The effect of polymer composition on hot mix asphalt (HMA) is the primary focus of this research. The primary goal is to examine how temperature affects HMA's mechanical characteristics and performance, especially concerning polymer concentration. Polymer composition and modifications to HMA, including synthetic rubber and high-density polyethylene (HDPE), are the object of this research. Optimizing HMA polymer mix to improve durability, load-bearing capacity, and structural integrity is the study's key issue. The study also seeks to understand the intricate interaction between polymer concentration and HMA parameters, such as compressive strength, modulus, and stress. The research findings indicate that the maximum load of 68.169 kN was achieved with a mixture containing 5 % synthetic rubber at a temperature of 200 °C. The material exhibited stiffness and resistance to deformation, with an average crack size of 0.01 kN/mm² and a modulus value of 0.309 kN/mm². According to the Marshall function, the optimal blend consists of 5 % asphalt mixed at 175 °C. The results indicate that polymer mix considerably affects HMA's mechanical properties, particularly load-bearing capacity and deformation resistance. To optimize HMA performance, polymer content and temperature must be optimized. The results show that HMA with 5 % synthetic rubber under specified temperature settings has better mechanical qualities, including load-bearing capacity and stiffness. These findings help optimize polymer composition for HMA performance. These findings can be used to create more lasting and eco-friendly paving solutions. Road engineers and designers can extend asphalt pavement life and reduce environmental effects by adjusting the HMA polymer mix and temperature

***Keywords:** hot mix asphalt, synthetic rubber, Marshall test, optimal asphalt content*

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IDENTIFYING THE EFFECT OF POLYMER COMPOSITION IN HOT MIX ASPHALT MODIFICATION

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1. Introduction

The unprocessed liquid bitumen, or asphalt, is a viscous, sticky mixture of hydrocarbon molecules, chlorine, sulfur, and oxygen [1]. Due to its viscoelastic properties, asphalt solidifies at room temperature, making it a suitable binding medium for flexible pavement construction [2]. Asphalt's chemical makeup is unknown despite its widespread use. Asphalt molecules are saturated, unsaturated, aliphatic, and aromatic carbon compounds with 150 carbon atoms each. Asphalt contains nitrogen, sulfur, oxygen, and others. Over 80 % of asphalt is carbon. Hydrogen is 10 %, sulfur is 6 %, nitrogen, oxygen, and trace metals, including iron, nickel, and vanadium, are the rest [3]. These chemicals are primarily asphaltenes and maltenes, with the former having a lower molecular mass. Asphaltene content is usually 5–25 %. Asphalt is predominantly a polar compound.

Asphalt is used to build road pavements due to its durability and flexibility. Pavement layers must be better and more stable to prevent vehicular damage. Integrating additives is crucial to improving pavement quality. Asphalt, made from natural or petroleum-processed components, is adaptable [4]. Modified material technology has led to many breakthroughs, including alloy asphalt [1, 5]. Many elements are added to typical asphalt compositions to create modified asphalt. Styrofoam, wood ash, bamboo sticks, avocado leaves, natural and synthetic rubber, plastic garbage, and other modified materials are included [6, 7]. This research examines the fusion or modification of waste polymer (plastic) materials with discarded rubber from old motor vehicle tires using a wealth of information and references [8].

Various alternatives, including natural and synthetic rubbers, can be explored using rubber as a modified material in asphalt mixtures [9]. Several sources emphasize the feasibility of using natural rubber, usually pre-cured latex with a high water content and long hydrocarbon chains with double bonds, called neoprene. The flexible and pliable properties of asphalt are improved by this modified natural rubber's capacity to absorb the asphalt's oil or molten. Nevertheless, keep in mind that natural rubber structures can be affected by changes in temperature. If the mixing temperatures are too high when blending, the rubber modifier's quality and effectiveness could be compromised [10].

One potential additive for improving asphalt binders is Crumb Rubber, often known as chopped rubber, made of synthetic or artificial rubber [11]. With its remarkable chemical properties, this Crumb Rubber composition blends natural and synthetic rubber components. This mixture has the right proportions of carbon (60.14 %), polymer (25.42 %), plasticizer (4.95 %), dust (7.57 %), and sulfur (1.64 %), making it an excellent choice for improving the asphalt binder's qualities. Specifically, binders that include 15 % Crumb Rubber combined at 6,000 rpm for 60 minutes at a temperature of 140 °C show the best results [12].

Various research initiatives are currently investigating the addition of different additives to improve the quality of road asphalt. These efforts aim to develop asphalt mixtures with the best strength and durability, leading to improved road surface performance and longer lifespan. Plastic and rubber are currently being explored as promising additives. Numerous research studies have investigated the impact of incorporating plastic or rubber into asphalt mixtures, seeking to understand how these materials affect different characteristics and performance measures. The importance of these studies is in the ability of plastic and rubber additives to enhance flexibility, boost resistance to cracking, and enhance the overall durability of asphalt mixtures. These improvements are crucial for improving the overall quality and durability of road surfaces. Therefore, research on the influence of added materials such as rubber, plastic aggregate, and asphalt is still relevant.

2. Literature review and problem statement

Research on polymer-modified asphalt has covered a lot of ground, illuminating the advantages of adding polymers to hot mix asphalt (HMA) mixes. Integrating polymers like styrene-butadiene-styrene (SBS) [13], styrene-butadiene rubber (SBR) [14], and polyethylene (PE) [15] into HMA formulations has been shown to have beneficial impacts in tests. The results of these studies provide strong evidence of improvements in various important pavement performance parameters. Polymer addition improves rutting resistance, increasing pavement strength to resist deformation from heavy traffic. Also, the fatigue performance has been improved, which means that the polymer-modified asphalt can withstand cyclic loading without breaking. More than that, adding polymers to pavement has increased its resilience to water, reduced the likelihood of damage from water seepage, and made it last longer. The structural integrity and performance of polymer-modified asphalt have been shown to remain intact over lengthy periods of service, making it an excellent aging material.

The study [13] illuminates how styrene-butadiene-styrene (SBS) polymer modifier affects asphalt binders. SBS polymer modifier's impacts on asphalt binder structure, characteristics, and performance are examined in this comprehensive study. This thorough examination explains the material's behavior under various settings. The study uses rigorous experimental methods like FTIR, XRD, DSC, and rheological testing to define and evaluate the asphalt binder. The study only examined AP-5 asphalt and solvent deasphalting pitch, which may limit its applicability to different asphalt combinations and polymer modifiers. Future research could apply the findings to more asphalt binders and modifiers. The work gives useful laboratory insights but lacks field trials or asphalt surface performance testing. Field validation would increase the findings' real-world applicability. This study affects pavement engineers and researchers who modify asphalt binders and design pavement. Understanding SBS polymer modifier effects can help create high-performance asphalt mixtures for long-lasting roads.

The work [14] tests polymeric aggregate treatment to reduce moisture damage in hot-mix asphalt. Specifically, the study evaluates HMA moisture damage potential and polymeric aggregate treatment efficacy. A clear goal guides the research. The study tests moisture damage using laboratory tests such as boiling water, TSR, and ITS. Asphalt mixture moisture susceptibility is often tested with these methods. A small sample size may reduce the statistical robustness of the investigation. A bigger sample size would increase data representativeness and conclusion dependability. The study prioritizes laboratory studies to determine immediate moisture damage. However, the endurance and effectiveness of polymeric aggregate treatment in field settings are unknown. Long-term field trials would better understand the treatment asphalt mixture performance. These findings are relevant to asphalt pavement engineers and HMA moisture damage mitigation practitioners. Polymeric aggregate treatments may improve asphalt pavement durability and performance in damp areas.

The study [15] examines how ultra-high-molecular-weight polyethylene (UHMWPE) affects hot mix asphalt performance. The research uses UHMWPE, an innovative new asphalt addition. Testing the effects of UHMWPE on HMA performance parameters fills a gap in the literature and advances asphalt pavement materials research. The study investigates Marshall stability, flow, voids in mineral aggregate (VMA), and indirect tensile strength of HMA with UHMWPE in a thorough manner. This multi-faceted testing method evaluates UHMWPE's effect on HMA characteristics. The study evaluates HMA with UHMWPE performance in the lab. Adding UHMWPE to asphalt pavements is challenging to evaluate without field validation or long-term performance data. Field tests or performance monitoring studies would reveal UHMWPE-modified HMA's durability and long-term performance. The study examines HMA with UHMWPE performance, not its processes or interactions with asphalt binder. Detailed chemical and physical interactions between UHMWPE and asphalt binder could help explain how UHMWPE impacts HMA characteristics. Field validation studies could assess the long-term performance of UHMWPE-modified HMA in real-world settings to address the deficiencies. Additionally, mechanistic studies of UHMWPE-asphalt binder interactions may reveal the reasons behind HMA property changes. An optimization study could find the best UHMWPE dosage and particle size distribution for HMA performance improvements.

The paper [16] demonstrates that asphalt performance can be enhanced by using polyethylene (PE). Asphalt's resistance to rutting, fatigue life, moisture susceptibility, and aging behavior are all improved by PE modification. The optimization and installation of PE-modified asphalt binder is still an open question, notwithstanding these encouraging findings. The inability to enhance all performance metrics, the high expenses of the necessary research plans, which makes some investigations economically unsustainable, or objective challenges related to PE and other additive interactions could be to blame for these unsolved concerns. Rethinking the research strategy and including more advanced testing procedures, modeling methodologies, or new material combinations may be able to solve the unanswered questions. Researchers, industry experts, and regulators could address these issues by collaborating. To better understand the complexities of PE-modified binders, developing a systematic approach to testing and assessment and sharing relevant data and experiences may be helpful.

The research [17] compares the applications of high-content styrene-butadiene-styrene (SBS) polymer-modified bitumen. Our study revealed that adding a significant amount of styrene-butadiene-styrene (SBS) greatly enhances the ability of asphalt to resist rutting, withstand fatigue, and maintain its durability over time. These advancements raise concerns regarding the widespread application and efficient utilization of high-content SBS polymer-modified bitumen. The unresolved concerns may stem from objective challenges associated with the intricate interplay of SBS polymers and asphalt binders, the difficulties in consistently attaining performance enhancements across various asphalt mix designs, or the expensive nature of thorough research studies. A practical approach is to engage in collaborative research to address the complex technological challenges associated with high-content SBS alteration. Collaborative research teams consisting of materials scientists, pavement engineers, and polymer chemists can potentially enhance the performance of SBS-modified bitumen by creating novel formulations and refining production techniques.

The review [18] assesses the present state of high polymer-modified asphalt binders and mixes. High polymer-modified asphalt binders and mixes provide superior performance compared to ordinary asphalt formulations in terms of resistance to rutting, fatigue, moisture damage, and aging. Despite the improvements, numerous issues remain regarding the broader implementation and improvement of high polymer-modified asphalt binders and mixtures. The unresolved issues stem from the intricate nature of polymer interactions within asphalt binders, the challenge of achieving consistent performance enhancements across various polymer types and dosages, and the substantial expenses associated with conducting extensive research studies on high polymer-modified asphalt mixtures. These difficulties may be resolved by collaborative research, which includes materials scientists, pavement engineers, polymer chemists, and industry partners. This technique would provide a comprehensive investigation of the technical issues related to high polymer-modified asphalt binders and mixtures and the development of innovative solutions.

The paper [19] examines incorporating recycled plastic into hot-mix asphalt (HMA) concrete through dry-mixing. Incorporating recycled plastic in HMA concrete mixtures enhances resistance to rutting, decreases the amount of asphalt binder used, and promotes sustainability. Despite some advancements, concerns persist regarding the overall utilization and optimization of HMA concrete mixed with recovered plastic. These issues persist because of objective challenges associated with the intricate interactions between recycled plastic particles and asphalt binder, the difficulties in consistently enhancing performance across various types and sizes of recycled plastic particles, and the high expenses involved in conducting comprehensive research studies on modified mix designs that incorporate recycled plastic. To address these problems, researchers might investigate the impact of various characteristics of recycled plastic, such as particle size, shape, and surface properties, on the performance of HMA concrete mixtures. Materials scientists, pavement engineers, recycling experts, and industry stakeholders can work together to include recovered plastic in HMA mixtures.

The research [20] investigates the impact of thermoplastic additives on asphalt concrete mixtures. Thermoplastic additives enhance the ability of asphalt concrete compositions to resist rutting, increase fatigue life, reduce moisture susceptibility, and improve aging behavior. Although the study presents positive results, it also expresses concerns over the widespread utilization and optimization of thermoplastic additives in asphalt concrete mixtures. The unresolved issues stem from objective challenges such as the intricate interplay between thermoplastic additives and asphalt binders, the struggle to consistently enhance performance across different types of asphalt concrete, and the expensive nature of conducting thorough research studies on modified mix designs incorporating thermoplastic additives. Additional research into the mechanisms through which thermoplastic additives impact asphalt concrete mixtures may solve these problems. Thorough thermoplastic-modified asphalt concrete testing in laboratory and field settings, including different climatic and loading conditions, may be necessary.

Research on hot-mix asphalt (HMA) has covered everything from asphalt mixes to modified bitumen polymers, rubber, and plastic. The literature has no systematic study of the best polymer mixture with asphalt. The percentage of rubber, plastic, and aggregate in asphalt will be varied in this research to address this gap. The influence of polymer % on asphalt is crucial to this study since it can improve quality. By systematically altering it, researchers can learn how polymer % affects asphalt qualities, including rutting resistance, fatigue life, moisture susceptibility, and aging. This empirical method finds the best polymer percentages for asphalt performance and durability. Pavement design and construction require knowledge of how polymer proportion affects asphalt qualities. Engineers and practitioners can build asphalt mixtures for certain environmental conditions and traffic loads by discovering the best polymer percentages. This can result in more robust and sustainable pavement solutions that improve transportation infrastructure longevity and performance.

3. The aim and objectives of the study

The aim of the study is identifying the effect of polymer composition such as synthetic rubber, high-density polyethylene (HDPE)+synthetic rubber, and aggregates in hot mix asphalt modification. This will make it possible to enhance road quality and significantly extend the lifespan of road surfaces. Roads can be constructed to have increased resistance to cracking, improved flexibility, and extended durability through the use of asphalt mixtures enhanced with additives like plastics and rubber. By implementing this solution, road maintenance costs can be reduced, and road user safety can be improved. Additionally, there will be a positive impact on the environment through waste reduction and using recycled materials. Therefore, applying the research findings is anticipated to yield substantial advantages for society and the environment.

To achieve this aim, the following objectives are accomplished:

– to determine the effect of a mixture of synthetic rubber with hot mix asphalt (HMA);

– to identify the optimal asphalt content and ideal mixing temperature produced by each synthetic rubber and rubber+HDPE mixture with hot mix asphalt (HMA).

4. Materials and methods of experiment

4. 1. Object and hypothesis of the study

Hot mix asphalt (HMA) alteration and polymer composition are complex topics, and this study aims to explore both. This study intends to reveal the complex effects of different polymer types and compositions on important HMA properties by conducting thorough research. An asphalt pavement's overall performance and longevity are greatly affected by its qualities, which include a range of important traits like rutting resistance, fatigue life, moisture susceptibility, and aging behavior. Taking a systematic approach, this study aims to investigate the complex relationship between polymer composition and HMA modification to understand them better. This study aims to optimize asphalt pavement design and construction methods by conducting a thorough analysis to find patterns, correlations, and insights. The ultimate goal of this project is to advance materials engineering by creating asphalt pavements that are more durable, environmentally friendly, and able to handle a wide range of traffic and environmental conditions.

This study hypothesizes that the modification and performance of hot mix asphalt (HMA) are heavily influenced by the complex relationship between its characteristics and the composition of polymers. According to the hypothesis, a key factor affecting the overall behavior and durability of HMA formulations is the proportion and choice of polymers. Rutting resistance, fatigue life, moisture susceptibility, and aging behavior are critical HMA qualities expected to be significantly affected by polymer type and content changes. We hope that by conducting a thorough and systematic analysis, our study will shed light on the complex effects of polymer composition on HMA modification. This analysis aims to find out how to build better asphalt pavements by carefully studying these consequences. In addition, the theory proposes that asphalt pavement engineering will undergo a paradigm shift when the function of polymer composition in HMA modification is better understood. The study hopes to contribute to the evolution of resilient and sustainable infrastructure by optimizing asphalt pavement options.

4. 2. Materials

The primary material used as the basis for this study is bulk asphalt pen.60/70, well-known for its extensive use in asphalt pavement construction because of its favorable viscosity and temperature susceptibility properties. This material is the main matrix used to incorporate different modifiers and study their impact on hot mix asphalt (HMA) properties. Aside from bulk asphalt pen.60/70 (Fig. 1, *a*), the study includes various modifiers to improve the performance and longevity of HMA. Out of all these modifiers, synthetic rubber waste (Fig. 1, *b*) is a standout sustainable alternative that helps reduce environmental impact and enhances the resilience of HMA against rutting and cracking. Utilizing high-density polyethylene (HDPE) polymer waste (Fig. 1, *c*) in the asphalt mixture enhances HMA stiffness and resistance to deformation from heavy traffic loads. Enhancing these modifiers are fine and coarse aggregates (Fig. 1, *d*), crucial elements that play a key role in the structural strength and durability of the asphalt mixture.

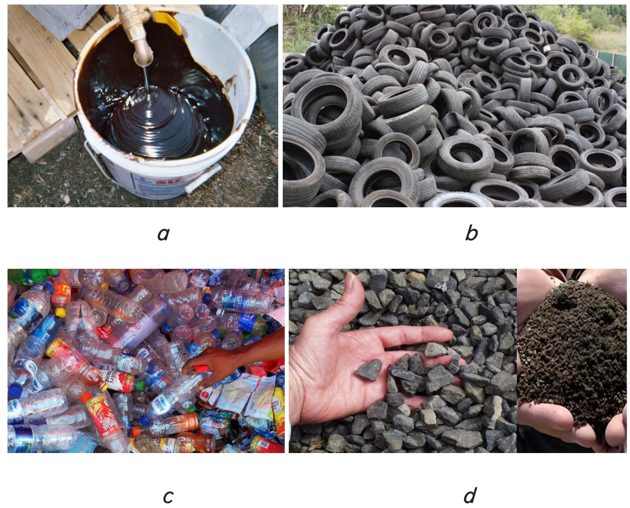

Fig. 1. The primary material for hot mix asphalt: *a* – bulk asphalt pen.60/70; *b* – synthetic rubber; *c* – high-density polyethylene; *d* – coarse and fine aggregates

By incorporating these additives into the asphalt mix, the study evaluates how they impact various HMA characteristics, such as resistance to rutting, fatigue life, susceptibility to moisture, and aging tendencies. By conducting thorough analysis and experiments, the study aims to explore the complex connection between modifier composition and HMA modification, ultimately enhancing sustainable and high-performance asphalt pavement solutions.

4. 3. Methods and sample testing

The aggregate and asphalt mixture is improved further by adding synthetic rubber or a mixture of synthetic rubber and High-Density Polyethylene (HDPE) after it has been made. Examining how these additives change the asphalt mixture's characteristics is the goal of this extra stage. The asphalt briquettes are then made from the mixture; they have a specified weight of 1,200 grams, a diameter of 101.6 mm, and a height of 63.5 mm (Fig. 2). In preparation for further testing, especially compression testing, these asphalt briquettes are used as representative examples. Compressive strength, a key indicator of the asphalt mixture's capacity to endure load-bearing situations in actual pavement applications, can be evaluated using this testing methodology. Researchers can determine asphalt briquettes' mechanical performance and pressure durability by compressing them under controlled conditions.

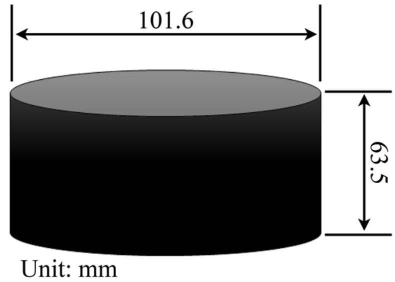

Fig. 2. Dimensions of asphalt briquettes

Providing an overview of the parameters used in creating asphalt briquettes, including temperature variations and additive percentages, is shown in Table 1. The experiment involves testing three temperature settings: 170 °C, 200 °C, and 230 °C, along with varying percentages of synthetic rubber added, ranging from 4 % to 6 %. The temperature fluctuations are crucial in determining the viscosity and flow properties of the asphalt mixture, affecting the compaction and mechanical traits of the resulting asphalt briquettes. Moreover, the following test includes blending synthetic rubber with High-Density Polyethylene (HDPE) additives, each at a 5 % ratio. Introducing this additional parameter variation brings a new dimension to the study to investigate the combined effects of these two modifiers on the properties of the asphalt mixture. Researchers are exploring the combination of synthetic rubber and HDPE additives to leverage each material's distinct properties, aiming to improve the performance and longevity of the asphalt briquettes. By incorporating various temperature variations and additive percentages in the experimental design, a thorough examination of their impact on the characteristics of the asphalt briquettes is facilitated. This systematic approach helps find the best conditions for creating asphalt mixtures with specific properties like enhanced compressive strength, durability, and resilience to different environmental factors.

Table 1

Hot mix asphalt composition parameters

Experiment number	Temperature (°C)	Synthetic rubber (%)
1	170	4
2		5
3		6
4	200	4
5		5
6		6
7	230	4
8		5
9		6
Experiment number	Temperature (°C)	Synthetic rubber + HDPE (%)
1	170	5
2	200	
3	230	

Critical testing to determine the compressive strength of hot mix asphalt modification briquette samples is the next crucial stage after their production. As a widely accepted standard for determining asphalt mixture compressive strength, the testing procedure follows the guidelines in ASTM D6931-12. The performance of asphalt mixtures can be reliably and consistently evaluated with the help of compression testing, which is laid out in detail in ASTM D6931 12. As part of this standard procedure, a universal testing machine (UTM) is commonly used to apply controlled compressive forces to asphalt briquette samples. Testing involves progressively increasing the compressive load on the briquette sample until it deforms or fails; this allows for assessing its compressive strength.

Marshall testing, a procedure widely recognized in the field of pavement engineering, is the next step in evaluating the stability and strength of hot mix asphalt (HMA) or asbestos-based aggregate mixtures. This comes after the compression testing. Using the Marshall test, researchers can evaluate essential factors such as density, voids in mix (VIM), voids in mineral aggregate (VMA), voids filled with asphalt (VFA), stability, and flow. This test is beneficial for gaining valuable insights into the performance characteristics of asphalt mixtures. When researchers conduct Marshall testing, they can acquire a comprehensive set of data that provides helpful information regarding the compactness, durability, and general quality of the asphalt mixture. The density measurement provides information on the compactness of the asphalt mixture and its resistance to deformation when subjected to traffic loads. The density measurement indicates its mass per unit volume. To optimize the mix design and ensure proper asphalt binder coverage, VIM, VMA, and VFA values are utilized to measure the proportions of void spaces present within the asphalt mixture.

However, the stability and flow values acquired by Marshall testing are significant indications of the asphalt mixture's resistance to rutting and deformation when subjected to traffic pressure. As a measure of the compacted specimen's total strength and resistance to permanent deformation, stability is determined by the highest load the specimen can withstand before showing signs of failure. Flow, on the other hand, is a method that measures the deformation or deformation resistance of the asphalt mixture when it is subjected to a particular load. This method provides information regarding the asphalt mixture's capacity to accommodate traffic-induced stresses. In addition, the information that is gathered during Marshall testing is utilized to ascertain the optimal asphalt content. This is significant since it is essential for obtaining the ideal equilibrium between durability, flexibility, and resistance to distresses such as cracking and rutting. Researchers can fine-tune the design of the asphalt mix to meet specific performance requirements by studying the findings of Marshall testing. This helps ensure that the pavement infrastructure will be in good structural condition and last for a long time.

5. Results of the experiment on a mixture of synthetic rubber and synthetic rubber+HDPE with hot mix asphalt

5. 1. Results of the effect of a mixture of synthetic rubber

The data collected from the compressive strength testing of the asphalt mixtures provides essential information regarding load, stress, and modulus values. Fig. 3 depicts the load values acquired from various temperature fluctuations on synthetic rubber mixtures, offering valuable insights into the performance of the asphalt mixtures across different temperature scenarios. Upon examining Fig. 3, it is clear that temperature changes can result in different outcomes for the load values of asphalt mixtures with varying percentages of synthetic rubber. It is intriguing to note that the findings reveal a pattern of higher load as the synthetic rubber content increases at lower temperatures (170 °C), suggesting a beneficial impact of synthetic rubber on the load-bearing capacity of the asphalt mixture.

However, at 200 °C, a noticeable shift in the load values is observed. Specifically, when the load decreases for asphalt mixtures containing 4 % and 6 % synthetic rubber, there is an increase in load for the mix with 5 % synthetic rubber. Investigation into the asphalt mixture's response to the synthetic rubber revealed that, due to temperature dependence, the 5 % mixture outperformed other compositions in load-bearing ability at 200 °C. Furthermore, at the highest temperature tested (230 °C), the load values exhibit a significant decrease for the asphalt mixture containing 6 % synthetic rubber, with the lowest load value recorded at this temperature. Higher temperatures might impact the strength of asphalt mixtures with added synthetic rubber, potentially due to changes in material properties or degradation processes. Highlighting that the asphalt mixture containing 5 % synthetic rubber demonstrates the highest load value of 68.17 kN at 200 °C, indicating an optimal combination of temperature and synthetic rubber content for improving load-bearing capacity. However, the asphalt mixture containing 6 % synthetic rubber demonstrates the lowest load value of 25.92 kN at a temperature of 230 °C. Highlighting the significant impact of temperature control and material composition on the mechanical behavior of asphalt mixtures.

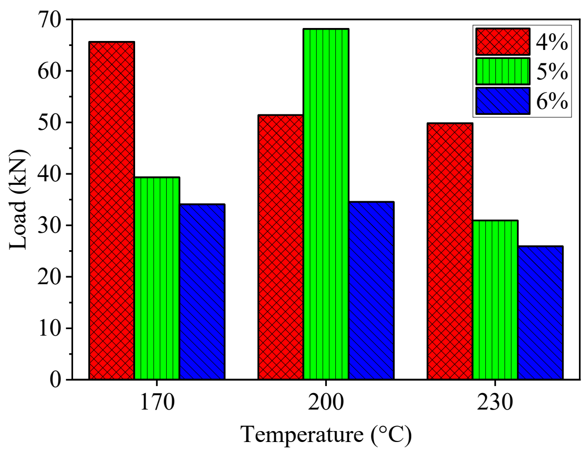

Fig. 3. Load value of synthetic rubber with hot mix asphalt

Fig. 4 depicts stress values for synthetic rubber and hot mix asphalt (HMA) at temperatures ranging from 170 °C to 230 °C, demonstrating varying amounts of synthetic rubber content. The data provides vital insights into the material's behavior under different temperature settings and concentrations of synthetic rubber. After examining the stress values across the whole temperature range, it is clear that at 170 °C, 200 °C, and 230 °C, the blend containing 4 % synthetic rubber consistently exhibits the highest stress level, reaching a peak of 0.01 kN/mm^2. Evidence suggests that using 4 % synthetic rubber in the asphalt mixture enhances its resistance to strain, particularly under high temperatures.

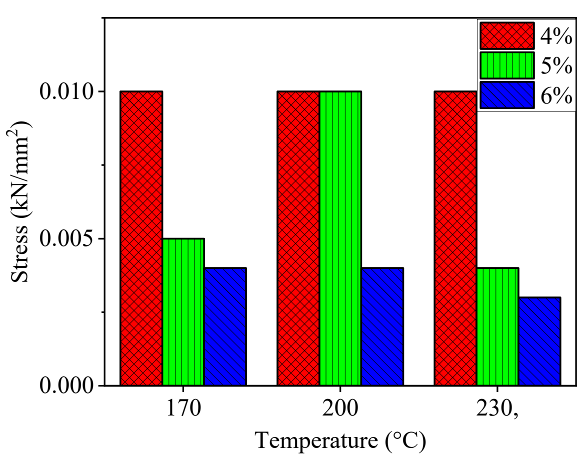

Fig. 4. Stress value of synthetic rubber with hot mix asphalt

When the temperature reaches 200 °C, the mixture containing 5 % synthetic rubber has a peak stress value of 0.01 kN/mm^2, indicating a comparable stress resistance to the mixture containing 4 % synthetic rubber in this particular situation. Evidence suggests that the asphalt combination, which includes 5 % synthetic rubber, maintains its structural integrity and can withstand high stress levels at increased temperatures. Conversely, the stress value decreases to 0.003 kN/mm^2 at a temperature of 230 °C for the combination containing 6 % synthetic rubber. Higher quantities of synthetic rubber at increasing temperatures lead to a significant decrease in stress resistance. This phenomenon can be ascribed to changes in the characteristics of the materials or the deterioration mechanisms associated with the increased proportion of synthetic rubber.

The modulus values obtained from the compressive strength test results are shown in Fig. 5. This figure illustrates the modulus fluctuations across various temperature settings and percentages of synthetic rubber mixture. The modulus values reveal important information about the asphalt mixtures' stiffness and resilience to deformation in different environments. A clear trend toward a temperature-dependent rise in modulus is seen when looking at the modulus values for the 4 % synthetic rubber combination. Heat makes the asphalt mixture with the 4 % synthetic rubber more rigid and deformation-resistant. The combination of temperature and synthetic rubber content results in the highest stiffness and structural integrity level, as the highest modulus value of 0.441 kN/mm^2 is seen at 230 °C.

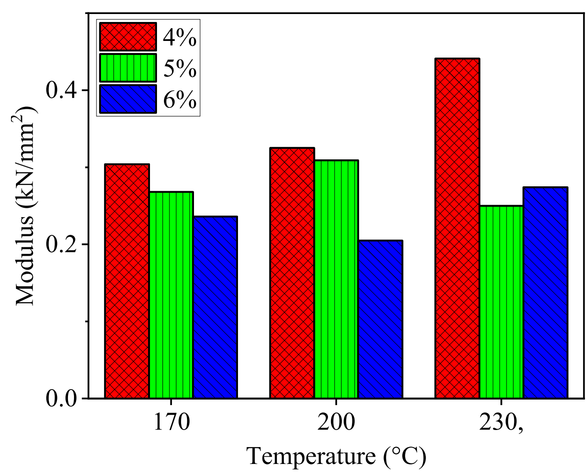

Fig. 5. Modulus value of synthetic rubber with hot mix asphalt

The modulus value pattern differs for the 4 % combination and the 5 % and 6 % synthetic rubber mixes. Modulus values at 200 °C exhibit both rises and declines for these mixes. Given the observed variation in modulus values, it is reasonable to assume that mixes, including varying amounts of synthetic rubber, may have different ideal temperatures and proportions to maximize stiffness and resistance to deformation. The mixture with 6 % synthetic rubber has the lowest modulus value of 0.205 kN/mm^2 when heated to 200 °C. This suggests that when asphalt is mixed with 6 % synthetic rubber and heated to 200 °C, the material becomes less stiff and more easily deformed.

5. 2. Results of the optimal asphalt content produced by each mixture of synthetic rubber and synthetic rubber+HDPE

The asphalt binder is crucial in designing asphalt mixtures and requires careful optimization to achieve the desired performance characteristics. Identifying the ideal asphalt content value is a critical aspect of the mix design process, as it plays a significant role in the quality, longevity, and effectiveness of the asphalt pavement. Decisions are usually made after thoroughly examining a range of Marshall parameters derived from research findings, such as density, stability, flow, VIM, VMA, and VFA. Fig. 6 displays the findings on identifying the ideal asphalt content, showing how asphalt content impacts crucial Marshall parameters. By carefully examining these parameters, researchers can pinpoint the asphalt content value that results in the most favorable mix properties and performance characteristics.

Examining density, stability, and flow offers valuable information about the asphalt mixture's compactness, strength, and workability. Asphalt content values should lead to asphalt mixtures with high density, stability, and flow, ensuring structural integrity and resistance to deformation under traffic loads. VIM, VMA, and VFA play crucial roles in determining the void structure of the asphalt mixture. VIM indicates the air voids in the compacted mixture, whereas VMA indicates the void space between aggregate particles. On the contrary, VFA represents the space filled with asphalt binder. Finding the ideal asphalt content values that can optimize VMA and VFA while reducing VIM is important. This will result in a strong, long-lasting asphalt mixture with suitable void characteristics.

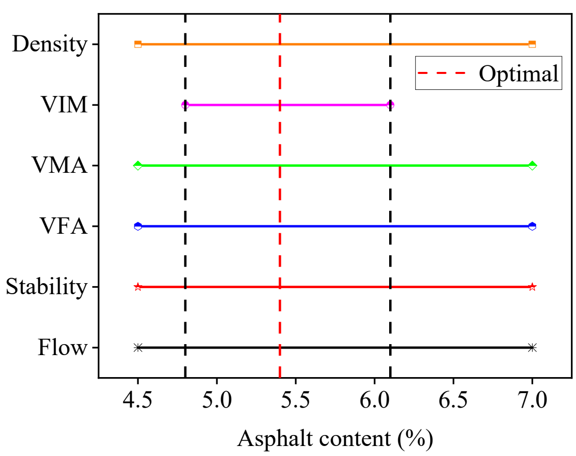

Fig. 6. Optimal asphalt content from synthetic rubber+HDPE with hot mix asphalt

The best asphalt content for the AC-WC (Asphalt Concrete - Wearing Course) mixture type must be found in the middle of the asphalt content range that meets requirements. This study's optimal asphalt content value affects pavement performance, durability, and quality. This study's extensive examination shows that the ideal asphalt concentration for AC-WC mixtures is 5.40 %. This value is in the center of the asphalt content range that meets the criteria and maintains the best asphalt binder content for pavement performance.

After compaction, asphalt mixture density affects structural integrity, durability, and performance. Many passes of compaction equipment are required to create uniform pavement layer density to meet specifications. Compaction may comprise applying compaction forces to each side of the test object 75 times at a regulated temperature. Temperature fluctuations during compaction can significantly affect asphalt mixture density. As temperature rises, asphalt binder viscosity falls, covering and compacting aggregate particles better and increasing density. The density values of modified asphalt mixtures with HDPE polymer and synthetic rubber additives vary depending on asphalt composition. The density values of modified asphalt mixes at varying asphalt content percentages are obtained by rigorous testing and analysis. Results show that the modified asphalt mixture has a density ranging from 2.25 g/cm^3 for low content to 2.27 g/cm^3 for high concentration (7 %).

Voids in Mix (VIM), the air voids between aggregate particles coated with asphalt binder, is a vital asphalt pavement mixing property. VIM stated as a percentage, indicates asphalt mixture compactness and void structure. Lower VIM percentages mean a denser, more compact mixture, which improves pavement performance and longevity. In this investigation, the VIM value that meets requirements is between 170 °C and 180 °C. Within this temperature range, the asphalt mixture has the desired VIM values of 3.08 % to 2.98 %. These VIM readings indicate good pavement quality since the asphalt mixture has reached the target compaction and void structure.

Voids in Mineral Aggregate (VMA), reported as a percentage of the mixture's volume, is a necessary quantity. It measures the air voids in the solid aggregate particles. VMA affects asphalt pavement structural integrity, durability, and performance. VMA levels were measured from 170 °C to 230 °C in this investigation. Results show VMA values between 15.81 % and 15.27 % at this temperature. The asphalt mixture's compactness and void structure can be determined by these VMA values, which show the fraction of void space in the aggregate particles.

Voids Filled with Asphalt (VFA) is a critical asphalt mixture metric that measures the volume of voids filled with asphalt binder. VFA shows asphalt binder coating and filling efficiency in asphalt mixture void spaces as a percentage. High VFA percentages indicate a well-coated and densely filled asphalt mixture, which resists rutting, moisture damage, and fatigue cracking. In this study, VFA values were measured from 170 °C to 230 °C. This temperature range yielded 80.45 % to 83.87 % VFA values. These values indicate the extent of asphalt binder coverage and adhesion to aggregate particles by the proportion of vacant areas in the asphalt mixture filled with asphalt binder.

The stability rating of an asphalt mixture indicates its capacity to resist deformation and preserve its shape under stresses without permanent distortion. Asphalt pavements' structural integrity and performance depend on their stability, which affects their resistance to rutting, fatigue cracking, and other traffic loading and environmental stresses. Stability values were measured from 170 °C to 230 °C in the investigation. The stability values at this temperature ranged from 2257.71 to 2963.13 kg.

Flow, which measures pavement layer vertical deformation under loading conditions, is an important performance parameter. This rutting shows the pavement's ability to withstand the load without permanent distortion. Flow values help assess pavement layer structural integrity and long-term performance by revealing load-induced deformation. The study tested flow values from 170 °C to 230 °C. In this temperature range, flow values were 3.88–4.27 mm. Following load application, the pavement layer undergoes vertical deformation or rutting.

As shown in Fig. 7, the ideal mixing temperature is determined by the Marshall value, a consequence of extensive Marshall testing. These tests are necessary for evaluating the performance and features of the asphalt mixture. They assess numerous crucial factors, such as density, voids in mix (VIM), voids in mineral aggregate (VMA), voids filled with asphalt (VFA), stability, and flow. It was found that 175 °C is the ideal mixing temperature for the combination of synthetic rubber, Hot Mix Asphalt (HMA), and High-Density Polyethylene (HDPE) polymer. A careful evaluation was conducted to determine the optimal temperature for the asphalt mixture, considering the qualities such as density, void structure, stability, and flow.

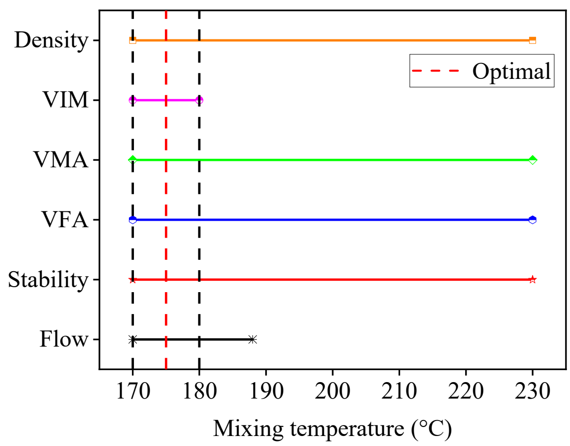

Fig. 7. Optimal mixing temperature from synthetic rubber+HDPE with hot mix asphalt

The next step is to add synthetic rubber and HDPE (High-Density Polyethylene) to the asphalt mixture, with a ratio of 5 %. Fig. 8 displays the compressive strength test results conducted on this experimental asphalt mixture. It should be noted that the maximum peak load value of 72.2 kN is recorded at a temperature of 170 °C. Also, at 200 °C, the peak modulus value is 0.77 kN/mm^2, the highest reported value. In addition, this stress value of 0.01 kN/mm^2 is maintained throughout all temperature parameters. These results improve our understanding of the asphalt mixture's mechanical characteristics and temperature-dependent behavior with synthetic rubber and HDPE additions. The measured peak load and modulus values throw light on the asphalt mixture's stiffness and load-bearing capabilities throughout different temperature ranges.

The asphalt mixture's remarkable peak load value at 170 °C shows it can sustain heavy loads without breaking. At this temperature, the addition of synthetic rubber and HDPE to the asphalt mixture has likely increased its load-bearing capability and structural integrity. At 200 °C, the peak modulus value also represents the asphalt mixture's rigidity and deformation resistance when subjected to loading. An increase in the modulus value indicates that the asphalt pavement is more resistant to permanent deformation and rutting, which improves its overall performance and longevity. The homogeneity and stability of the asphalt mixture are demonstrated by the consistent stress value across all temperature parameters, which implies homogeneous stress distribution throughout the mixture.

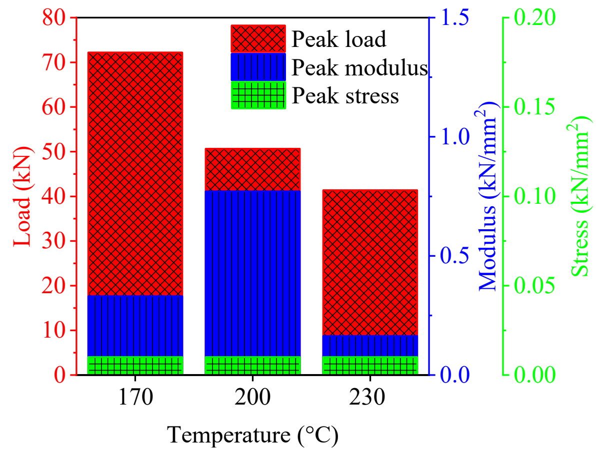

Fig. 8. Compressive strength value from synthetic rubber+HDPE with hot mix asphalt

6. Discussion of the experiment on the briquette stove performance of various stove cylinder materials

Synthetic rubber composition increases load-bearing capacity at lower temperatures (170 °C). This shows synthetic rubber may increase asphalt mixture cohesiveness and load-bearing capacity at lower temperatures [21]. When the temperature rises to 200 °C, load values change significantly. The load increases for asphalt combinations with 5 % synthetic rubber but reduces for those with 4 % and 6 %. This temperature-dependent response emphasizes the importance of temperature and material composition in assessing the mechanical performance of asphalt mixtures. At the highest temperature (230 °C), the load values for the asphalt mixture with 6 % synthetic rubber decline, suggesting that higher temperatures may reduce the load-bearing ability of such mixtures. Elevated temperatures may change material qualities or cause degradation, lowering load values [22]. The asphalt mixture with 5 % synthetic rubber has the greatest load value of 68.17 kN at 200 °C, showing an excellent temperature-synthetic rubber balance to increase load-bearing capacity. At 230 °C, the asphalt mixture with 6 % synthetic rubber has the lowest load value of 25.92 kN, demonstrating the importance of temperature management and material composition in the mechanical performance of the asphalt mixture (Fig. 3).

The asphalt combination with 4 % synthetic rubber has the highest stress level, peaking at 0.01 kN/mm^2 from 170 °C to 230 °C. This implies that adding 4 % synthetic rubber to asphalt improves its stress resistance, especially at high temperatures [23]. The persistent high-stress readings imply increased structural integrity and stress resistance with 4 % synthetic rubber. At 200 °C, the asphalt mixture with 5 % synthetic rubber has a peak stress value of 0.01 kN/mm^2, similar to the 4 % mixture (Fig. 4). This shows that the 5 % synthetic rubber asphalt blend maintains structural soundness and stress-bearing capacity at high temperatures, like the 4 % composition. Maximum temperature (230 °C) reduces the stress value to 0.003 kN/mm^2 for the asphalt mixture with 6 % synthetic rubber. This significant decrease in stress resistance at greater synthetic rubber concentrations shows potential constraints or issues with adding more synthetic rubber into asphalt, especially at high temperatures [24]. Material features or degradation mechanisms associated with more excellent synthetic rubber content may explain this stress resistance drop. Higher quantities of synthetic rubber may influence the asphalt mix's rheological properties or binder-aggregate interactions, lowering its stress-bearing capacity under extreme temperatures.

As seen in Fig. 5, asphalt mixtures with 4 % synthetic rubber increase modulus with temperature. A 4 % synthetic rubber asphalt mixture stiffens and resists deformation as temperature rises. Higher temperatures increase asphalt mixture stiffness and structural integrity, with the greatest modulus value of 0.441 kN/ mm^2 at 230 °C. However, 5 % and 6 % synthetic rubber asphalt mixtures have different modulus values. These combinations show modulus changes at 200 °C, demonstrating that synthetic rubber fraction affects stiffness and deformation resistance. Optimizing asphalt mixture stiffness and deformation resistance requires consideration of temperature and synthetic rubber content due to this unpredictability. The 6 % synthetic rubber asphalt mixture has the lowest modulus value of 0.205 kN/mm^2 at 200 °C. The larger concentrations of synthetic rubber may decrease stiffness and increase deformation, especially at high temperatures [25].

The asphalt binder is a key component in asphalt mixture formulation, determining pavement performance. An adequate asphalt composition is essential for maximum asphalt quality, lifespan, and effectiveness. Fig. 6 and 7 show how the correct asphalt composition and mixing temperature affect Marshall characteristics such as density, stability, flow, voids in mix (VIM), voids in mineral aggregate (VMA), and voids filled with asphalt (VFA). These factors are crucial for assessing mix attributes and performance. By examining these parameters, researchers can determine the best asphalt content for mix qualities. This study finds that the ideal asphalt concentration for AC-WC mixtures is 5.40 % by examining the range of asphalt content that meets requirements. Pavement performance, longevity, and quality are optimal at this asphalt content value in the center. The comprehensive investigation in this study underlines the importance of asphalt content in pavement qualities and performance. Synthetic rubber, Hot Mix Asphalt (HMA), and High-Density Polyethylene (HDPE) polymer should be mixed at 175 °C for the appropriate mix qualities. Density, void structure, stability, and flow are evaluated, emphasizing the importance of temperature control in asphalt mixture optimization.

The addition of synthetic rubber and HDPE to asphalt at 5 % indicates a significant advance in improving asphalt performance. Fig. 8 shows how the compressive strength test results of this experimental asphalt mixture reveal its mechanical properties and temperature-dependent behavior. The asphalt mixture's maximum peak load value of 72.2 kN at 170 °C shows its strong load-bearing capabilities at moderate temperatures. The asphalt blend's peak load value shows its structural integrity and resilience to external loads and strains. At 200 °C, the peak modulus value of 0.77 kN/mm^2 emerged as the highest in the test series. This higher modulus number emphasizes the asphalt mixture's rigidity and deformation resilience, especially at high temperatures. Keeping a high modulus value at 200 °C shows the asphalt blend can endure thermal loads and environmental conditions in real-world applications. The asphalt mixture's steady stress value of 0.01 kN/mm^2 across all temperature parameters indicates its consistent stress resistance. This homogeneous stress behavior shows the asphalt blend's stability and predictability in different temperatures, making it suitable for various climates [26].

One potential limitation of the study is that the research may have been carried out in controlled laboratory settings, which might not accurately replicate the real-world conditions faced by asphalt pavements under various environmental factors and traffic loads. The study assesses the initial effects of polymer-modified asphalt mixtures, providing significant findings on short-term performance while omitting information on long-term durability and effectiveness. The study may focus mainly on performance criteria like compressive strength or modulus, potentially overlooking other important factors affecting asphalt pavement performance, such as fatigue resistance, rutting, and moisture susceptibility.

The primary disadvantage of this study is the assumption that the polymer is evenly dispersed and uniformly distributed in the asphalt mixture, which might not reflect real-world scenarios accurately. Polymer dispersion in the asphalt matrix can be challenging because of inadequate mixing or material properties. Future research could explore more advanced mixing techniques and additional components to enhance polymer distribution and uniformity in asphalt mixtures. Utilizing high-shear mixing or incorporating surfactants or compatibilizers can improve the dispersion of polymers and their interaction with asphalt binders. Exploring new additives or modifiers may enhance polymer dispersibility and compatibility in asphalt mixtures. These additives facilitate the even distribution of polymers throughout the asphalt matrix, improving the performance and lifespan of the polymer-modified pavement.

Research on polymer composition in hot mix asphalt (HMA) modification could be conducted in different ways to advance understanding and overcome limits. Researching asphalt modification polymers' molecular structure and rheology could be a future direction. The complex molecular interactions between polymers and asphalt binders may reveal the mechanics behind polymer-modified asphalt performance. The molecular structure of polymers and their influence on asphalt binder characteristics may make it difficult to quantify and analyze these complicated interactions. Analysis using spectroscopy or molecular modeling may be needed to address these obstacles. Experimental challenges may occur while studying the impact of polymer composition on HMA performance under different temperatures. With so many polymer compositions and temperature settings to study, consistent findings and varied control in laboratory research might be complex. Translating lab findings to real-world applications may be tricky. Validating laboratory results and determining the practicality of using specific polymer compositions in asphalt pavements requires field experiments and long-term performance evaluations. Field trials require acquiring test locations, arranging construction, and evaluating pavement performance over time.

7. Conclusions

1. The highest compressive strength was achieved with hot mix asphalt and 5 % synthetic rubber at 200 °C. This mixture has a strong load-bearing capacity, as the load peaked at 68.169 kN. The minimal crack found (0.01 kN/mm^2) indicates the mixture's resistance to deformation and structural integrity under compressive stresses. Additionally, the mixture's modulus value of 0.309 kN/mm^2 indicates its stiffness and resistance to deformation. These results demonstrate the

excellent mechanical performance of hot mix asphalt modified with 5 % synthetic rubber at the required temperature, making it suitable for applications with high compressive strength and structural stability.

2. The research finds the ideal asphalt concentration and mixing temperature by conducting a thorough investigation of Marshall values, which include stability, density, and flow, as well as characteristics like voids filled with asphalt (VFA), voids in mix (VIM), and voids filled with bitumen (VFB). The optimal combination for attaining the specified performance characteristics in the asphalt mixture is a mixing temperature of 175 °C and an asphalt concentration of 5 %, according to the results. These results are essential for directing their formulation and manufacturing procedures to guarantee the best possible quality, longevity, and performance in real-world applications of asphalt mixtures.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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The study was performed without financial support.

Data availability

Data will be made available on reasonable request.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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References

1. Caputo, P., Porto, M., Angelico, R., Loise, V., Calandra, P., Oliviero Rossi, C. (2020). Bitumen and asphalt concrete modified by nanometer-sized particles: Basic concepts, the state of the art and future perspectives of the nanoscale approach. Advances in Colloid and Interface Science, 285, 102283. https://doi.org/10.1016/j.cis.2020.102283
2. Al-Gurah, E. R., Al-Humeidawi, B. H. (2023). Assessment of performance of hot mix asphalt contained various types of mineral fillers and newly polymer modified bitumen. Materials Today: Proceedings, 80, 3877–3886. https://doi.org/10.1016/j.matpr.2021.07.406
3. Menapace, I., Yiming, W., Masad, E. (2018). Effects of Environmental Factors on the Chemical Composition of Asphalt Binders. Energy & Fuels, 33 (4), 2614–2624. https://doi.org/10.1021/acs.energyfuels.8b03273
4. Ekejiuba, A. I. B. (2021). Natural Petroleum: Chemistry and Valuable Products Fractions. Inter- World Journal Of Science And Technology, 4 (2), 300–337. Available at: https://www.researchgate.net/publication/350790219_Natural_Petroleum_Chemistry_and_Valuable_Products_Fractions
5. Li, R., Xiao, F., Amirkhanian, S., You, Z., Huang, J. (2017). Developments of nano materials and technologies on asphalt materials – A review. Construction and Building Materials, 143, 633–648. https://doi.org/10.1016/j.conbuildmat.2017.03.158
6. Behnood, A., Modiri Gharehveran, M. (2019). Morphology, rheology, and physical properties of polymer-modified asphalt binders. European Polymer Journal, 112, 766–791. https://doi.org/10.1016/j.eurpolymj.2018.10.049
7. Sun, D., Lu, T., Xiao, F., Zhu, X., Sun, G. (2017). Formulation and aging resistance of modified bio-asphalt containing high percentage of waste cooking oil residues. Journal of Cleaner Production, 161, 1203–1214. https://doi.org/10.1016/j.jclepro.2017.06.155
8. Revelo, C. F., Correa, M., Aguilar, C., Colorado, H. A. (2021). Composite materials made of waste tires and polyurethane resin: A case study of flexible tiles successfully applied in industry. Case Studies in Construction Materials, 15, e00681. https://doi.org/10.1016/j.cscm.2021.e00681
9. Al-Sabaeei, A., Yussof, N. I. Md., Napiah, M., Sutanto, M. (2019). A review of using natural rubber in the modification of bitumen and asphalt mixtures used for road construction. Jurnal Teknologi, 81 (6). https://doi.org/10.11113/jt.v81.13487
10. Wu, X., Lu, C., Han, Y., Zhou, Z., Yuan, G., Zhang, X. (2016). Cellulose nanowhisker modulated 3D hierarchical conductive structure of carbon black/natural rubber nanocomposites for liquid and strain sensing application. Composites Science and Technology, 124, 44–51. https://doi.org/10.1016/j.compscitech.2016.01.012
11. Gogoi, R., Biligiri, K. P., Das, N. C. (2015). Performance prediction analyses of styrene-butadiene rubber and crumb rubber materials in asphalt road applications. Materials and Structures, 49 (9), 3479–3493. https://doi.org/10.1617/s11527-015-0733-0
12. Yu, H., Leng, Z., Zhou, Z., Shih, K., Xiao, F., Gao, Z. (2017). Optimization of preparation procedure of liquid warm mix additive modified asphalt rubber. Journal of Cleaner Production, 141, 336–345. https://doi.org/10.1016/j.jclepro.2016.09.043
13. Nciri, N., Kim, N., Cho, N. (2017). New insights into the effects of styrene-butadiene-styrene polymer modifier on the structure, properties, and performance of asphalt binder: The case of AP-5 asphalt and solvent deasphalting pitch. Materials Chemistry and Physics, 193, 477–495. https://doi.org/10.1016/j.matchemphys.2017.03.014
14. Raza, A., Khan, I., Tufail, R., Frankovska, J., Mushtaq, M., Salmi, A. et al. (2022). Evaluation of Moisture Damage Potential in Hot Mix Asphalt Using Polymeric Aggregate Treatment. Materials, 15 (15), 5437. https://doi.org/10.3390/ma15155437

15. Hossein Hamedi, G., Ghalandari Shamami, K., Mazhari Pakenari, M. (2020). Effect of ultra-high-molecular-weight polyethylene on the performance characteristics of hot mix asphalt. Construction and Building Materials, 258, 119729. https://doi.org/10.1016/j.conbuildmat.2020.119729
16. Tahmoorian, F., Liyanapathirana, S., Yeaman, J., Egwurube, J. (2023). Performance of Hot-Mix Asphalt and Modified Binders Containing Polyethylene. Journal of Transportation Engineering, Part B: Pavements, 149 (1). https://doi.org/10.1061/jpeodx.pveng-502
17. Wu, W., Cavalli, M. C., Jiang, W., Kringos, N. (2024). Differing perspectives on the use of high-content SBS polymer-modified bitumen. Construction and Building Materials, 411, 134433. https://doi.org/10.1016/j.conbuildmat.2023.134433
18. Masad, E., Roja, K. L., Rehman, A., Abdala, A. (2020). A review of asphalt modification using plastics: a focus on polyethylene. Qatar. https://doi.org/10.13140/RG.2.2.36633.77920
19. Jitsangiam, P., Nusit, K., Teeratitayangkul, P., Ping Ong, G., Thienchai, C. (2023). Development of a modified Marshall mix design for Hot-mix asphalt concrete mixed with recycled plastic based on dry mixing processes. Construction and Building Materials, 404, 133127. https://doi.org/10.1016/j.conbuildmat.2023.133127
20. Zhdaniuk, V., Volovyk, O., Kostin, D., Lisovin, S. (2021). An investigation of the effect of thermoplastic additives in asphalt concrete mixtures on the properties of different types of asphalt concrete. Eastern-European Journal of Enterprise Technologies, 2 (6 (110)), 61–70. https://doi.org/10.15587/1729-4061.2021.227806
21. Aliha, M. R. M., Razmi, A., Mansourian, A. (2017). The influence of natural and synthetic fibers on low temperature mixed mode I + II fracture behavior of warm mix asphalt (WMA) materials. Engineering Fracture Mechanics, 182, 322–336. https://doi.org/10.1016/j.engfracmech.2017.06.003
22. Kodur, V. (2014). Properties of Concrete at Elevated Temperatures. ISRN Civil Engineering, 2014, 1–15. https://doi.org/10.1155/2014/468510
23. Wang, T., Xiao, F., Amirkhanian, S., Huang, W., Zheng, M. (2017). A review on low temperature performances of rubberized asphalt materials. Construction and Building Materials, 145, 483–505. https://doi.org/10.1016/j.conbuildmat.2017.04.031
24. Han, L., Zheng, M., Wang, C. (2016). Current status and development of terminal blend tyre rubber modified asphalt. Construction and Building Materials, 128, 399–409. https://doi.org/10.1016/j.conbuildmat.2016.10.080
25. Ruellan, B., Le Cam, J.-B., Jeanneau, I., Can vet, F., Mortier, F., Robin, E. (2019). Fatigue of natural rubber under different temperatures. International Journal of Fatigue, 124, 544–557. https://doi.org/10.1016/j.ijfatigue.2018.10.009
26. Fatemi, S., Zarei, M., Ziaee, S. A., Shad, R., Amir Saadatjoo, S., Tabasi, E. (2023). Low and intermediate temperatures fracture behavior of amorphous poly alpha olefin (APAO)-modified hot mix asphalt subjected to constant and variable temperatures. Construction and Building Materials, 364, 129840. https://doi.org/10.1016/j.conbuildmat.2022.129840