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An Effect of Different Temperatures on the Mechanical Properties of Hot-Mix Asphalt with Rubber Addition

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تأثير درجات الحرارة المختلفة على الخواص الميكانيكية للإسفلت الساخن المخلوط مع إضافة المطاط

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الملخص:
تُعد خصائص أسطح الرصف ذات أهمية بالغة نظرًا لارتباطها المباشر بالسلامة وراحة الركوب. تهدف هذه الدراسة إلى استخدام الطريقة الجافة لتحديد كيفية تأثير فتات المطاط على الرصف المرن. تُعرف نفايات المطاط التي تُطحن ميكانيكيًا أو تُطحن بالإطارات إلى قطع صغيرة باسم فتات المطاط. يتأثر بناء الطرق وإصلاحها في كلا البلدين بهذا الاختلاف. على سبيل المثال، هناك حاجة إلى كمية كبيرة من الأسفلت البترولي كمادة رابطة لأسطح الرصف في ليبيا. يحدث الضرر عادةً بسبب ارتفاع درجات الحرارة وهطول الأمطار. بسبب التمزق والتشقق وأنواع أخرى من التدهور، غالبًا ما تُظهر هذه الأسطح انخفاضًا في عمر الخدمة. قد تختلف المتانة العالية المُحسّنة لكل نوع، وهذا يمكن أن يُتوقع تشوهًا لا رجعة فيه مع ارتفاع درجة الحرارة؛ بالإضافة إلى ذلك، قد يكون لهذا تأثير على متانة الرصف وقوته. يُحسّن فتات المطاط بنسبة 2.5% خصائص قوة الشد غير المباشرة (ITS) في المناطق الباردة منخفضة الحرارة. فشلت العينات ذات المحتوى الأعلى من المطاط بشكل أسرع عند مستويات إجهاد محددة.

الكلمات الدالة: نفايات الإطارات ، HMA، UCS، ITS ، و ITSM.

Abstract
Pavement surface properties are of paramount importance due to their direct relation to safety and ride comfort. The purpose of this study is to use the dry method to ascertain how crumb rubber affects flexible pavement. Rubber waste that has been mechanically ground or tire-ground into tiny pieces is known as crumb rubber. Both nations' road building and repair are impacted by this difference. For instance, a significant quantity of petroleum asphalt is needed as a binder for pavement surfaces in Libya. Damage typically occurs due to high temperatures and rainfall. Because of tearing, cracking, and other types of degradation, these surfaces frequently exhibit a reduction in service life. The enhanced high toughness of each type may vary, and this can anticipate irreversible deformation as the temperature rises; additionally, this may have an impact on the pavement's durability and strength. With 2.5% Crumb Rubber (CR) improves indirect tensile strength (ITS) characteristics in the cold, low-

temperature zone.Samples with a higher crumb rubber content failed more quickly at specific stress levels.

Keywords: HMA, UCS, ITS, ITSM, tire wastes.

Introduction

The mechanical properties of asphalt mixtures are crucial in determining the performance and durability of roads, especially under changing environmental conditions. Asphalt pavements experience a variety of pressures, including chemical ones like oxidative aging and moisture degradation, as well as mechanical ones like traffic loads, which can eventually cause pavement cracking. [Kristjánsdóttir et al, 2007, Phan, et al, 2025]. Pavement durability is greatly impacted by asphalt's water-absorbing and oxidation-resistant qualities. Water absorption in asphalt frequently lowers the pavement's effective binder concentration, and oxidative asphalt hardening causes fatigue cracking in the pavement. [Azi et al., 2006, Phan, et al, 2025]. There is substantial evidence that asphalt oxidation affects the pavement's durability throughout its depth. [Phan et al, 2025]. However, with crumb rubber modified asphalt, the behavior of asphalt water absorption and oxidation in the field is still largely unknown.(CRMA) pavements, particularly in reference to their relationship to pavement longevity. Consequently, additional research on CRMA is still needed to comprehend the field's significance of CRMA pavement. [Kazemianet al, 2025].

The issue of disposing of used tires has gotten worse in recent years due to the continuous rise in the global car population, raising grave worries about pollution in the environment. [Czarna-Juszkiewicz et al, 2023]. Tires can stay in landfills for 80 to 100 years since they don't break down readily. [Batayneh et al., 2008, Phan,et al, 2025]. This problem has led to the search for sustainable solutions for recycling these wastes, and one of the most prominent solutions is the use of crumb rubber from discarded tires as an additive in asphalt mixtures [Ramroopet al, 2025,].

The purpose of this study is to investigate how various temperatures affect the mechanical characteristics of HMA when aggregate is added with crumb rubber. The research focuses on the southern Libya region as a model, as this region is characterized by harsh climatic conditions with high temperatures and significant temperature fluctuations, which directly affect the performance and durability of asphalt pavements. The importance of this research lies in providing innovative and sustainable solutions to improve road performance under these challenging conditions, in addition to contributing to addressing the environmental waste problem resulting from discarded tires.

Although the use of crumb rubber in asphalt mixtures to enhance their qualities is becoming more popular, there are still knowledge gaps that require further research, especially regarding the effect of high and low temperatures on the performance of these mixtures in regions with harsh climatic conditions such as southern Libya. The research problem is manifested in the following points:

- ❖ Lack of Specific Studies: Few researches have examined the impact of varying temperatures. (Particularly extremely high and extremely low temperatures) on the mechanical characteristics of HMAtreated with crumb rubber in the context of the climate of southern Libya. Most research focuses on regions with temperate or cold climates, making their results not directly applicable to hot desert regions.
- ❖ Effect of CR on Thermal Properties: Although it is well established that crumb rubber increases asphalt mixtures' resistance to both permanent deformation brought on by high temperatures and low-temperature cracking, the precise mechanisms by which crumb rubber interacts with asphalt and aggregate under these extreme thermal conditions still require deeper understanding [Hamedi et al, 2025, Xie et al, 2024, Xieet al, 2025].

- ❖ Determining the Optimal CR Content: Under the severe heat conditions of southern Libya, the ideal CR content for asphalt mixtures that produces the optimum mechanical performance has not yet been identified. Different percentages of CR can lead to varying results, necessitating precise experiments to determine this optimal content [Borinelli et al, 2024].
- ❖ Effect of Addition Method (Dry vs. Wet):Although the current research focuses on the dry method, It is necessary to use both dry and wet methodologies to compare the performance of CR modified mixes., especially regarding their effect on mechanical properties under different temperatures [Ramroop et al, 2025].

In order to close these gaps, this study thoroughly examines the mechanical characteristics of Hot Mix Asphalt (HMA) amended with CR at various temperatures, with a focus on the climatic conditions of southern Libya. This research will contribute to providing valuable data and practical recommendations to improve the design and construction of roads in regions with harsh climatic conditions, thereby enhancing the sustainability of road infrastructure and reducing costs associated with maintenance and repair.

This research has multiple aspects of significance, as it contributes to:

- ❖ Scientific Contribution: This research adds new knowledge to the scientific literature related to CR modified asphalt mixtures, especially concerning their performance under harsh climatic conditions characteristic of regions like southern Libya. It also highlights current research gaps and provides a methodology to address them.
- ❖ Practical Application: The research provides practical recommendations for engineers and decision-makers in road construction and maintenance, enabling them to design more durable asphalt mixtures resistant to harsh weather conditions. This will lead to extending the lifespan of roads and reducing maintenance costs in the long run.
- ❖ Environmental Sustainability: The research contributes to promoting sustainable construction practices by exploring the use of recycled CR from discarded tires. This not only reduces the amount of waste ending up in landfills but also provides a sustainable alternative to traditional raw materials, supporting the circular economy.
- ❖ Economic Impact: By improving road performance and reducing the need for frequent maintenance, this research can achieve significant economic savings at the national level, especially in countries facing similar environmental challenges.
- ❖ Adaptation to Climate Change:With the increasing severity of extreme weather events, developing road construction materials capable of withstanding these conditions becomes crucial. This research offers solutions that contribute to enhancing the adaptability of road infrastructure to climate change.

Through these aspects, the research seeks to provide a comprehensive contribution that extends beyond the academic aspect to include environmental, economic, and social dimensions, thereby enhancing the quality of life and supporting sustainable development in the targeted regions.

1. Methodlogy

2.1 Unconfined Compressive Stress (UCS) Test

The unconfined creep test, sometimes referred to as the basic creep test or the uniaxial creep test, was the foundation for numerous investigations aimed at forecasting permanent HMA deformation. In order to prevent the specimen from failing too soon, the creep experiment is carried out at relatively low stress levels (often not approaching 30 psi (206.9 kPa)) and low temperatures (typically not exceeding 104° F (40° C). (Brown et al, 2001, Phan,et al, 2025).

The material known as HMA is influenced by temperature, tension, and time. The mechanical behavior of HMA is described by a wide range of constitutive models, including elasticity, viscoelasticity, plasticity, and creep. HMA only exhibits elastic behaviour at low temperatures, however. According to Al-Qadi et al. (2009) and Phan et al. (2025), it measures the creep pressure of HMA. The suggested nonlinear time-hardening creep model could forecast shear creep strains at the tire imprint's edge brought on by various tire designs as well as main rutting damage in HMA.

A method for calibrating micro fiber discrete element modelling (MDEM) to estimate the complex modulus of asphalt mixtures in extension/compression across a range of test temperatures and load frequencies was developed by Buttlar (Buttlar, 2004). Compared to more traditional calibration techniques, their method yielded precise estimations of the modulus across a range of test temperatures and frequencies. (Liu, 2005, Phan,et al, 2025).

The rutting potential of HMA mixtures has been estimated using the creep test (confined or unconfined). In this test, an HMA specimen is subjected to a static load, and the permanent deformation that results is measured. The unconfined creep test has been used extensively in research to estimate permanent deformation in HMA. It has been discovered that in order to prevent the sample from failing too soon, the creep test needs to be carried out at relatively low stress levels (cannot typically exceed 30 psi (206.9 kPa) and low temperatures (cannot typically exceed 104°F (40°C) [Brown et al., 20011, Phan, et al, 2025].

The compressive strength (F) is calculated using the following equation:

$F = \, Load\ applied\ per\ unit\ area\ of\ the\ sample\ surface = \frac{P}{A}$.........................(1)

2.2 Indirect Tensile Test (ITS)

For the design and study of asphalt concrete pavements, it is crucial to forecast how the material will behave under realistic repetitive loading. Both the development of damage and the robust recovery brought on by crack propagation, relaxation, and healing must be taken into account when modelling the fatigue behaviour of asphalt concrete under repeated loading with rest intervals. Because these mechanisms happen simultaneously, judging them is challenging.The following formula is used to determine the compacted bituminous mixture's tensile strength:

$ITS = 2F / (\pi * h * d)$.................................(2.)

2.3Indirect Tensile Resilient Modulus (MR) Test

Radziszewski (2007), states that the compaction process of asphalt concrete has a significant impact on its strength and overall longevity.High shear strength and rut resistance are characteristics of rubberized concrete pavement. (Lee et al, 2007). The average static ITSof conditioned specimens, expressed as a percentage of the average static ITSof unconditioned specimens, is known as the tensile strength ratio. The material's vulnerability to moisture affects this ratio. (Palit et al, 2004).

The amended ASTM D4123 states that the indirect tensile resilient modulus test must be performed at 40° C. (10). This test measures the robust modulus of asphalt mixtures using repetitive load indirect tension. The horizontal (δH) and vertical (δV) deformations, The indirect tensile resilient modulus was calculated using recoverable materials.Resilient Modulus is calculated using the following equation:

MR $= \frac{P.(\,\mu+0.27)}{t.\delta H}$..(3)

$\mu = 3.59 \cdot \frac{\delta H}{\delta V} - 0.27$..(4)

2. Resulat and dissuction :

3.1 ITS

The specimen mixture's tensile strength and pressure were evaluated using the stress test. Along the vertical diametric axis, specimens were monotonically primed to fail at a steady rate of 3 in/min (76.2 mm/min). The ITStest is an additional technique for determining the tensile strength of stable materials.This test involves driving a compressive filled cylindrical model together with two opposite generators. As a result, the tensile stress is comparatively uniform and perpendicular. It causes a splitting failure, which often happens along the diametric planes, in accordance with the demurral plan of the applied load. The three samples were measured for each type of HMAwith and without CR at temperatures of 10°C, 25°C, 40°C, and 60°C. The ITStest findings for each type of HMA in OBC, both with and without crumb rubber, are summarized in Figure 1 and Table 1. The following formula is used to determine the compacted bituminous mixture's tensile strength:

$ITS = \frac{2F}{3.14(h.d)}$TS2F/3.14(h.d) ……………………………………………………….………… (5.)

Table 1 Comparison of indirect tensile strength test at OBC

CR%	OBC	ITS@10C°	ITS@25C°	ITS@ 40C°	ITS@ 60C°
without CR	6.10	210.810	71.757	23.977	13.147
2.5% CR	6.20	217.90	87.274	27.024	15.028
4.5% CR	6.25	154.60	54.294	20.881	7.955
6.5% CR	6.35	125.041	45.222	24.334	5.791

The relationship between the various temperatures and the ITS is shown below in Figure 1

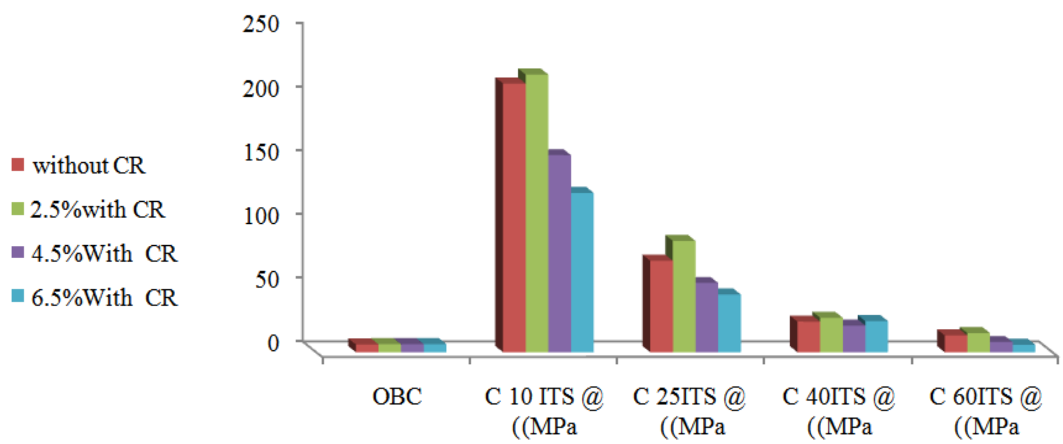

Figure 1 Results of the ITS each and HMA Concrete without and with CR

The impact of varying CR percentages on the ITS of HMA at different temperatures (10, 25, 40, and 60°C) is shown in Table 1 and Figure 1. The following observations can be drawn:

1. At 10C°temperature.

- ✓ The combination of asphalt that containsg 2.5% CRshowed the highest ITS value (217.90 MPa), surpassing the mixture without CR(210.810 MPa). This indicates that adding 2.5% CR effectively enhances the tensile strength of the mixture at low temperatures.
- ✓ With an increase in CR content to 4.5% and 6.5%, ITS values significantly decreased (154.60 and 125.041 MPa, respectively). This suggests an optimal CRcontent, beyond which an increase can lead to performance deterioration.

2.At 25C°temperature.

- ✓ The 2.5% CR content still achieved the highest ITS value (87.274 MPa), confirming its effectiveness in improving tensile strength at moderate temperatures compared to the mixture without CR (71.757 MPa).
- ✓ The decrease in ITS values continued with increasing CR content to 4.5% and 6.5% (54.294 and 45.222 MPa, respectively), reinforcing the idea of an optimal content.

3.At 40C° temperature.

- ✓ At this high temperature, 2.5% CR content remained the best (27.024 MPa). However, it is noted that the mixture containing 6.5% CR (24.334 MPa) outperformed the mixture without CR (23.977 MPa) and the mixture containing 4.5% CR (20.881 MPa). This suggests that higher percentages of CRmight show better performance at very high temperatures compared to traditional mixtures, although not generally the best.

4.At 60C°temperature.

- ✓ The 2.5% CR content continued to achieve the highest ITS value (15.028 MPa). However, all values significantly decreased at this high temperature, indicating that high temperatures negatively affect the tensile strength of all mixture types.
- ✓ The mixture containing 6.5% CR showed the lowest ITS value (5.791 MPa) at this temperature, confirming that very high percentages of CR might not be beneficial at extreme temperatures.

Across all measured temperatures, the asphalt mixture amended with 2.5% CR performs best overall in terms of indirect tensile strength. This indicates that crumb rubber, at an optimal percentage, significantly enhances the asphalt mixture's mechanical characteristics, increasing its resistance to tensile cracking, especially in changing climatic conditions. Additionally, the asphalt mixture with CR is stronger than the one without. The 2.5% CR asphalt mixture is more durable than the 4.5% and 6.5% CRasphalt mixtures. This is because the asphalt mixture becomes thicker and more resistant to cracking when the spaces are filled in with crumb rubber. [Phan et al, 2025].

3.2 The Unconfined Strength Properties

This method was used to evaluate bitumen mixtures to determine their resistance to deformation under the influence of loads at selected temperatures (24, 30, 40 and 60) degrees Celsius, and different loads. The actual load is obtained after the continuous application of the OBC to the specimens. This approach was used to evaluate the permanent deformation of HMA without CR. HMA was assessed at 3% CR by using UTM with a force of 1 kg. The unconfined test method is considered the most widely used for measuring shear strength, largely due to its simplicity and low cost.

The results of the unconfined compressive strength test are shown in Table 2 and Figure 2.

Table 2. Comparison of the Unconfined compressive strength test at OBC at different temperatures °C

CR %	OBC	UCS @24 C°	UCS @ 30C°	UCS @40C°	UCS @60C°
without CR	6.10	5060	3990	2280	1620
with CR 2.5%	6.20	3030	2770	2470	1080
With CR 4.5%	6.25	2010	3170	1900	1100
With CR 6.5	6.35	2465	1400	2790	1730

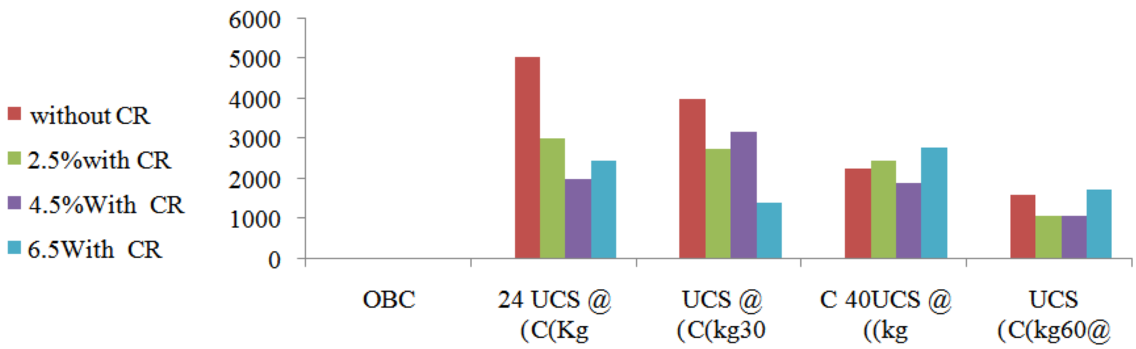

Figure 2. Results of the UCS each and HMA concrete without and with CR at different temperatures °C

- **At 24C° temperature.**
  - ✓ An asphalt mixture without CR achieved the highest UCS value (5060 kg) [Lhwaint2020], indicating it is the most resistant to compression at this temperature compared to CR modified mixtures.
  - ✓ Mixtures containing CR showed lower UCS values: 2.5% CR (3030 kg), 4.5% CR (2010 kg), and 6.5% CR (2465 kg). This may indicate that adding CR can reduce the unconfined compressive strength at relatively low temperatures.

- **At 30C° temperature.**
  - ✓ The mixture without CR still achieved the highest UCS value (3990 kg). However, the mixture containing 4.5% CR (3170 kg) performed better than 2.5% CR (2770 kg) and 6.5% CR (1400 kg) at this temperature.
  - ✓ It is noted that the UCS value significantly decreased for 6.5% CR at this temperature, indicating that this percentage might not be suitable at moderate temperatures.

- **At 40C° temperature.**
  - ✓ The mixture containing 6.5% CR showed the highest UCS value (2790 kg), surpassing the mixture without CR (2280 kg), 2.5% CR (2470 kg), and 4.5% CR (1900 kg). This suggests that higher percentages of CR might be more effective in improving compressive strength at high temperatures.

- **At 60C°temperature.**
  - ✓ The mixture containing 6.5% CR continued to achieve the highest UCS value (1730 kg), followed by the mixture without CR (1620 kg). Meanwhile, 2.5% CR and 4.5% CR showed lower values (1080 kg and 1100 kg, respectively).
  - ✓ Overall, the results show that adding CR can improve the performance of asphalt mixtures in the UCS test at high temperatures (40°C and 60°C), especially with 6.5% CR. Due to the presence of CR, it has been indicated that it reduces the sensitivity of asphalt to different temperature changes, making it more resistant to permanent deformation in hot conditions [1].

The results show that the asphalt mixture without CR has higher unconfined compressive strength at low temperatures (24 and 30°C). However, at high temperatures (40 and 60°C), CR modified mixtures, especially those with 6.5% CR, show better performance. This indicates that CR contributes to reducing the asphalt mixture's sensitivity to high temperatures, enhancing its resistance to permanent deformation in hot environments. This variation in performance emphasizes the importance of selecting the optimal CR content based on anticipated climatic conditions.

3.3 The Indirect Tensile Strength Modulus Properties

Using UMMATTAP, the ITSM test was performed on HMA and thin reference samples. Table 3 and Figure 3 present the results of the analysis, which was conducted at room temperature. Three samples were evaluated for each combo, both with and without CR. To determine the stiffness modulus for a mixture, the sample was assessed under three distinct conditions; the mean value was chosen.

Table.3 Comparison of ITSModulus test.

CR%	OBC	ITSM (MPa) @ 20C⁰					Average (MPa)
No CR	6.10	2893	3071	2771	2801	2804	2868
2.5%	6.20	1652	1654	1658	1653	1679	1659
4.5%	6.25	1482	1484	1457	1444	1433	1460
6.5%	6.35	1103	1069	1031	921	474	920

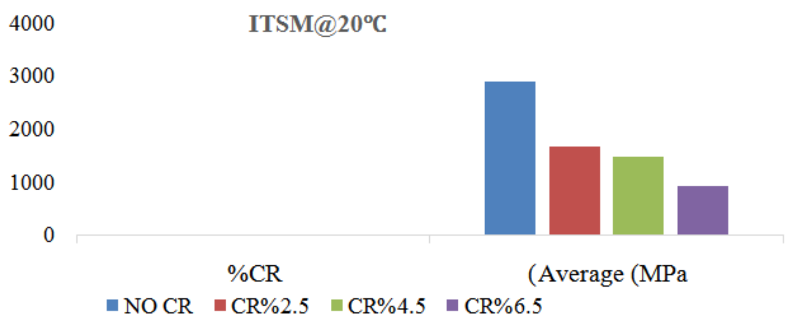

Figure 3 The results of ITSM each and HMA concrete without and with CR

Table 3 and Figure 3 shown the results that adding CR reduces the ITS Modulus of the asphalt mixture, meaning it becomes less stiff and more flexible. This change in properties can be beneficial in improving the mixture's resistance to low-temperature cracking and repeated stresses. However, the optimal CR content must be carefully selected, as very high percentages can lead to an excessive reduction in stiffness, which could negatively affect pavement performance under high traffic loads. The ITSM odulus test at 20°C with 2.5% CR exhibited the best performance of 1659 MPa, suggesting that this percentage strikes a reasonable balance between stiffness and flexibility.

Conclusion

It is thought that a number of quantifiable chemical characteristics are connected to pavement's structural or mechanical resistance. Based on this finding, comparative findings for viscous and elastic behavior varied according on the structure. This suggests that:

• Pavement surface properties are of critical importance due to their direct correlation with safety and ride comfort.

• In nations with extremely high annual temperature fluctuations, samples of hot-mix asphalt concrete with a 2.5% elastic modulus CR outperformed other samples evaluated in all temperature settings, such as Libya, according to ITS results.

• In order to forecast permanent HMA deformation in UCS results, samples with a 6.5% elastic modulus CR were the suggested CR composition inside the CRMA for maximum performance in hot-mix asphalt concrete with extremely high temperature changes (40 and 60°C). This suggests that high temperatures are the source of damage. These surfaces often exhibit reduced service life due to cracking, spalling, and other forms of damage.

• Each type may vary in its increased hardness.It may forecast irreversible deformation as the temperature rises; additionally, this may impact the pavement's durability and strength under stress. Samples with a higher rubber content degrade more rapidly at specific stress levels..

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