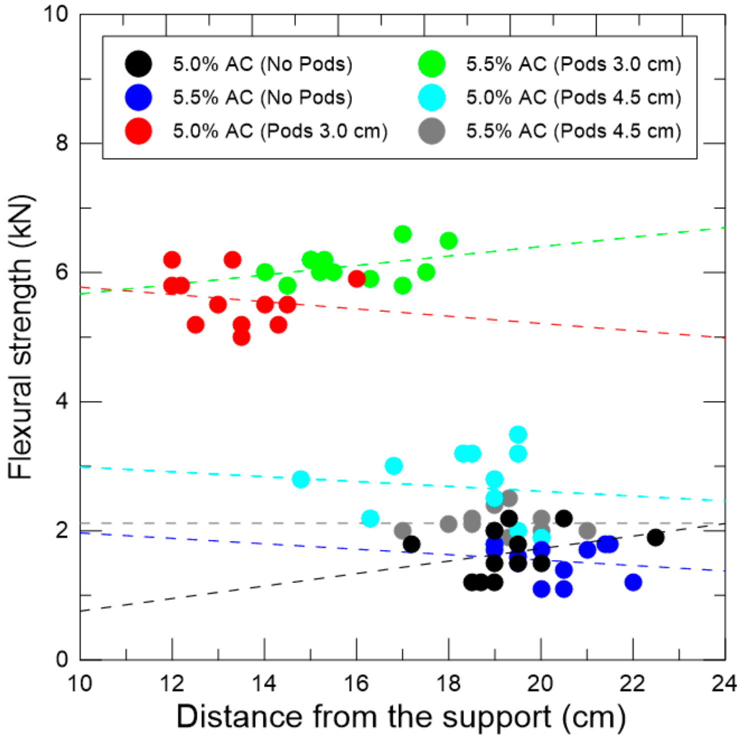

Figure 14. Distance from the support vs flexural strength.

3.1. Flexural Strength

The findings from the 5% AC specimens lacking capsules in the lower third reveal that while the loads are relatively low, they exhibit consistent stability at approximately 2 kN, indicating a lack of outliers in the results (refer to Figure 10). Conversely, in the case of specimens containing 4.5 cm diameter capsules, an increase in flexural strength to values approaching 3 kN is observed, signaling a distinct impact of the capsule network. Notably, when utilizing 3 cm diameter capsules, the value triples in comparison to that of the control sample, with average values reaching approximately 6 kN.

The specimens containing a 5.5% asphalt content (AC) exhibited a marginal decrease in flexural strength compared to those with 5.0% AC. Additionally, the specimens with 4.5 cm diameter capsules demonstrated an increase in strength compared to that of the control specimen without capsules; however, their strength decreased compared to that of the 5.0% AC specimens. In contrast, the 3 cm diameter specimens displayed enhanced incorporation of the capsules, as evidenced by increased resistance values that approached those of the specimens with 5.0% asphalt content. In essence, the findings indicate that the specimens with 5.5% AC experienced a reduction of approximately 30% in monotonic load, leading to specimen failure (Figure 11).

Upon review, it is evident that specimens featuring the 3 cm diameter pods exhibit superior performance in terms of flexural strength. This can be attributed to the smaller capsules, which yield a higher density within the same volume. As a result, the cross-linked fabric of the 3 cm specimens demonstrates greater stiffness compared to that of their 4.5 cm counterparts.

3.2. Deformations

In regards to deformations, we studied the value of the deformation at the center of the beam at the point of the first crack's appearance, which was assessed visually. The control specimens were expected to have higher deformations, and the results confirmed this expectation. For instance, as shown in Figure 12, samples without capsules deformed an average of 1.1 mm. In contrast, samples with 4.5 cm capsules showed a reduction in the deformation to about 1.0 mm. Furthermore, the deformation decreased to values close to 0.7 mm in the samples with 3 cm diameter capsules.

Regarding the findings of the specimens containing the 5.5% asphalt content, it is evident that deformations display a slight increase for both the control specimens and those with capsules of 3.0 and 4.5 cm in diameter. This particular variable does not exhibit significant variations in the percentage, contrasting with the observations related to flexural strength. While the presence of capsules demonstrates a slight enhancement, the overall improvement across all analyzed results appears to be relatively modest (Figure 13).

As in the strength analysis, the difference is not as significant for this aspect. The denser grid (3.0 cm pods) makes the sample stiffer and consequently, decreases the deformations.

3.3. First Crack

The study of cracking in asphalt mixtures is primarily focused on assessing fatigue resistance and consequently, the pavement's life cycle. Understanding the flexural strength at the onset of the initial crack is imperative for comprehending the degradation of asphalt mixtures, as it is closely linked to factors such as the quality of the asphalt cement and external elements like temperature differentials.

The asphalt binder, characterized by its coupled viscosity and elasticity, plays a pivotal role in determining the propensity for cracking within an asphalt mix. Despite its relatively low stiffness compared to other components, cracks typically manifest near the aggregate–binder interface, a phenomenon substantiated by our current investigation [87,88].

The thermal gradient, particularly the temperature differentials experienced by the mixture, also exerts considerable influence. Cracks tend to emerge on the surface layer exposed to the surroundings. Notably, the laboratory conditions in our study were controlled, minimizing the impact of this variable [89–93].

In light of the above, a comparison was made between the flexural strength and the distance from the support to the first crack, and the results are presented in Figure 14. Despite the relatively low R^2 values observed in nearly all samples, indicating a weak correlation between flexural strength and support distance, this response can be attributed to the erratic and challenging nature of first crack appearances, making measurements difficult at times. Nonetheless, discernible and consistent trends indicative of the anticipated behavior are evident. Notably, in samples exhibiting greater deformations, specifically those lacking pods, the distance from the support to the failure line is extended.

4. Discussion

It was evident from the anticipated outcomes that the incorporation of capsules, irrespective of their diameter and configuration, would enhance both flexural strength and deformation. The challenge lay in quantifying the extent of this enhancement. The inclusion of the 4.5 cm diameter capsule net exhibited no significant increase in flexural strength or reduction in deformation, likely due to its lower density, resulting in less stiffness compared to that of the 3 cm diameter capsule net, which had a higher capsule count per unit area. This configuration's higher density and greater coordination number for each capsule, as per the number of capsules in contact, contribute to its superior performance.

Such capsule network inclusions are suitable for specialized pavement structures where capsule insertion into the asphalt mix is feasible, particularly in locations with high subgrade deformations or those where reducing asphalt layer thickness is desired. This is because the capsule network enhances resistance and reduces deformation in asphalt mixtures subjected to bending. In specific contexts where the aforementioned issues are observed, it is advisable to employ these pods. This is particularly applicable in scenarios where the timely manual placement of capsules does not pose a significant constraint during road construction.

Future research should broaden its scope to encompass different asphalt and aggregate types, alternative capsule network configurations, and the use of capsules in the form of flakes or powder to modify asphalt mixes and cement.

5. Conclusions

The experimental investigation aimed at determining the flexural strength of MDC-19 incorporating a network of coffee waste capsules has been successfully accomplished. Furthermore, conventional specimens without inclusions were tested to serve as initial control specimens.

The modified test designed to evaluate the flexural strength of beam-shaped asphalt mix specimens has proven to be suitable for this study, yielding reasonable results in accordance with the proposed specimen and test configuration. In quantitative terms, the incorporation of the capsule lattice increased flexural strength by up to threefold compared to that of the samples lacking capsules.

The utilization of waste coffee capsules not only mitigates the serious environmental impact they pose but also enhances the specimens by effectively minimizing the tensile stress in the lower fibers, thereby demonstrating a favorable response under monotonic bending loads. Nonetheless, further testing is required to validate this effect in a more comprehensive manner.

Analysis of the beam deflection at the point of failure indicates lower values for specimens with waste capsule inclusions because of the stiffness it causes in the specimens. However, these values remain inconclusive, warranting additional measurements at multiple locations on the specimens to bolster the confidence in the results. It is important to note that the laboratory practices and methodology employed affirm that the results are directly correlated to the execution processes. Therefore, it can be inferred that adherence to standards and the use of calibrated equipment enhances the reliability of the obtained data.

The deformation measurements were exclusively obtained from the central region of the beam, potentially constraining the comprehensive analysis of the results. Subsequent research endeavors should address this limitation to enhance the applicability of the findings to real-world construction scenarios.

While acknowledging that the present work represents an experimental laboratory test which is not standardized for asphaltic concrete, the results are of significance and pave the way for future research endeavors in this domain.

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