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INVESTIGATION OF HOT MIX ASPHALT PROPERTIES WITH INCORPORATION OF CRUMB TYRE AND POLYCARBONATE

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Abstract — Asphalt, a crucial material in construction, demands constant improvement to meet evolving infrastructure requirements. This research addressed the need for enhancing asphalt properties by incorporating crumb tyre, crumb polycarbonate, and their combined formulation as additives. The objective was to modify bitumen properties for optimized asphalt production, specifically focusing on strength characteristics. The study employed a comprehensive methodology to assess the impact of these additives on bitumen. It examined their influence on penetration, ductility, softening point, viscosity, and thermal stability, particularly the flash and fire points. Various proportions of additives were investigated, seeking the most effective composition. The results of this research unveil promising outcomes. The additives exerted a stiffening effect on bitumen, altering its molecular structure and intermolecular interactions. Consequently, penetration values decreased, indicating enhanced stiffness. Moreover, ductility significantly increased, suggesting improved resistance to deformation. Furthermore, the softening point of bitumen rose, indicating heightened resistance to softening at elevated temperatures. The viscosity of bitumen decreased upon additive introduction, simplifying mixing with aggregates during asphalt production. The additives also elevated the flash and fire points, signifying enhanced thermal stability. Based on these findings, the recommended mix consists of 10% crumb tyre, 10% crumb polycarbonate, and 10% of both additives combined. This composition outperforms other proportions, presenting a viable solution to enhance asphalt properties for a wide range of road applications.

Keywords**:** asphalt modification, crumb tyre, crumb polycarbonate, bitumen additive, asphalt strength characteristic

1.0 INTRODUCTION

In recent decades, the world has witnessed a remarkable increase in global population, consumerism, and evolving lifestyles, leading to an unprecedented demand for a diverse range of polymeric materials that cater to the needs of modern society. In response to this surging demand, the manufacturing industry has diligently produced an extensive array of polymeric materials, primarily categorized into two distinct classes: thermoplastics and thermosets [1–3]. These versatile polymers have permeated numerous industries, catalyzing innovations in packaging, textiles, electronics, and infrastructure development. Thermoplastics, distinguished by their capacity to undergo multiple heating and cooling cycles, play a pivotal role across industries, serving applications from clothing fibers to food and beverage packaging. Their versatility stems from the unique properties exhibited by various thermoplastics, including crystalline thermoplastics and amorphous or semi-crystalline thermoplastics [4–7]. However, these materials, characterized by long and short carbon chains, demonstrate a remarkable resistance to degradation or hydrolytic cleaving of chemical bonds, rendering them non-biodegradable. A prominent example of thermoplastics is polyethylene terephthalate (PET), widely employed in textile fibers and the packaging of beverages and food products. In stark contrast, thermosets exhibit highly complex, three-dimensional cross-linked structures that remain impervious to melting or softening during heating cycles. This intrinsic property ensures that the material's form remains unchanged even under high temperatures. Importantly, thermosets resist decomposition through heating, and they find extensive use in durable applications spanning aerospace and automotive manufacturing, wind turbine production, and the creation of structural components [8–10]. Approximately 80% of plastics consumed globally fall under the thermoplastic category, primarily serving the functions of packaging and textile fibers. Worryingly, nearly 50% of these thermoplastics are used for single-use applications, exacerbating the environmental challenge posed by their non-biodegradable nature. The remaining thermoplastics are allocated to long-term infrastructure applications like pipes, cable coatings, and structural materials, as well as durable consumer products such as electronic goods, furniture, and vehicles [11–15]. Conversely, thermosets are predominantly employed in long-lasting applications, including composites utilized in the aerospace and automotive industries, wind turbine blade construction, and the manufacturing of structural components. This escalating demand for thermoset composites is evident in the projection that the global market size for thermoset composites will reach USD 54,360 million by 2026, up from USD 43,510 million in 2020 [16–19].

However, the proliferation of polymeric materials, encompassing plastics and rubber, has precipitated a pressing environmental crisis characterized by the accumulation of waste in landfills. Furthermore, the production of these polymers, primarily derived from petroleum-based sources, contributes to the depletion of finite natural resources. Consequently, there is an increasingly urgent need to explore sustainable solutions that not only transform plastic waste into a valuable resource but also mitigate the detrimental effects of environmental pollution resulting from plastics littering ecosystems[20–22]. Polycarbonate, a prevalent plastic found in various products such as water bottles, eyeglasses, and electronic devices, poses significant environmental challenges when not disposed of properly. This durable material can persist in the environment for centuries, releasing harmful chemicals during decomposition that can negatively impact wildlife, soil, and water systems. Additionally, plastic waste, including polycarbonate, contributes to the formation of marine debris, endangering marine life and ecosystems. Simultaneously, waste tyres, or scrap tyres, present another pressing environmental concern [13, 15, 17, 19]. Comprising rubber and other materials, these tyres can take decades to decompose in natural environments. When accumulated in large quantities, discarded tyres can become fire hazards and breeding grounds for disease-carrying insects like mosquitoes. Moreover, the chemicals present in tyre rubber can leach into soil and water, posing contamination risks. The sheer volume of tyres discarded in landfills consumes valuable land resources and creates unsightly eyesores within communities.

In recent years, both small-scale research-based and large-scale industrial efforts have been made to explore new recycling methods or optimize existing approaches [1, 7–9, 23]. Recycling offers a viable solution to reduce the demand for new raw materials and decrease the amount of waste materials ending up in landfills. Beyond waste reduction, recycling also contributes to preventing environmental pollution associated with raw material extraction, conserving energy, and creating employment opportunities. Recycling methods for waste plastics encompass mechanical recycling, chemical recycling, and energy recovery. Mechanical recycling entails reusing waste materials as raw materials for second-grade products with minimal alteration of the material's chemical structure or utilizing them as fillers in composites [17–19, 22]. The typical steps in mechanical recycling involve sorting, cutting or shredding, contaminant removal, processing, and milling. Chemical recycling, on the other hand, includes chemolysis or pyrolysis, processes where polymers are chemically converted into monomers or oligomers through chemical reactions and structural changes. The resulting monomers can be employed as fuel or in the production of polymeric materials. Chemolysis methods involve depolymerization with chemicals, including glycolysis, hydrolysis, methanolysis, alcoholysis, and aminolysis. Pyrolysis, the decomposition of polymers into smaller molecules through heating in the absence of oxygen, is another chemical recycling method (typically at temperatures of 500–800°C and high pressure) [15, 16]. Pyrolysis employs end-chain scission, random-chain scission, chain-stripping, or cross-linking mechanisms. The by-products of pyrolysis include condensable hydrocarbon oil and non-condensable gases with high calorific value. Continuous mechanical recycling may result in low-quality products, a phenomenon known as downcycling. Chemical recycling often requires a significant quantity of chemicals and is not universally applicable to all plastic types, rendering these processes economically and environmentally challenging. Consequently, many plastics end up in landfills. Alternatively, some of these plastics are used for energy production, serving as feedstock for incineration plants that utilize plastics as fuel. However, this method releases substantial pollutants into the air. Recognizing the critical need for sustainable practices, Fengchi et al. [5] have explored the use of recycled waste plastic in asphalt binders and mixtures. Their study comprehensively analyzed and compared various forms of waste plastic employed in asphalt modification and explores approaches to incorporating waste plastic into asphalt mixtures, both for single and composite modifications. The study places particular emphasis on examining the properties of waste plastics, asphalt binders, and asphalt mixtures.

Zair et al. [18] deem plastic, particularly polyethylene terephthalate (PET), as one of the most significant industrial materials of this era. However, the proliferation of PET waste presents environmental challenges, given its non-biodegradable nature. Their research investigated the physical and chemical properties of PET, justifying its use as an additive and aggregate replacement in asphalt mixtures. The findings highlighted the promising results achieved through the addition of PET to asphalt mixtures. Ismail and Salmabanu [6] assessed geo-polymeric composites, seeking to incorporate a diverse array of waste materials into their manufacture. The researchers identified the adverse environmental impacts of landfills filled with rubber tyre waste, including soil and water contamination and health hazards from toxic gas emissions. To address this challenge, they proposed processing tyre waste into alternative aggregates for the production of geo-polymer construction composites. This approach, which replaces natural aggregates with recycled tyre rubber in geo-polymer binders, mortar, concrete, and other construction materials, not only adds economic value but also mitigates the depletion of natural aggregate resources. Ji et al. [4] explored the influence of silica-coated rubber on the performance of rubber mortars. Employing a Stöber sol-gel method, they created a silica coating on rubber particles and incorporated them as partial replacements for fine aggregates in concrete. Their research encompassed the examination of flow ability, mechanical strength, capillary water absorption rate, and microstructure of mortars. The results demonstrated that the silica coating on rubber particles altered their hydrophobic properties and significantly improved the mechanical strengths of mortars.

Garcia et al. [24] addressed the challenge of recycling end-of-life tyres (ELTs) by combining a cryo-grinding process with chemical treatment to modify the surface of ground tyre rubber (GTR). Through various cryo-grinding protocols, they achieved an optimal particle size. Chemical treatments with sulfuric acid (H_2SO_4) further modified GTR, making it compatible with a styrene-butadiene rubber (SBR) matrix. The incorporation of this modified GTR into the matrix resulted in a composite with significantly improved mechanical performance, including a 115% increase in tensile strength and a 761% increase in elongation at break. These results validate the use of recycled tyre waste as a sustainable filler in rubber composites. Sandeep et al. [15] highlighted the extensive use of rubber and plastics in various applications, highlighting their long durability and ease of manufacturing. However, they acknowledged the critical issue of long-term durability and environmental concerns, given that these materials are often treated as hazardous waste polymeric materials at the end of their life cycles. Traditional disposal methods, such as land filling and combustion, have been widely employed, but they pose significant environmental challenges. Consequently, there is a pressing need for effective solutions that not only reduce plastic consumption but also improve plastic waste management practices. Moreover, promoting recycling and exploring alternative materials is essential to mitigate the adverse impacts of plastic waste on the environment, wildlife, and human health.

In line with these critical environmental concerns, this research aimed to investigate the potential of recycled crumb tyre rubber and polycarbonate as additives in asphalt concrete. By doing so, it seek to offer a sustainable solution to both waste management and the enhancement of construction material performance. In the subsequent sections, the researchers explained into the methodology, experimental procedures, and results of the laboratory investigations, with the overarching goal of contributing to ongoing efforts to create environmentally responsible and resilient infrastructure.

2.0 METHODOLOGY

In this section, an overview of the materials used in the research is provided, and the methodology employed is described. The selection of materials for the study was guided by the need to meet established standards and requirements. Recycled rubber materials were processed into crumb rubber tyres through a grinding process, while polycarbonate compact discs (CDs), recognized for their durability and scratch resistance, were converted into crumb form through grinding. Materials with a particle size less than 4.75mm, including sand, silt, clay, and crushed stone or gravel resized to sand particle dimensions, fell into the category of fine aggregate. Coarse aggregates, exceeding 4.75mm in size and typically ranging from 9.5mm to 37.5mm in diameter, were employed. The binder used in the asphalt concrete production was 70/80 grade bitumen. All materials utilized in the research were locally sourced in Akure, Ondo State, and stringent quality control measures were implemented to ensure compliance with the requirements for producing crumb tyre-polycarbonate blend modified bitumen. In the study, crumb tyre and waste polycarbonate were employed as additives. Marshall stability test samples were meticulously prepared, incorporating the optimal bitumen content and varying percentages of additives (2%, 4%, 6%, 8%, and 10%). These modified bitumen samples underwent a series of tests to determine the optimal bitumen content. Subsequently, the optimal bitumen content was used to produce Marshall stability testing samples for performance evaluation, facilitating the assessment of the strength characteristics of the resulting asphalt concrete.

Table 1 Percentage Composition of Crumb Tyre, Polycarbonate and Crumb Tyre-Polycarbonate Blend

Material	Percentage Composition	No. of Test Sample 1	No. of Test Sample 2	No. of Test Sample 3	Total
Crumb Tyre Waste (CTW) (%)	2	3	3	3	9
	4	3	3	3	9
	6	3	3	3	9
	8	3	3	3	9
	10	3	3	3	9
Polycarbonate Waste (PW) (%)	2	3	3	3	9
	4	3	3	3	9
	6	3	3	3	9
	8	3	3	3	9
	10	3	3	3	9
Crumb Tyre Waste (CTW) (%)	2	3	3	3	9
+	4	3	3	3	9
Polycarbonate Waste (PW) (%)	6	3	3	3	9
	8	3	3	3	9
	10	3	3	3	9

2.1. Physical Properties of Aggregates and Tests on Bitumen

The research involved a comprehensive examination of aggregate physical properties to ascertain their suitability. This examination encompassed various tests, including the water absorption test (ASTM C127), bulk density measurement (ASTM C29), Aggregate Impact Value (AIV) test (BS 812, Part 112), Aggregate Crushing Value (ACV) test (BS 812, Part 110), aggregate abrasion test (BS 812, Part 113), specific gravity determination (ASTM C128), flakiness and elongation test (ASTM D4791), and particle size distribution analysis (ASTM D6913).Furthermore, a series of tests were conducted on bitumen and modified bitumen to determine the optimal additive blend for improved performance. These tests included the penetration test (ASTM D5), ductility test (ASTM D113), softening point test (ASTM D36), and flash and fire point tests (ASTM D92).

2.2. Performance Evaluation Tests

To comprehensively assess the performance characteristics of the resulting asphalt concrete, the research incorporated the Marshall stability test (ASTM D 6927) and the indirect tensile strength test (ASTM 6931). These performance evaluation tests provided essential insights into the strength and stability of the asphalt concrete, enabling a thorough assessment of its performance across diverse conditions.

3.0 RESULTS AND DISCUSSION

3.1. Tests on Aggregates

Tests were performed to relevant standards to determine the properties of fine aggregates, coarse aggregate and fillers and their suitability for use in asphalt production. The results of the tests are presented in the following sections.

3.1.1. Water absorption

The water absorption test results reveal that fine aggregates had a water absorption percentage of 0.70%, while coarse aggregates exhibited a slightly higher value of 0.91%. These percentages fell within the range of low water absorption, which is highly desirable for aggregates used in construction materials like concrete and asphalt. Low water absorption indicates that the aggregates had limited moisture absorption capacity, a crucial factor in maintaining the desired properties and performance of the final product. In the context of asphalt mixtures, aggregates with low water absorption offer several advantages. They facilitate strong adhesion with the asphalt binder and mitigate the risk of moisture-related damage. To put these results into perspective, it is important to reference the Standard Test Method for Relative Density (Specific Gravity) and Absorption of Coarse Aggregate ASTM C127, which typically imposes a maximum allowable water absorption limit of 2% by weight for both fine and coarse aggregates used in asphalt. This requirement is significant because excessive water absorption can have detrimental effects on the performance of asphalt mixtures. When aggregates absorb an excessive amount of water, it can lead to issues such as compromised adhesion between the asphalt binder and aggregate particles, heightened susceptibility to moisture-induced problems, and reduced overall durability of the asphalt pavement. Therefore, the observed low water absorption values in this study align with industry standards and contribute to the quality and longevity of the asphalt concrete.

3.1.2. Particle grading of fine and coarse aggregates

The Coefficient of Uniformity (Cu) and the Coefficient of Gradation (Cc) are fundamental parameters used in soil analysis to assess the particle size distribution of soil samples. Cu is a measure of the range of particle sizes in the soil. For fine aggregates, Cu was found to be 2.31, indicating a relatively wide range of particle sizes within the sample. The calculated Cc value for fine aggregates was 1.03, classifying them as well-graded soil based on industry standards. For coarse aggregates, Cu was determined as 1.43, suggesting a narrower range of particle sizes compared to fine aggregates. The Cc value for coarse aggregates was 0.80, indicating that they are also well-graded according to the classification criteria for aggregates. Overall, these parameters provide valuable insights into the particle size distribution and uniformity of soil and aggregate samples, which are essential considerations in various engineering and construction applications. Figure 1 provides the grainsize distribution of the fine and coarse aggregates.

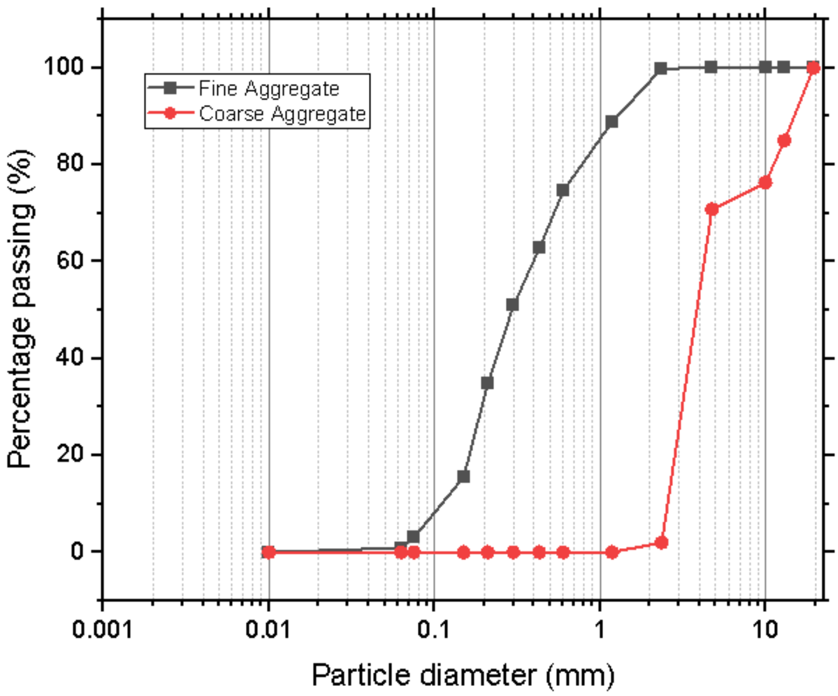

Figure 1 Grainsize distribution of fine and coarse aggregates

3.1.3. Specific gravity

The specific gravity values reported as follows: 2.6 for fine aggregate, 2.8 for coarse aggregate, and 1.9 for filler material. These specific gravity measurements are crucial for assessing the suitability of these components in asphalt production. For fine aggregate, ASTM C128 outlines the standard test method and specifies that the specific gravity typically falls within the range of 2.5 to 2.8. In this study, the specific gravity of fine aggregate, which was found to be 2.6, falls comfortably within this established range, indicating its compatibility with industry standards. Similarly, coarse aggregate is evaluated using ASTM C127, which suggests a specific gravity range of 2.6 to 2.9. The specific gravity value of 2.8 obtained for coarse aggregate aligns with this prescribed range, affirming its suitability for use in asphalt production. The specific gravity of fillers can vary depending on the material used. Common filler materials in asphalt production, such as stone dust, limestone powder, or fly ash, may exhibit different specific gravity values. In this case, the specific gravity of the filler material was determined to be 1.9.

This value falls within the acceptable range for fillers, which typically spans from 1.9 to 2.9, as outlined in ASTM C110, the standard test method for determining the specific gravity of fine aggregate. In summary, the specific gravity measurements obtained for the fine aggregate, coarse aggregate, and filler material in this study align with industry standards, demonstrating their suitability for use in asphalt production.

3.1.4. Flakiness and elongation indices

The average flakiness index obtained as presented in Table 2 was 20.1%. ASTM D4791 which provides the standard test method for flat particles, elongated particles, or flat and elongated particles in coarse aggregate does not provide any limit for flakiness index of coarse aggregate. However, lower values of flakiness index indicate a lower proportion of flaky particles and are generally preferred for better aggregate performance. Therefore, the flakiness index of 20.1% obtained indicated lower percentage of flaky particles which is good for asphalt production. Furthermore, the elongation index of 18.82% obtained as presented in Table 1 revealed that the coarse aggregates has just 18.82% of it elongated, which is good for coarse aggregate to be used for asphalt production. It is generally recommended to minimize the presence of elongated particles in aggregates used for asphalt and concrete mixtures. Excessive elongation can negatively impact the workability, stability and performance of the mixtures. The flakiness and elongation indices of the coarse aggregates used in this research is presented in Table 1.

Table 2 Flakiness and Elongation Indices

Sample ID	A	B
Total Weight of Sample (g)	1660	1650
Total Weight of Sample Passing Through Thickness Guage (g)	326.0	339.0
Flakiness Index (%)	**19.6**	**20.5**
Average Flakiness Index (%)	**20.1**	
Total Weight of Sample Retained on Various Length Guage (g)	313.0	310.0
Elongation Index (%)	**18.9**	**18.8**
Average Elongation Index (%)	**18.82**	

3.1.5. Bulk density

The bulk density measurement for fine aggregate, which was determined to be 1808 kg/m³, provides valuable insights into the mass of the fine aggregate per unit volume. This measurement encompasses both the solid particles and the void spaces within the aggregate. The recorded bulk density of 1808 kg/m³ for the fine aggregate is indicative of its relative density and compactness. A bulk density value of 1808 kg/m³ for fine aggregate signifies that this aggregate material possesses a relatively high density and compactness. These attributes are key indicators of superior aggregate quality. In practical terms, the density of the aggregate material plays a crucial role in achieving the desired performance characteristics and density of the asphalt mixture. It is important to note that the bulk density values obtained for coarse aggregate and filler material were 2120 kg/m³ and 1708 kg/m³, respectively. These values are also significant as they will significantly influence the proportions of aggregates and bitumen required to attain the targeted density and performance attributes of the final asphalt mixture. In essence, the bulk density measurements for the fine aggregate, coarse aggregate, and filler provide essential data for optimizing the composition of the asphalt mixture, ensuring that it meets the desired density and performance criteria.

3.1.6. Aggregate impact value and aggregate crushing value

The coarse AIV result reveals an average AIV of 17.50%, signifying that the coarse aggregate exhibited significant toughness and resilience against impact loads. In accordance with BS 812, Part 112, which provides guidelines for aggregate properties, the AIV of coarse aggregates is typically expected to be below 30% for a wide range of applications. Nevertheless, for specialized uses like airport pavements or heavy-duty industrial floors, lower specified AIV limits, such as 25% or even 20%, might apply. Thus, the AIV result of 17.50% comfortably meets these requirements. Similarly, the Coarse Aggregate Crushing Value (ACV) result indicates an average ACV of 13.43%, underscoring the robustness of the coarse aggregate against crushing loads. According to BS 812, Part 110, which outlines standards for aggregate testing, the ACV of aggregates is generally recommended to be below 30% for most applications. However, for specialized uses like heavy-duty concrete or road construction, lower specified ACV limits, such as 25% or 20%, may be imposed. Consequently, the ACV result of 13.43% satisfies these stipulated requirements.

3.2. Tests on Bitumen

3.2.1. Penetration test

The addition of crumb tyre and polycarbonate as an additive added to bitumen affects the penetration value, which measures the consistency or hardness of the bitumen. As the percentage of additive was increased from 0% to 10%, the penetration value decreased from 69 dmm (tenths of a millimeter) to 54 dmm for both additive. Likewise, the combination of both crumb tyre and polycarbonate used together to modify bitumen also followed the same trend of reducing the penetration of the bitumen with the corresponding increase in its percentage composition. This reduction in penetration value indicates that the bitumen becomes harder or less penetrable. These additives were able to modify the properties of bitumen, affecting its stiffness by altering the molecular structure and intermolecular interactions within the bitumen, resulting in changes to its physical properties. This increase in stiffness made it more resistant to penetration, leading to a decrease in the penetration value. The additive molecules interacted with the bitumen molecules, creating a network or cross-linking structure that restricts the movement of bitumen molecules and reduces its penetrability. The result of penetration test to determine the grade and consistency of bitumen and modified bitumen used in this research is presented in Table 3.

Table 3 Penetration of Crumb Tyre and Crumb Polycarbonate Modified Bitumen

Percentage Additive Composition	Penetration Test @ 25ºC			Test Method	Specification
	Crumb Tyre (CT)	Crumb Polycarbonate (CP)	CT+CP		
0	69	69	69	ASTM D-5	60 -70
2	63	68	64		
4	61	67	62		
6	58	60	59		
8	55	57	54		
10	54	54	50		

3.2.2. Penetration index

The penetration indices derived from the bitumen and modified bitumen penetration tests conducted in this study are illustrated in Figure 2. The findings reveal that the Penetration Index (PI) of crumb tyre modified bitumen initially rose from 0.106 to 0.785, after which it exhibited a gradual decline, eventually stabilizing at 0.383. This observed behavior suggests that the heat sensitivity of the crumb tyre modified bitumen experienced an increment of up to 8% before subsequently decreasing to 0.383. Conversely, the introduction of crumb polycarbonate into the mix led to a reduction in the penetration indices of crumb polycarbonate modified bitumen, with values dropping from 0.106 to -0.508 at a 4% additive concentration, after which they began to rise once more. Interestingly, when both crumb tyre and polycarbonate were combined, there was a consistent upward trend observed. These trends collectively indicate that the addition of polycarbonate additives enhances the heat susceptibility of the bitumen.

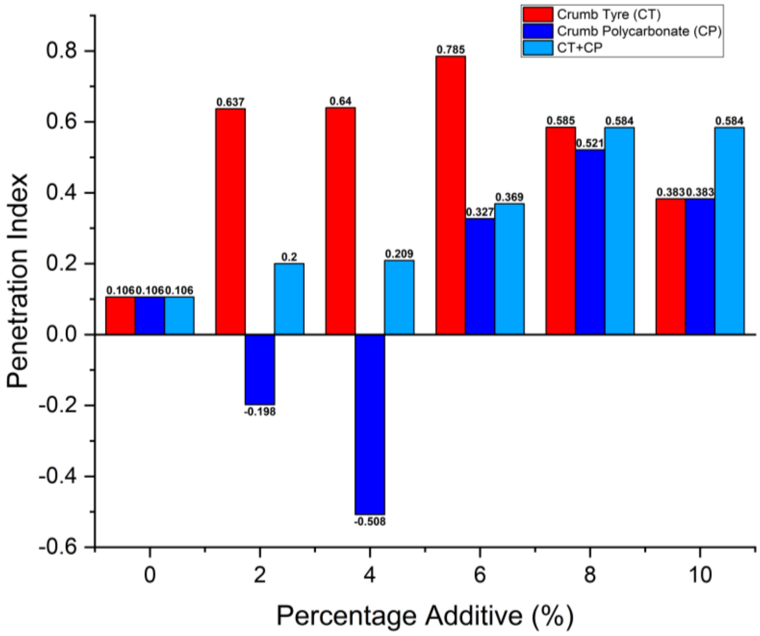

Figure 2 Penetration index

3.2.3. Ductility test

From Figure 3, the results obtained from the ductility tests conducted on both the bitumen and modified bitumen samples reveal interesting trends. As the percentage of additive content increases from 0% to 10%, the ductility of crumb tyre modified bitumen exhibited an upward trajectory, rising from 112 cm to 121 cm. Similarly, the ductility of polycarbonate modified bitumen showed an increase, ranging from 112 cm to 118 cm within the same additive percentage range. However, the ductility of the bitumen modified by the combination of crumb tyre and polycarbonate displayed a slightly different pattern. Initially, it increased to 115 cm at a 6% composition of the additive blend before returning to 112 cm at a 10% composition. This observed increase in ductility is indicative of enhanced flexibility in the bitumen, allowing it to stretch without fracturing. The additives played a crucial role in modifying the bitumen's properties, influencing its resistance to deformation. This modification likely involved the formation of a more interconnected network or alterations in the molecular structure of the bitumen, enabling it to stretch further before reaching its breaking point. In practical terms, this heightened ductility implies that the additives positively impact the bitumen's elastic behavior. It grants the bitumen the ability to deform and stretch more extensively before experiencing failure. Such attributes are highly advantageous, especially in applications where flexibility and resistance to cracking are paramount, such as road construction and asphalt pavements. The ductility data for both the bitumen and modified bitumen samples are graphically presented in Figure 3.

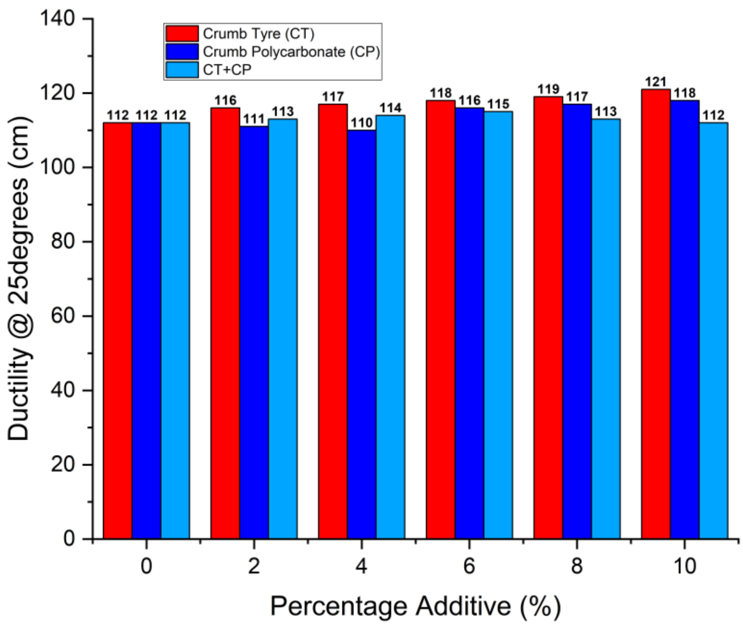

Figure 3 Ductility test results

3.2.4. Softening point test

The incorporation of crumb tyre and polycarbonate additives led to an elevation in the softening point of the modified bitumen, resulting in a notable increase from 52°C to 56°C for both types of modified bitumen. Notably, the combination of crumb tyre and polycarbonate in the modified bitumen composition achieved the highest softening point, reaching 58°C at a 10% additive composition. This significant rise in the softening point implies that the bitumen underwent a transformation towards increased hardness and heightened resistance to softening when exposed to elevated temperatures. The softening point, in essence, signifies the temperature at which the bitumen initiates the softening process and begins to lose its solid-like characteristics. The augmentation in the softening point strongly indicates that the additive exerts a transformative effect on the molecular structure or composition of the bitumen. Consequently, the modified bitumen becomes less susceptible to softening and deformation, especially when subjected to high temperatures. This particular quality holds great significance in applications demanding bitumen's resilience to elevated temperatures without experiencing significant deformation, rutting, or flow. Such applications are typically encountered in regions with hot climates or under conditions of heavy traffic load. The heightened softening point serves as a clear indicator of enhanced temperature resistance and stability within the modified bitumen. It assures that the bitumen will maintain its solid-like behavior even under elevated temperatures, thus minimizing the risks associated with deformation, rutting, or flow in response to both traffic and environmental conditions. Figure 4 visually presents the softening point data for both bitumen and the modified bitumen samples.

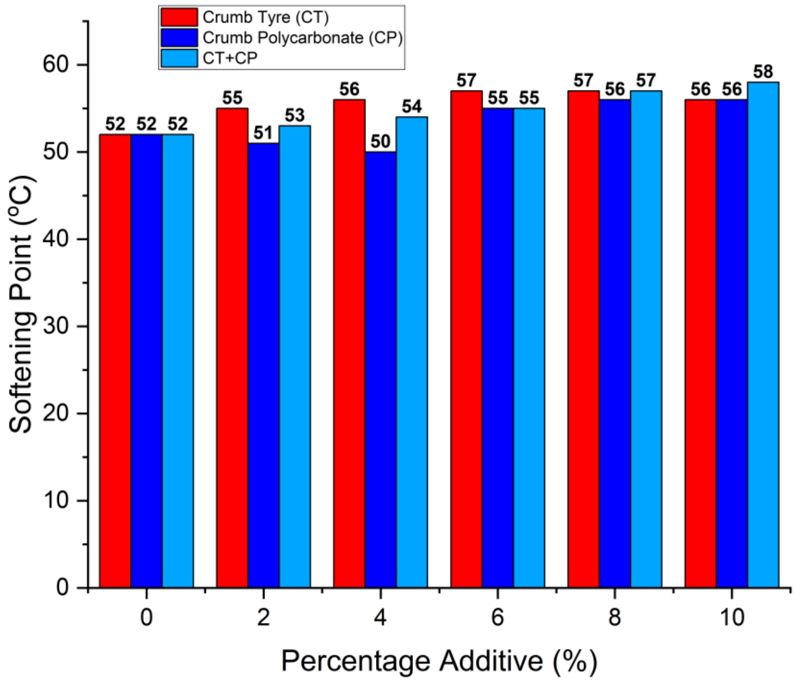

Figure 4 Softening point test

3.2.5. Loss on heating test

Figure 5 shows that the loss on heating increased from 0.13 to 0.2 from crumb tyre modified bitumen and it increased from 0.13 to 0.17 for crumb polycarbonate modified bitumen. The bitumen modification with the combination of crumb tyre and polycarbonate however outperformed the other forms of bitumen modification with the 10% composition having the highest loss on heating of 0.20. This implies that the modified bitumen exhibits a higher level of volatile content when subjected to heating. Loss on heating refers to the weight loss experienced by bitumen when heated under specific conditions. The increase in loss on heating suggests that the additive introduces additional volatile components or enhances the release of volatile substances from the bitumen when heated. Volatile components are typically lighter fractions of the bitumen that evaporate at elevated temperatures. The implications of increased loss on heating asphalt mixture properties are that the increased volatile content can affect the workability and compatibility of asphalt mixtures. Higher loss on heating may result in increased asphalt binder viscosity during mixing and compaction, potentially impacting the coating and adhesion of aggregates. It can contribute to increased aging and hardening of the bitumen over time [15]. The volatile components that are lost during heating may play a role in the bitumen's ability to resist oxidation and aging, which can affect the long-term durability of asphalt pavements.

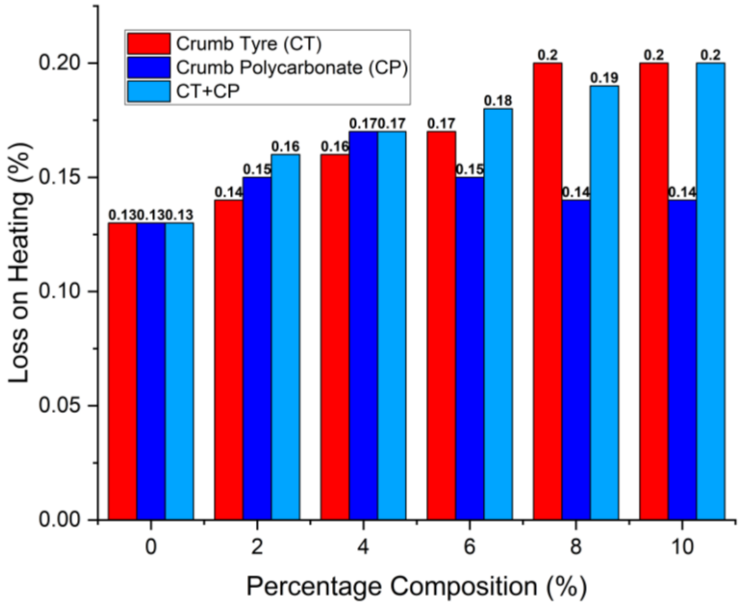

Figure 5 Loss on heating test

3.2.6. Viscosity

From the data in Table 4, the incorporation of crumb tyre and polycarbonate additives yielded a reduction in viscosity within the modified bitumen compositions. Specifically, the viscosity decreased from 2615 centistokes to 2463 centistokes for crumb tyre modified bitumen, from 2615 centistokes to 2416 centistokes for crumb polycarbonate modified bitumen, and from 2615 centistokes to 2449 centistokes for the combination of crumb tyre and polycarbonate modified bitumen. This reduction in viscosity shows that the modified bitumen exhibited a lower viscosity or increased fluidity compared to the original bitumen. Viscosity, in this context, serves as a metric for quantifying a fluid's resistance to flow. For bitumen, viscosity holds paramount importance as it profoundly influences various aspects, including workability, mixing characteristics, and coating properties during asphalt production and placement. Lower viscosity values indicate heightened fluidity, rendering the bitumen more manageable [19, 21, 22]. The implications of reduced viscosity in modified bitumen are far-reaching. Firstly, it simplifies the task of achieving comprehensive mixing of the bitumen with aggregates during asphalt production. This, in turn, enhances the coating of aggregates, leading to improved adhesion and overall stability of the asphalt mixture. Additionally, it facilitates superior workability during the process of asphalt placement and compaction. The modified bitumen, with its lower viscosity, can flow more readily, streamlining proper compaction and enabling the attainment of the desired pavement density. Furthermore, the decrease in viscosity may open doors to the utilization of lower mixing and compaction temperatures during asphalt production. This potential shift could yield energy savings and contribute to reduced environmental impact. Importantly, the reduced viscosity of the modified bitumen can play a pivotal role in enhancing resistance against rutting. It enables the bitumen to deform and recover more effectively under the load of traffic, thereby bolstering the overall performance of the asphalt pavement.

Table 4 Viscosity

Percentage Additive Composition	**Viscosity (centistokes)**			**Test Method**	**Specification**
	Crumb Tyre (CT)	**Crumb Polycarbonate (CP)**	**CT+CP**		
0	2615	2615	2615	ASTM D-2171	2400 Min.
2	2543	2565	2480		
4	2525	2515	2478		
6	2504	2475	2470		
8	2466	2454	2458		
10	2463	2416	2449		

3.2.7. Flash and fire point

From Table 5, the elevation in both the flash and fire points of bitumen, resulting from the addition of crumb tyre and polycarbonate, is noteworthy. Specifically, the flash point increased from 281°C to 319°C, while the fire point increased from 281°C to 317°C. These increments signify that the modified bitumen possessed a higher threshold temperature at which it released flammable vapors and became susceptible to ignition. The significance of these heightened flash and fire point values lies in the realm of safety. The modified bitumen, with its higher flash and fire points, demands elevated temperatures to initiate the release of flammable vapors. This, in turn, mitigates the risk of inadvertent ignition or fire during storage, transportation, and handling operations. Moreover, the augmented flash and fire points of the modified bitumen imply an enhancement in its thermal stability. It can endure higher temperatures without undergoing rapid decomposition or combustion. This attribute proves advantageous in scenarios where the bitumen may encounter elevated temperatures during mixing, transportation, or construction phases. The heightened flash and fire points also expand the spectrum of potential applications, encompassing environments with elevated temperatures or potential heat sources. The modified bitumen thus becomes a viable choice for use in settings where conventional bitumen, characterized by lower flash and fire points, may not be suitable [13]. In summary, it becomes evident that the additive compositions containing 10% crumb tyre, 10% crumb polycarbonate, and 10% of the combination of crumb tyre and polycarbonate outperformed other percentage compositions. Consequently, these values are identified as the optimum proportions for the binder additive.

Table 5 Flash and Fire Point

Percentage Additive Composition	Flash and Fire Point (^{O}C)			Test Method	Specification
	Crumb Tyre (CT)	Crumb Polycarbonate (CP)	CT+CP		
0	281	281	281	ASTM D-92	≥ 250
2	287	291	287		
4	287	301	279		
6	301	297	276		
8	307	311	272		
10	319	317	268		

3.3. Marshall Mix Design Ratio and Optimum Bitumen Content

The Marshall mix design used to determine the ratio of aggregates and filler to be used in the production of asphalt concrete is presented in Table 6.

Table 6 Marshal Mix Design

Bitumen Content	Wt. of Coarse Aggregate	Wt. of Fine Aggregate	Wt. of Filler	Wt. of Bitumen	Materials	Gs of Materials	Parameters	Value
8	708	144	252	96	CA	2.8	Max Stability	5.5
7.5	750	144	216	90	FA	2.6	Max GM	7
7	756	144	216	84	Filler	1.9	Vv @ 4%	6.3
6.5	762	144	216	78	Bitumen	0.98	Average	6.27
6	768	144	216	72				
5.5	774	144	216	66				
5	780	144	216	60				

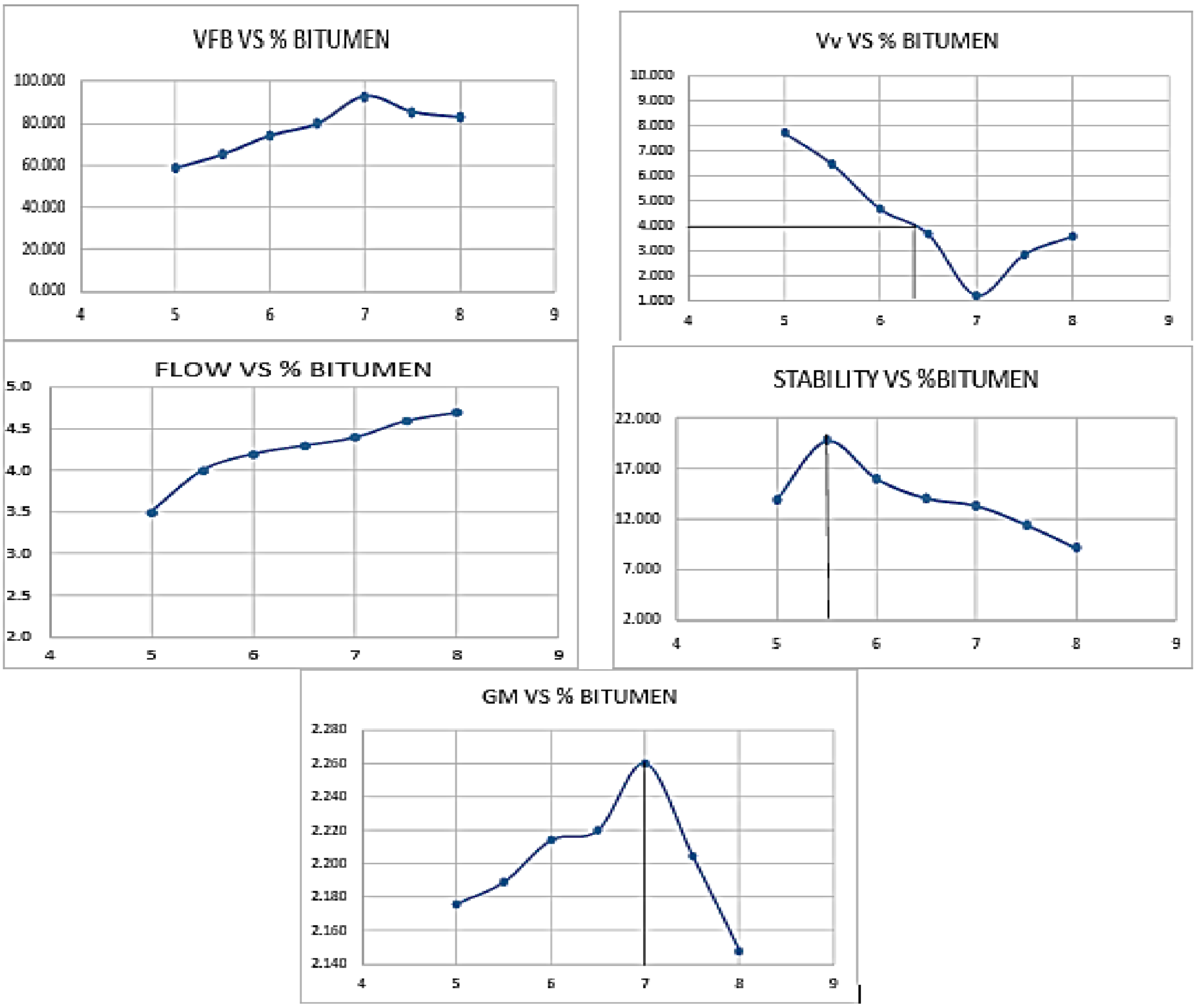

Figure 6 Marshall mix design

3.4. Performance Evaluation Tests

The results of performance evaluation tests (Marshall stability and indirect tensile tests) performed on the asphalt concrete produced with optimum bitumen content and optimum additive content are discussed in the following sections.

3.4.1. Marshall stability test

The results of Marshall stability tests done to determine the flow and stability of the asphalt concrete produced with optimum binder content and optimum additive content is presented in Table 7.The Marshall stability test results reveal that, when employing the optimum additive content at the ideal binder content, the asphalt concrete exhibited average Marshall stability values of 7.93 kN for crumb tyre, 8.25 kN for crumb polycarbonate, and 10.50 kN for the combination of crumb tyre and polycarbonate. In a similar vein, the average flow values for these respective mixtures were 3.50 mm, 3.33 mm, and 3.53 mm. To assess these results against industry standards, the typical Marshall design criteria, as outlined by the Asphalt Institute in 1997, prescribes 2.224 kN for light traffic roads, 3.336 kN for medium traffic roads, and 6.672 kN for heavy traffic roads. It is evident that the stability and flow values obtained comfortably meet the minimum requirements stipulated by the Asphalt Institute (1997) for all categories of roads, as summarized in Table A in the appendix section. Furthermore, the result of the Marshall stability quotient obtained showed larger values which is an indication of greater stability and strength of the asphalt mix, which is desirable for the construction of durable and long-lasting roads.

Table 7 Marshall Stability

Crumb Tyre (CT)			Crumb Polycarbonate (CP)			CT + CP		
Stability (kN)	**Flow (mm)**	**Marshall Quotient (kN/mm)**	**Stability (kN)**	**Flow (mm)**	**Marshall Quotient (kN/mm)**	**Stability (kN)**	**Flow (mm)**	**Marshall Quotient (kN/mm)**
6.79	3.7	1.84	9.11	3.70	2.46	10.70	4.00	2.67
8.74	3.6	2.43	7.21	3.00	2.40	10.75	3.40	3.16
8.27	3.2	2.58	8.44	3.30	2.56	10.07	3.20	3.15
7.93	3.50	2.28	8.25	3.33	2.47	10.50	3.53	2.99

3.4.2. Indirect tensile strength test

The results of indirect tensile strength test done to assess the tensile properties of materials used in asphalt concrete produced with optimum binder content and optimum additive content is presented in Table 7.The indirect tensile strength result showed that the average wet indirect tensile strength of the asphalt concrete produced with optimum additive content at optimum binder content were 363.18 kN/m^2 for crumb tyre, 543.15 kN/m^2 for crumb polycarbonate and 970.21 kN/ m^2 for the combination of crumb tyre and polycarbonate. Likewise, the average dry indirect tensile strength for crumb tyre, crumb polycarbonate and the combination of crumb tyre and polycarbonate are 3603.31 kN/m^2, 873.61 kN/m^2 and 1247.41 kN/m^2 respectively. These higher values of indirect strength of the asphalt concrete implies that the material has a greater ability to resist tensile stresses and maintain its structural integrity when subjected to forces pulling it apart. This property is essential for ensuring the durability, safety, and long-term performance of materials used in various construction and engineering applications. At this juncture, it is important to say that the combination of crumb tyre and polycarbonate gives the highest Marshall stability flow and indirect tensile strength values which makes them perform better than other additives.

Table 8 Indirect Tensile Strength Test

Crumb Tyre (CT)			Crumb Polycarbonate (CP)			CT + CP		
Wet ITS (kN/m^2)	**Dry ITS (kN/m^2)**	**TSR (%)**	**Wet ITS (kN/m^2)**	**Dry ITS (kN/m^2)**	**TSR (%)**	**Wet ITS (kN/m^2)**	**Dry ITS (kN/m^2)**	**TSR (%)**
377.41	636.04	59.34	497.70	790.41	62.97	845.241	1132.34	74.65
246.20	570.58	43.15	636.04	956.81	66.48	998.01	1362.49	73.25
465.93	603.31	77.23	495.70	873.61	56.74	1067.38	1247.41	85.57
363.18	603.31	59.91	543.15	873.61	62.06	970.21	1247.41	77.82

4.0 CONCLUSIONS AND RECOMMENDATIONS

This section presents the summary of findings from the laboratory experiments carried out, the conclusion and recommendations.

This research has focused on the use of crumb tyre, crumb polycarbonate and a combination of both crumb tyre and polycarbonate as additives for the modification of bitumen and the determination of the strength properties asphalt produced with optimum bitumen content and optimum additive content. Based on the research conducted and findings made, the following conclusions are made:

i. Crumb tyre and crumb polycarbonate and a combination of crumb tyre and polycarbonate had stiffening effects on bitumen. The additives caused an alteration of the molecular structure and intermolecular interactions within the bitumen. This is confirmed by the decrease in the penetration value of the modified bitumen.

ii. The ductility of bitumen increased tremendously when the additives were added to the bitumen in the proportion used. This is in consonance with the hardening and stiffening effect the additive had on the bitumen. There is a formation of a more interconnected network or the modification of the molecular structure of the bitumen, allowing it to stretch further before reaching its breaking point. The additives modify the properties of bitumen, influencing its ability to resist deformation.

iii. The softening point of the natural unmodified bitumen increased with the introduction of additives to the bitumen. This is a further confirmation of the stiffening effect the additives had on the bitumen. The increase in the softening point suggests that the additive modifies the bitumen's molecular structure or composition, making it less susceptible to softening and deformation at elevated temperatures.

iv. The viscosity of the bitumen decreased when the additives were added to modify the bitumen, the implication of decreased viscosity in modified bitumen is that lower viscosity makes it easier to achieve thorough mixing of the bitumen with aggregates during asphalt production.

v. The additives were also able to increase the flash and fire point properties of the bitumen which suggests an improved thermal stability, which means that it can withstand higher temperatures without undergoing rapid decomposition or combustion.

vi. In the final analysis, it is evident that 10% crumb tyre, 10% crumb polycarbonate and 10% combination of crumb tyre and polycarbonate outperformed other percentage additive compositions, and therefore taken as the optimum value for the binder additive.

vii. The Marshall mix design showed that the optimum bitumen content was 6.3%.

viii. There stability and flow of the asphalt concrete samples produced with an optimum binder content of 6.3% and optimum additive content of 10% meet the requirement of the asphalt institute for light, medium and heavy traffic roads.

ix. The indirect tensile strength of the asphalt concrete samples produced with optimum binder content of 6.3% and optimum additive content of 10% had higher values. These higher values of indirect strength of the asphalt concrete imply that the material has a greater ability to resist tensile stresses and maintain its structural integrity when subjected to forces pulling it apart.

x. The 10% combination of crumb tyre and polycarbonate performed best out of the optimum additive contents.

Conflicts of Interest

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

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Appendix

Table A Typical Marshall Design Criteria

Marshall Mix Criteria	Light Traffic ($<10^4$ ESALs) Min	Light Traffic ($<10^4$ ESALs) Max	Medium Traffic ($<10^4$ ESALs) Min	Medium Traffic ($<10^4$ ESALs) Max	Heavy Traffic ($<10^4$ ESALs) Min	Heavy Traffic ($<10^4$ ESALs) Max
Compaction (number of blows on each end of the sample	35		50		75	
Stability	2224N (500Ibs)		3336 (750Ibs)		6672 (1500Ibs)	
Flow (0.25mm (0.01 inch)	8	20	8	18	8	16
Percent Air Voids %	3	5	3	5	3	5

Source: Asphalt Institute (1997)