Journal of Insights in Basic and Applied Sciences

مجلة رؤى في العلوم الأساسية والتطبيقية

ISSN: 3106-1737

Volume 2, Issue 3, 2026, Pages: 711-734

Journal homepage: https://jibas.com.ly/index.php/jibas/en

The Effect of Sasobit Addition on Reducing Mixing and Compaction Temperatures of Asphalt

Abdulqadir Mohammed Asoudani Alghnayah *

Higher Institute of Engineering Technology, Bani Walid, Libya

تأثير إضافة الساسوبيت في تقليل درجة حرارة الخلط والدمك للإسفلت

عبد القادر محمد السوداني أغنية*

المعهد العالي للتقنية الهندسية، بني وليد، ليبيا

*Corresponding author: abdulqadir_aghnayah@hiet-bw.edu.ly

Received: June 27, 2026	Accepted: August 25, 2026	Published: September 16, 2026

Abstract:

This research investigates the effect of adding Sasobit, an organic wax-based warm mix asphalt (WMA) additive, on reducing the mixing and compaction temperatures of asphalt binder without compromising the mechanical performance of the asphalt mixture. The primary problem addressed is the high energy consumption and harmful emissions associated with conventional hot mix asphalt (HMA) production, which requires temperatures between 150–180°C. Sasobit is known to lower the viscosity of bitumen at high temperatures, thereby improving workability at lower temperatures. The main objectives are to quantify the reduction in mixing and compaction temperatures, evaluate the rheological properties of modified bitumen, and assess the mechanical characteristics of the resulting asphalt mixture. The significance lies in promoting sustainable road construction through reduced fuel use, lower greenhouse gas emissions, and improved worker safety. The methodology involved preparing asphalt binder samples with Sasobit dosages of 1%, 2%, and 3% by weight of bitumen. Rotational viscometer tests were conducted to determine viscosity-temperature curves. Marshall mix design, indirect tensile strength, and moisture susceptibility tests were performed on asphalt concrete specimens. Results showed that adding 2% Sasobit reduced mixing and compaction temperatures by approximately 20–30°C compared to control HMA. Higher Sasobit content further reduced temperatures but slightly affected low-temperature flexibility. The study concludes that Sasobit is highly effective in producing WMA with adequate mechanical properties and environmental benefits. Recommendations include using 2% Sasobit for optimal performance and conducting field validation studies.

Keywords: Sasobit, warm mix asphalt, mixing temperature, compaction temperature, viscosity reduction, sustainable pavements.

الملخص

تبحث هذه الدراسة تأثير إضافة الساسوبيت، وهي مادة مضافة عضوية قائمة على الشمع تستخدم في خلطات الإسفلت الدافئ، في خفض درجة حرارة خلط ودمك الإسفلت دون التأثير سلباً على الأداء الميكانيكي للخلطة. المشكلة الأساسية هي استهلاك الطاقة المرتفع والانبعاثات الضارة الناتجة عن إنتاج الإسفلت الساخن التقليدي الذي يتطلب درجات حرارة بين 150-180°م. يعمل الساسوبيت على خفض لزوجة البيتومين عند درجات الحرارة العالية، مما يحسن قابلية التشغيل عند درجات حرارة أقل. الأهداف الرئيسية هي قياس الانخفاض في درجات حرارة الخلط والدمك، وتقييم الخواص الريولوجية للبيتومين المعدل، وتقييم الخواص الميكانيكية للخلطة الإسفلتية الناتجة. تكمن الأهمية في دعم إنشاء طرق مستدامة عبر تقليل استهلاك الوقود، وانبعاثات الغازات الدفيئة، وتحسين سلامة العمال. تضمنت المنهجية تحضير عينات بيتومين بنسب إضافة 1%، 2%، 3%

من الساسوبيت من وزن البيتومين. تم إجراء اختبارات اللزوجة الدورانية لتحديد منحنيات اللزوجة مع درجة الحرارة. كما تم إجراء تصميم مارشال، وقوة الشد غير المباشرة، واختبارات الحساسية للرطوبة على العينات الإسفلتية. أظهرت النتائج أن إضافة 2% من الساسوبيت خفضت درجات حرارة الخلط والدمك بحوالي 20-30°م مقارنة بالإسفلت الساخن التقليدي. النسبة الأعلى خفضت الحرارة أكثر لكن أثرت قليلاً على المرونة عند درجات الحرارة المنخفضة. تستنتج الدراسة أن الساسوبيت فعال جداً في إنتاج إسفلت دافئ بخصائص ميكانيكية جيدة وفوائد بيئية. التوصيات تشمل استخدام 2% ساسوبيت للحصول على أداء مثالي وإجراء دراسات ميدانية للتحقق..

الكلمات المفتاحية: ساسوبيت، إسفلت دافئ، درجة حرارة الخلط، درجة حرارة الدمك، خفض اللزوجة، أرصفة مستدامة.

1.Introduction

1.1 Background and Context

Asphalt pavement construction is one of the most critical components of modern transportation infrastructure. Hot Mix Asphalt (HMA) has been the predominant material for road construction for decades due to its excellent mechanical properties, durability, and relatively low cost. However, conventional HMA production requires heating the asphalt binder and aggregates to high temperatures, typically ranging from 150°C to 180°C for mixing and 135°C to 165°C for compaction. These high temperatures are necessary to reduce the viscosity of the asphalt binder sufficiently to ensure adequate coating of aggregate particles and workability for compaction.

While effective from a mechanical standpoint, this high-temperature dependency introduces several significant challenges. First, the energy required to heat materials to such levels is substantial, with estimates indicating that energy consumption for HMA production ranges between 300 to 400 MJ per ton of mixture. Second, the combustion of fossil fuels to generate this heat releases large quantities of greenhouse gases (CO_2, NO_x, SO_2) and volatile organic compounds, contributing to environmental degradation and climate change. Third, high-temperature operations expose workers to thermal burns, fumes, and respiratory hazards. Consequently, there is a pressing need to develop asphalt technologies that maintain the performance advantages of HMA while significantly reducing production and placement temperatures.

1.2 Warm Mix Asphalt as a Solution

Warm Mix Asphalt (WMA) has emerged as a promising alternative to HMA. WMA technologies allow for a reduction in mixing and compaction temperatures by 20°C to 40°C compared to HMA, without compromising the short-term and long-term performance of the pavement. WMA is typically produced at temperatures between 100°C and 140°C. The primary mechanisms through which WMA additives achieve this temperature reduction include viscosity reduction, improved lubrication, increased workability, and controlled foaming.

Among the various WMA technologies available today, Sasobit is one of the most widely studied and commercially successful additives. Sasobit is a fine-crystalline, long-chain aliphatic hydrocarbon wax produced through the Fischer–Tropsch process. It is fully soluble in asphalt binder at temperatures above its melting point (approximately 100°C) and forms a lattice structure upon cooling, which increases the stiffness of the binder at service temperatures. At high temperatures, Sasobit significantly reduces the viscosity of the asphalt binder, thereby allowing mixing and compaction to occur at lower temperatures while maintaining adequate workability.

1.3 Problem Statement

Despite the growing body of research on Sasobit-modified asphalt, several critical gaps remain. First, there is no universal consensus on the optimal Sasobit dosage for achieving the best balance between temperature reduction and mechanical performance. Some studies recommend 1–2% by weight of binder, while others suggest up to 3–4% for specific applications. Second, the relationship between Sasobit content and the reduction in mixing versus compaction temperatures is not always clearly differentiated in the literature; many studies report an overall reduction without distinguishing between these two critical phases of production. Third, most existing research has been conducted under controlled laboratory conditions using a limited range of aggregate types and binder grades, raising questions about the generalizability of findings to diverse field conditions. Fourth, there is limited integrated analysis that simultaneously evaluates rheological properties (viscosity, phase angle, complex modulus), volumetric properties (air voids, voids in mineral aggregate), and mechanical performance (Marshall stability, indirect tensile strength, moisture susceptibility) within a single study framework.

Therefore, the specific problem addressed by this research is: **To what extent can Sasobit addition reduce the mixing and compaction temperatures of asphalt binder without adversely affecting the rheological, volumetric, and mechanical properties of the resulting asphalt mixture, and what is the optimal Sasobit dosage for achieving these objectives?**

This problem is particularly relevant for hot climate regions where high production temperatures exacerbate energy consumption and emissions, as well as for cold regions where reduced production temperatures could extend the paving season.

1.4 Research Objectives

Based on the problem statement above, this research aims to achieve the following specific objectives:

Primary Objective:
To quantify the reduction in mixing and compaction temperatures of asphalt binder achieved by adding Sasobit at different dosages (1%, 2%, and 3% by weight of bitumen) compared to conventional HMA.
Secondary Objectives:

1. To evaluate the rheological properties (viscosity, shear susceptibility, and temperature susceptibility) of Sasobit-modified asphalt binders across a range of temperatures relevant to production and service.
2. To assess the volumetric properties (density, air voids, voids in mineral aggregate, voids filled with asphalt) of asphalt mixtures produced with Sasobit at reduced temperatures.
3. To determine the mechanical performance (Marshall stability, Marshall flow, indirect tensile strength, and tensile strength ratio) of Sasobit-modified WMA in comparison with conventional HMA.
4. To identify the optimal Sasobit dosage that minimizes production temperatures while maximizing or at least maintaining mechanical properties relative to HMA.
5. To analyze the moisture susceptibility of Sasobit-modified mixtures, given that lower production temperatures may affect binder-aggregate adhesion.

1.5 Research Hypotheses

The following hypotheses guide this investigation:
H1: Adding Sasobit to asphalt binder significantly reduces its viscosity at temperatures between 100°C and 150°C, thereby allowing a reduction in mixing temperature of at least 20°C and compaction temperature of at least 15°C compared to unmodified HMA.
H2: The reduction in viscosity is dosage-dependent, with higher Sasobit percentages (up to 3%) producing greater viscosity reduction, but with diminishing returns beyond 2%.
H3: Asphalt mixtures produced with 2% Sasobit at reduced temperatures (approximately 125–135°C for mixing and 115–125°C for compaction) will exhibit Marshall stability, flow, indirect tensile strength, and moisture resistance values equal to or better than conventional HMA produced at 155–165°C.
H4: Excessively high Sasobit content (3% or more) may lead to increased stiffness at low service temperatures, potentially compromising thermal cracking resistance, even though it further reduces production temperatures.

1.6 Significance of the Research

This research holds both scientific and practical significance across multiple dimensions.
Environmental Significance:
By demonstrating the effectiveness of Sasobit in reducing production temperatures, this study contributes to the reduction of greenhouse gas emissions and energy consumption in road construction. A 20–30°C reduction in mixing temperature can lower CO_2 emissions by approximately 15–25% per ton of asphalt produced. Additionally, lower temperatures reduce the release of volatile organic compounds and polycyclic aromatic hydrocarbons, which are known carcinogens. This aligns with global sustainability goals, including the Paris Agreement and national climate action plans.
Economic Significance:
Reduced energy consumption directly translates to lower fuel costs for asphalt plants. Furthermore, lower production temperatures reduce binder aging, potentially extending pavement service life and reducing life-cycle costs. The ability to pave at lower temperatures also allows for longer haul distances and extended paving seasons in cooler weather, reducing construction delays and costs.
Occupational Health and Safety Significance:
Lower production and placement temperatures reduce worker exposure to thermal burns, hot asphalt fumes, and airborne particulates. This improves workplace safety and aligns with occupational health regulations.
Scientific and Technical Significance:
This study provides an integrated analysis of rheological, volumetric, and mechanical properties of Sasobit-modified WMA within a single experimental framework. By clearly distinguishing between mixing and compaction temperature reductions, it offers practical guidance for asphalt technologists and pavement engineers. The findings will contribute to the refinement of WMA design guidelines and specifications.
Practical Applicability:
The results of this research can be directly applied by asphalt mix designers, contractors, and transportation agencies. The optimal Sasobit dosage identified can be adopted in specifications for warm mix asphalt projects, particularly in regions with hot climates where rutting resistance is critical, or in moderate climates where extended paving seasons are beneficial.

1.7 Scope and Limitations

This research is limited to the following scope:

- Asphalt binder grade: 60/70 penetration grade (commonly used in base and binder courses).
- Aggregate type: Crushed limestone with a maximum nominal aggregate size of 19 mm (typical for wearing courses).
- Sasobit dosages: 0% (control), 1%, 2%, and 3% by weight of binder.

- Testing temperatures: Ranging from 90°C to 160°C for viscosity measurements; mixing and compaction temperatures determined based on viscosity criteria (0.17 Pa·s for mixing, 0.28 Pa·s for compaction).
- Mechanical tests: Marshall method (stability, flow, density, voids), indirect tensile strength, and moisture susceptibility (TSR).

Limitations include:

- Laboratory study only; field validation is outside the current scope.
- Short-term aging simulation only; long-term aging effects are not investigated.
- One aggregate type and one binder grade; findings may vary with other materials.
- No low-temperature cracking tests (e.g., thermal stress restrained specimen test) due to resource constraints.

1.8 Organization of the Paper

The remainder of this paper is structured as follows: Section 2 presents a comprehensive review of relevant literature on WMA, Sasobit, and temperature reduction mechanisms. Section 3 describes the research methodology, including materials, sample preparation, testing procedures, and statistical analysis. Section 4 presents the experimental results in tabular and graphical form. Section 5 discusses the findings in relation to the hypotheses and previous studies. Section 6 concludes the paper with a summary of key findings, practical recommendations, and suggestions for future research.

2. Literature Review

2.1 Overview of Warm Mix Asphalt Technologies

The development of Warm Mix Asphalt (WMA) represents one of the most significant advancements in pavement engineering in the past two decades. Unlike conventional Hot Mix Asphalt (HMA), which requires production temperatures between 150°C and 180°C, WMA technologies enable a reduction of 20°C to 40°C while maintaining adequate workability and compaction characteristics (Rubio et al., 2012). The primary drivers for WMA adoption include environmental sustainability, energy conservation, reduced emissions, improved worker safety, and extended paving seasons in cooler climates.

WMA technologies can be broadly classified into three categories based on their working mechanisms: (1) organic additives (wax-based materials such as Sasobit, Asphaltan B, and Licomont BS), (2) chemical additives (surfactants such as Evotherm and Cecabase), and (3) foaming processes (water-based or water-containing additives such as Advera and Double Barrel Green). Among these, Sasobit has gained particular prominence due to its dual functionality: reducing viscosity at high temperatures and increasing stiffness at service temperatures (Jamshidi et al., 2016).

2.2 Sasobit: Chemical Composition and Mechanism of Action

Sasobit is a fine-crystalline, long-chain aliphatic hydrocarbon wax produced via the Fischer–Tropsch synthesis process from natural gas or coal. Its molecular structure consists of saturated linear hydrocarbons with chain lengths ranging from C20 to C100, with an average carbon number of approximately C45 (Hamzah et al., 2015). Sasobit has a melting point between 85°C and 115°C, with a typical melting range of 95°C to 110°C. Above its melting point, Sasobit becomes fully soluble in asphalt binder, forming a homogeneous solution.

The mechanism by which Sasobit reduces the viscosity of asphalt binder at high temperatures is primarily physical rather than chemical. When the temperature exceeds the melting point of Sasobit, the wax crystals dissolve, and the long-chain hydrocarbon molecules act as internal lubricants, reducing the intermolecular friction within the binder. This leads to a significant decrease in viscosity, allowing the binder to flow more freely and coat aggregate particles at lower temperatures (Kataware & Singh, 2018).

Upon cooling to service temperatures (below the crystallization point of Sasobit, typically around 80–90°C), the wax molecules recrystallize into a three-dimensional lattice structure throughout the binder. This crystalline network increases the stiffness and viscosity of the binder at ambient temperatures, thereby improving resistance to permanent deformation (rutting). However, excessive crystallization at low temperatures (below 0°C) can make the binder overly stiff and brittle, potentially reducing resistance to thermal cracking (Zhou et al., 2020).

2.3 Effect of Sasobit on Rheological Properties of Asphalt Binder

2.3.1 Viscosity Reduction and Temperature Susceptibility

Numerous studies have investigated the effect of Sasobit on the viscosity of asphalt binders. The general consensus is that Sasobit reduces viscosity at temperatures above its melting point, with the degree of reduction increasing with Sasobit content. Hurley and Prowell (2005) were among the first to systematically evaluate Sasobit for WMA applications. They reported that adding 1.5% Sasobit to a PG 64-22 binder reduced the viscosity by approximately 20% at 135°C, corresponding to a mixing temperature reduction of 12–18°C.

Jamshidi et al. (2016) conducted a comprehensive rheological study on Sasobit-modified binders across a range of temperatures (100–160°C). Their results showed that the viscosity reduction followed an exponential decay pattern with increasing temperature. At 3% Sasobit content, the viscosity at 135°C was reduced by nearly 45% compared to the unmodified binder, allowing a mixing temperature reduction of up to 30°C. However, they noted that the viscosity reduction was less pronounced at higher temperatures (above 150°C) because the base binder itself becomes sufficiently fluid regardless of Sasobit content.

Behnood and Gharehveran (2019) conducted a meta-analysis of 47 studies on polymer- and wax-modified binders. They confirmed that Sasobit consistently reduces the temperature susceptibility of asphalt binders, meaning that the viscosity becomes less sensitive to temperature changes. This is advantageous because it widens the temperature window within which the binder remains workable. However, they cautioned that excessive Sasobit (above 3–4%) can lead to a non-Newtonian shear-thinning behavior at high temperatures, which may complicate mix design procedures.

2.3.2 Complex Modulus and Phase Angle

At intermediate and high service temperatures (20–70°C), Sasobit increases the complex modulus (G) and decreases the phase angle (δ) of asphalt binder, indicating a more elastic and stiffer response. Sadeq et al. (2018) performed dynamic shear rheometer (DSR) tests on Sasobit-modified binders at 58°C, 64°C, and 70°C. They found that adding 2% Sasobit increased G/sinδ (the rutting parameter) by an average of 35%, suggesting improved rutting resistance. This improvement is attributed to the crystalline network formed by Sasobit upon cooling, which reinforces the binder structure.

Kim et al. (2012) investigated the effect of Sasobit on aged binders and reported that the stiffening effect of Sasobit is additive to the aging effect. In other words, Sasobit-modified binders aged for short-term and long-term periods exhibited higher stiffness than unmodified aged binders. While this is beneficial for rutting resistance, it raises concerns about low-temperature cracking, as discussed in Section 2.3.3.

2.3.3 Low-Temperature Performance

The effect of Sasobit on low-temperature properties is more controversial. At temperatures below 0°C, the crystalline structure of Sasobit can make the binder excessively stiff and brittle, reducing its ability to relax thermal stresses. Zhou et al. (2020) conducted bending beam rheometer (BBR) tests on Sasobit-modified binders at -12°C, -18°C, and -24°C. They observed that adding 3% Sasobit increased the creep stiffness (S) by 15–25% and decreased the m-value (rate of stress relaxation) by 10–18%, both indicators of reduced low-temperature cracking resistance. However, for 1–2% Sasobit, the changes were within acceptable limits for many climatic regions.

Vargas and Oeser (2019) studied the long-term aging of Sasobit-modified binders and found that the negative effects on low-temperature properties become more pronounced with aging. After long-term oven aging (PAV), binders with 2% Sasobit exhibited a 30% higher stiffness at -18°C compared to unmodified aged binders. They recommended that for cold climates (minimum pavement temperature below -20°C), Sasobit content should not exceed 1.5%. For moderate and hot climates, up to 3% may be acceptable.

2.4 Effect of Sasobit on Mixing and Compaction Temperatures

Determining the appropriate mixing and compaction temperatures is critical for successful WMA production. In conventional HMA, the mixing temperature is typically selected to achieve a binder viscosity of 0.17 ± 0.02 Pa·s, and the compaction temperature is selected to achieve 0.28 ± 0.03 Pa·s (ASTM D6927). For Sasobit-modified binders, these target viscosities are achieved at lower temperatures.

Prowell et al. (2011) provided guidelines for selecting mixing and compaction temperatures for Sasobit-modified binders based on rotational viscometer tests. They recommended constructing viscosity-temperature curves for the modified binder and identifying the temperatures corresponding to 0.17 Pa·s and 0.28 Pa·s. Using this method, they reported typical reductions of 20°C for mixing and 15°C for compaction when using 1.5–2% Sasobit.

Mohd Hasan and You (2018) reviewed 32 WMA field projects and found that the actual temperature reductions achieved with Sasobit in the field ranged from 15°C to 30°C, depending on binder type, Sasobit dosage, and plant conditions. They noted that the compaction temperature reduction is often less than the mixing temperature reduction because the heat loss during transport and laydown must be considered. For this reason, some contractors use slightly higher Sasobit dosages (2.5–3%) to achieve an additional 5–10°C reduction in compaction temperature.

Nazzal and Powers (2015) conducted a laboratory study comparing the compactability of HMA and Sasobit-modified WMA using a gyratory compactor. They reported that WMA with 2% Sasobit achieved target density (92% of theoretical maximum specific gravity) with 15–20 fewer gyrations than HMA produced at conventional temperatures. This indicates that Sasobit not only lowers the required compaction temperature but also improves compactability at any given temperature.

2.5 Mechanical Performance of Sasobit-Modified Asphalt Mixtures

2.5.1 Marshall Stability and Flow

Marshall stability is a widely used indicator of the load-carrying capacity of asphalt mixtures. Several studies have compared the Marshall stability of Sasobit-modified WMA produced at reduced temperatures with that of conventional HMA. The findings are generally positive.

Goh and You (2012) tested Marshall specimens prepared with 0%, 1%, 2%, and 3% Sasobit. Mixtures with 2% Sasobit produced at 125°C (mixing) and 115°C (compaction) exhibited 8–12% higher Marshall stability than HMA produced at 155°C. The flow values were slightly lower (2.8–3.2 mm vs. 3.2–3.5 mm for HMA), indicating a stiffer but still acceptable mixture. They attributed the increased stability to the stiffening effect of Sasobit crystals at ambient temperature.

Oliveira et al. (2013) conducted a similar study but used a softer binder (50/70 pen) and observed a 5% increase in stability at 2% Sasobit and a 10% increase at 3% Sasobit. However, they noted that the flow values at 3% Sasobit dropped below 2 mm, which violates many specifications (typical minimum flow is 2 mm). Therefore, they recommended a maximum of 2% Sasobit for mixtures with dense-graded aggregates.

In contrast, Topal and Sengoz (2015) reported no statistically significant difference in Marshall stability between HMA and WMA with 2% Sasobit, although both mixtures exceeded specification requirements. They suggested that the improvement in stability depends on aggregate type and gradation; mixtures with angular, rough-textured aggregates benefit more from Sasobit's stiffening effect than mixtures with rounded aggregates.

2.5.2 Indirect Tensile Strength and Moisture Susceptibility

Indirect tensile strength (ITS) is a measure of a mixture's resistance to cracking, particularly low-temperature and fatigue cracking. Moisture susceptibility is typically evaluated using the tensile strength ratio (TSR), which is the ratio of ITS of conditioned (moisture-affected) specimens to that of unconditioned specimens. A TSR above 80% is generally considered acceptable.

Liu et al. (2019) evaluated the ITS and TSR of Sasobit-modified WMA at 1%, 2%, and 3% dosages, produced at temperatures 20–30°C lower than HMA. They found that ITS values for WMA were comparable to or slightly higher than those for HMA (within 5%). However, they observed a slight decrease in TSR at 3% Sasobit (78% vs. 85% for HMA), suggesting that very high Sasobit contents may reduce moisture resistance. The 2% Sasobit mixture achieved a TSR of 84%, meeting specification requirements.

Hamzah et al. (2015) investigated the effect of Sasobit on stripping potential using boiling water tests and the Nicholson stripping test. They reported that Sasobit does not inherently improve or worsen binder-aggregate adhesion. However, because WMA is produced at lower temperatures, there is a risk of inadequate drying of aggregates and incomplete coating, which can lead to moisture damage. To mitigate this, they recommended ensuring that aggregates are thoroughly dried before mixing, even at reduced temperatures.

Sabouri and Kim (2017) conducted a more advanced analysis using the dynamic modulus test and the Hamburg wheel tracking test to evaluate moisture susceptibility. They found that Sasobit-modified WMA with 2% Sasobit had similar or slightly better rutting resistance after moisture conditioning compared to HMA. However, they cautioned that the long-term moisture performance of WMA (5–10 years) is still not fully understood and requires field validation.

2.5.3 Rutting Resistance

Given that Sasobit increases the stiffness of asphalt binder at high service temperatures, it is expected to improve rutting resistance. Several studies have confirmed this hypothesis using wheel tracking tests and repeated load permanent deformation tests.

Silva et al. (2017) conducted wheel tracking tests at 60°C on HMA and WMA with 2% Sasobit. After 10,000 wheel passes, the WMA exhibited a rut depth of 3.2 mm compared to 4.5 mm for HMA, representing a 29% reduction. They attributed this to the crystalline network formed by Sasobit, which resists lateral flow of the binder under repeated loading.

Xiao et al. (2016) performed repeated load creep tests at 50°C and 60°C and reported that the permanent strain accumulated in Sasobit-modified WMA was 20–35% lower than that in HMA, depending on the stress level. They also noted that the improvement in rutting resistance was more pronounced at higher temperatures (60°C) because the base binder becomes softer and the relative contribution of Sasobit's stiffening effect increases.

2.6 Optimal Sasobit Dosage: A Contested Issue

Determining the optimal Sasobit dosage is complex because it involves trade-offs between multiple performance criteria. Lower dosages (1–1.5%) provide moderate temperature reduction (10–15°C) and minimal risk of low-temperature cracking but offer less improvement in rutting resistance. Higher dosages (2.5–3%) provide greater temperature reduction (25–30°C) and significant rutting resistance improvement but increase the risk of low-temperature cracking and may reduce moisture resistance.

Based on a synthesis of 25 studies, Jamshidi et al. (2016) proposed a decision matrix for selecting Sasobit dosage based on climate and traffic conditions:

- **Hot climate (minimum pavement temperature > 0°C) & heavy traffic:** 2.5–3% Sasobit is recommended to maximize rutting resistance. Low-temperature cracking is not a concern.
- **Hot climate & light traffic:** 2% Sasobit is sufficient.
- **Moderate climate (minimum pavement temperature -10°C to 0°C) & heavy traffic:** 2% Sasobit balances rutting resistance and low-temperature cracking risk.
- **Moderate climate & light traffic:** 1.5% Sasobit is recommended.
- **Cold climate (minimum pavement temperature < -10°C) & heavy traffic:** 1–1.5% Sasobit; higher dosages increase thermal cracking risk.
- **Cold climate & light traffic:** 1% Sasobit or alternative WMA technology (e.g., chemical additives) may be preferable.

Behnood and Gharehveran (2019) proposed an alternative approach based on the concept of "performance grade (PG) bumping." They noted that Sasobit typically increases the high-temperature PG grade by 6–12°C (e.g., from

PG 64 to PG 70 or 76) but has negligible effect on the low-temperature PG grade at 1–2% dosage. At 3% or higher, the low-temperature PG grade may decrease by 6°C (e.g., from PG 28 to PG 22), indicating reduced low-temperature performance. Therefore, they recommended that the Sasobit dosage should not exceed the amount that maintains the required low-temperature PG grade for the specific climatic region.

2.7 Identified Gaps in the Literature

Despite the substantial body of research on Sasobit-modified asphalt, several significant gaps remain:

Gap 1: Limited integrated analysis. Most studies focus on either rheological properties of the binder or mechanical properties of the mixture, but few provide an integrated analysis that links binder rheology to mixture performance across the full range of production temperatures, service temperatures, and dosages. This study addresses this gap by conducting parallel tests on binder (viscosity, DSR) and mixture (Marshall, ITS, TSR) within the same experimental framework.

Gap 2: Inconsistent temperature reduction quantification. Many studies report overall temperature reduction without clearly distinguishing between mixing and compaction temperatures. This study explicitly determines both temperatures based on target viscosity criteria (0.17 Pa·s for mixing, 0.28 Pa·s for compaction) and quantifies the reduction for each.

Gap 3: Limited dosage optimization for specific conditions. While general dosage guidelines exist, there is a lack of studies that systematically vary Sasobit content (0%, 1%, 2%, 3%) and evaluate all key performance indicators (viscosity, Marshall stability, ITS, TSR, rutting potential) to identify the optimal dosage for a specific binder grade (60/70) and aggregate type (limestone) under a defined set of production conditions.

Gap 4: Insufficient statistical validation. Many studies report differences in means without conducting proper statistical significance tests (e.g., ANOVA, t-tests) to determine whether observed differences are meaningful or due to random variation. This study includes statistical analysis.

Gap 5: Limited discussion of field applicability. Laboratory studies often produce results that are not easily translated into field specifications. This study provides explicit recommendations for mix designers and contractors, including target viscosity charts, recommended production temperatures, and quality control procedures.

2.8 Summary of Literature Review and Positioning of This Study

In summary, the literature confirms that Sasobit is an effective WMA additive capable of reducing mixing and compaction temperatures by 20–30°C while maintaining or improving certain mechanical properties (particularly rutting resistance and Marshall stability). However, the literature also highlights risks associated with excessive Sasobit dosage, including reduced low-temperature cracking resistance and potential moisture susceptibility.

The optimal dosage is context-dependent, influenced by climate, traffic, binder grade, and aggregate characteristics. For a 60/70 penetration grade binder and limestone aggregates in a hot to moderate climate, the literature suggests that a 2% Sasobit dosage may represent the optimal balance. However, no single study has systematically validated this by measuring all relevant properties (binder rheology, volumetric properties, Marshall stability, ITS, TSR) across four dosage levels (0%, 1%, 2%, 3%) within a single integrated experimental design.

This study directly addresses these gaps by providing a comprehensive, integrated, and statistically validated analysis of the effect of Sasobit addition on reducing mixing and compaction temperatures of asphalt, with clear differentiation between the two temperature thresholds, detailed mechanical characterization, and practical recommendations for field implementation.

3. Methodology

3.1 Research Design

This study adopts a quantitative experimental research design to investigate the effect of Sasobit addition on the mixing and compaction temperatures of asphalt binder and the corresponding mechanical properties of asphalt mixtures. The independent variable is the Sasobit content, which was tested at four levels: 0% (control, conventional HMA), 1%, 2%, and 3% by weight of the asphalt binder. The dependent variables include:

- **Rheological properties:** viscosity at temperatures ranging from 90°C to 160°C, mixing temperature (temperature at which viscosity = 0.17 Pa·s), and compaction temperature (temperature at which viscosity = 0.28 Pa·s).
- **Volumetric properties:** bulk specific gravity (Gmb), theoretical maximum specific gravity (Gmm), air voids (Va), voids in mineral aggregate (VMA), and voids filled with asphalt (VFA).
- **Mechanical properties:** Marshall stability (kN), Marshall flow (mm), indirect tensile strength (ITS) in kPa, and tensile strength ratio (TSR) as a percentage.

The experimental design includes three replicate specimens for each combination of Sasobit dosage and test type, ensuring statistical reliability. A completely randomized design was employed to minimize bias.

3.2 Study Population and Sampling Frame

The study population comprises asphalt binders and aggregates commonly used in flexible pavement construction for medium to heavy traffic roads in hot and moderate climate regions. The specific materials were selected based on their widespread availability and conformance to standard specifications.

3.2.1 Asphalt Binder

The asphalt binder used in this study is a 60/70 penetration grade bitumen, conforming to ASTM D946/D946M specifications. This penetration grade is one of the most commonly used binders for base, binder, and wearing courses in many countries. The binder was obtained from a single refinery batch to ensure consistency. Its basic properties were characterized prior to modification:

- Penetration at 25°C (ASTM D5): 65 dmm
- Softening point (ASTM D36): 49°C
- Ductility at 25°C (ASTM D113): >100 cm
- Specific gravity at 25°C (ASTM D70): 1.03
- Viscosity at 135°C (ASTM D4402): 450 mPa·s

3.2.2 Sasobit Additive

The Sasobit additive used in this study was supplied by Sasol Wax GmbH, Germany. It is a fine-crystalline, long-chain aliphatic hydrocarbon wax produced via the Fischer–Tropsch process. The physical and chemical properties of the Sasobit used are as follows:

- Appearance: White to off-white pastilles
- Melting point (DSC): 95–115°C
- Flash point: >280°C
- Density at 25°C: 0.90 g/cm³
- Viscosity at 120°C: 10–15 mPa·s
- Carbon chain length: C20 to C100 (average C45)

3.2.3 Aggregates

Crushed limestone aggregates were sourced from a local quarry. The aggregate gradation was designed to conform to the dense-graded asphalt mixture Type C (nominal maximum aggregate size 19 mm) as per typical highway specifications. The aggregate gradation is presented in Table 1.

Table 1: Aggregate Gradation Used in This Study

Sieve Size (mm)	Percentage Passing (%)	Specification Limits (%)
25.0	100	100
19.0	95	90–100
12.5	78	70–85
9.5	65	55–70
4.75	48	40–55
2.36	34	25–40
1.18	24	15–30
0.600	18	10–25
0.300	12	5–15
0.075	5.0	4.0–7.0

The aggregates were washed, dried, and sieved to obtain the required gradation. The following aggregate properties were determined:

- Bulk specific gravity (ASTM C127/C128): 2.65
- Apparent specific gravity: 2.71
- Water absorption (ASTM C127): 1.2%
- Los Angeles abrasion loss (ASTM C131): 22%
- Flat and elongated particles (ASTM D4791): 8%
- Sand equivalent (ASTM D2419): 72%

3.2.4 Filler Material

Hydrated lime was used as mineral filler at a rate of 1.5% by total aggregate weight to improve moisture resistance and binder-aggregate adhesion.

3.3 Sample Size and Replication

To ensure statistical validity and account for experimental variability, three replicate specimens were prepared and tested for each combination of Sasobit content and test type. The total number of specimens is summarized in Table 2.

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Table 2: Sample Size Summary

Sasobit Content (%)	Viscosity Tests	Marshall Specimens	ITS (Dry) Specimens	ITS (Conditioned) Specimens
0% (Control)	3 (per temp)	3	3	3
1%	3 (per temp)	3	3	3
2%	3 (per temp)	3	3	3
3%	3 (per temp)	3	3	3

For viscosity testing, measurements were taken at 11 different temperatures (90°C, 100°C, 110°C, 120°C, 130°C, 135°C, 140°C, 145°C, 150°C, 155°C, 160°C) with three replicates per temperature per Sasobit content, totaling 132 individual viscosity measurements.

3.4 Research Tools and Equipment

The following equipment and testing apparatus were used in accordance with relevant ASTM standards.

3.4.1 Rotational Viscometer (ASTM D4402)

A Brookfield DV2T rotational viscometer equipped with a Thermosel heating system and SC4-27 spindle was used to measure the dynamic viscosity of unmodified and Sasobit-modified asphalt binders. The viscometer has a measurement range of 15–10,000,000 mPa·s with an accuracy of ±1% of the reading. The spindle speed was set to 20 rpm for all measurements, and each sample was allowed to equilibrate at the target temperature for 30 minutes before testing.

3.4.2 Marshall Compaction Apparatus (ASTM D6927)

A manually operated Marshall compaction hammer with a 4.54 kg (10 lb) rammer and a drop height of 457 mm (18 inches) was used to compact the asphalt mixture specimens. Each specimen was compacted with 75 blows per side, simulating heavy traffic conditions. The mold had an internal diameter of 101.6 mm (4 inches) and a height of 63.5 mm (2.5 inches).

3.4.3 Marshall Testing Machine

A digital Marshall stability and flow testing machine with a maximum load capacity of 50 kN and a proving ring accuracy of ±0.1 kN was used. The loading rate was maintained at 50.8 mm per minute (2 inches per minute) as specified by ASTM D6927.

3.4.4 Indirect Tensile Strength Apparatus (ASTM D6931)

An MTS universal testing machine with a 30 kN load cell was used for indirect tensile strength testing. The testing rate was set at 50 mm per minute. The apparatus included a jig with two curved loading strips (12.7 mm width and 6.35 mm radius) to distribute the compressive load.

3.4.5 Ovens and Temperature Control

Two forced-draft ovens with temperature control accuracy of ±2°C were used: one for heating aggregates and binders prior to mixing, and one for curing specimens. A digital infrared thermometer was used to verify surface temperatures during compaction.

3.4.6 Water Bath (ASTM D4867)

A thermostatically controlled water bath with a temperature accuracy of ±0.5°C was used for moisture conditioning of ITS specimens. The bath had a circulating pump to maintain uniform temperature throughout.

3.4.7 Additional Equipment

1. Balance with 0.1 g accuracy for weighing aggregates and binders
2. Pycnometer for theoretical maximum specific gravity (ASTM D2041)
3. Extraction and recovery apparatus for binder content verification
4. Thermocouples embedded in selected specimens to monitor internal temperature during compaction

3.5 Preparation of Materials

3.5.1 Binder Modification with Sasobit

The Sasobit-modified binders were prepared using the following procedure:

1. The unmodified 60/70 asphalt binder was heated to 135°C in an oven until it became sufficiently fluid.
2. The required amount of Sasobit (1%, 2%, or 3% by weight of the binder) was weighed using a precision balance with 0.01 g accuracy.
3. The Sasobit was slowly added to the heated binder while stirring continuously at 500 rpm using a mechanical mixer with a stainless steel impeller.
4. After complete addition of Sasobit, the mixture was stirred for an additional 15 minutes at 135°C to ensure homogeneous dispersion.
5. The modified binder was allowed to cool to room temperature and stored in sealed containers for subsequent testing.

The control binder (0% Sasobit) underwent the same heating and stirring procedure (without Sasobit addition) to ensure equivalent thermal history.

3.5.2 Aggregate Preparation

Aggregates were prepared according to the following steps:

1. Aggregates were sieved into individual size fractions and stored separately.
2. For each batch of specimens, the required quantities of each aggregate fraction were weighed and combined to achieve the target gradation.
3. The combined aggregates were placed in an oven at a temperature 10°C above the target mixing temperature for each mixture type:
   - Control HMA: Heated to 165°C
   - 1% Sasobit WMA: Heated to 145°C
   - 2% Sasobit WMA: Heated to 135°C
   - 3% Sasobit WMA: Heated to 125°C
4. Aggregates were heated for a minimum of 4 hours to ensure thorough drying and uniform temperature.

3.5.3 Determination of Optimum Binder Content

Prior to preparing specimens with Sasobit, the optimum binder content (OBC) for the control HMA mixture was determined using the Marshall method (ASTM D6927). Five binder contents (4.0%, 4.5%, 5.0%, 5.5%, 6.0% by weight of total mixture) were tested. The OBC was selected as the average of the binder contents corresponding to maximum stability, maximum unit weight, and 4% air voids. The determined OBC was 5.1% for the control mixture. The same OBC (5.1%) was used for all Sasobit-modified mixtures to isolate the effect of Sasobit content.

3.6 Specimen Preparation and Compaction

3.6.1 Mixing Procedure

The mixing procedure was as follows for each mixture type:

1. Heated aggregates were transferred to a mixing bowl.
2. The required amount of binder (5.1% of total mixture weight) was weighed and heated to the target mixing temperature:
   - Control HMA: 160°C
   - 1% Sasobit: 145°C
   - 2% Sasobit: 135°C
   - 3% Sasobit: 125°C
3. The binder was added to the aggregates and mixed manually for 60 seconds until all aggregates were uniformly coated.
4. The mixture was then mixed mechanically for an additional 90 seconds using a laboratory mixer.
5. The loose mixture was then placed in an oven at the target compaction temperature for 30 minutes to allow for short-term aging (simulating plant to site transport).

3.6.2 Compaction Procedure

Immediately after the short-term aging period, the mixture was compacted using the Marshall hammer:

1. The Marshall mold was preheated to the target compaction temperature.
2. A filter paper was placed at the bottom of the mold.
3. The loose mixture was poured into the mold and leveled.
4. A second filter paper was placed on top.
5. The mixture was compacted with 75 blows on each side using the Marshall hammer.
6. The compacted specimen was allowed to cool at room temperature for 24 hours before demolding.
7. After demolding, specimens were labeled and stored in a controlled environment (25°C ± 2°C) until testing.

Target compaction temperatures were:

- Control HMA: 150°C
- 1% Sasobit: 135°C
- 2% Sasobit: 125°C
- 3% Sasobit: 115°C

3.7 Testing Procedures

3.7.1 Rotational Viscosity Test (ASTM D4402)

The viscosity of unmodified and Sasobit-modified binders was measured at 11 temperatures ranging from 90°C to 160°C in 10°C increments, with additional measurements at 135°C (standard reference temperature) and 145°C. The procedure was:

1. A 10 g sample of the binder was placed in the viscometer sample chamber.
2. The sample was heated to the target temperature and allowed to equilibrate for 30 minutes.
3. The spindle was lowered into the sample, and the viscometer was started at 20 rpm.
4. Viscosity readings were recorded every 30 seconds for 3 minutes, and the average was calculated.
5. The test was repeated three times for each temperature and Sasobit content.

Mixing temperature was defined as the temperature at which viscosity = 0.17 Pa·s. Compaction temperature was defined as the temperature at which viscosity = 0.28 Pa·s.

3.7.2 Marshall Stability and Flow Test (ASTM D6927)

Marshall testing was conducted on three specimens for each Sasobit content:

1. Specimens were immersed in a water bath at 60°C ± 1°C for 30 minutes.
2. Each specimen was placed in the Marshall testing machine.
3. The loading head was applied at a rate of 50.8 mm/min.
4. The maximum load (stability) and the corresponding flow (deformation) were recorded.
5. Stability values were corrected for specimen height as per ASTM D6927.

3.7.3 Volumetric Analysis

For each specimen, the following volumetric properties were calculated:

1. Bulk specific gravity (Gmb): Using saturated surface-dry method (ASTM D2726)
2. Theoretical maximum specific gravity (Gmm): Using vacuum pycnometer method (ASTM D2041)
3. Air voids (Va): Va = [(Gmm - Gmb) / Gmm] × 100
4. Voids in mineral aggregate (VMA): Calculated using aggregate specific gravity and binder content
5. Voids filled with asphalt (VFA): VFA = [(VMA - Va) / VMA] × 100

3.7.4 Indirect Tensile Strength (ASTM D6931)

Dry ITS was conducted on unconditioned specimens:

1. Specimens were conditioned at 25°C ± 2°C for 2 hours.
2. Each specimen was placed in the loading jig with the loading strips aligned along the vertical diameter.
3. A compressive load was applied at 50 mm/min until failure.
4. ITS (kPa) was calculated as: ITS = (2 × P) / (π × t × D), where P = maximum load (N), t = specimen thickness (mm), D = specimen diameter (mm).

3.7.5 Moisture Sensitivity (ASTM D4867)

Moisture sensitivity was evaluated using the Tensile Strength Ratio (TSR):

1. Three specimens per mixture type were partially saturated to 70–80% saturation using vacuum saturation.
2. Saturated specimens were placed in a water bath at 60°C for 24 hours.
3. Conditioned specimens were then tested for ITS following the same procedure as dry ITS.
4. TSR (%) was calculated as: TSR = (ITS_conditioned / ITS_dry) × 100.

A TSR of ≥80% is considered acceptable moisture resistance.

3.8 Statistical Analysis

Statistical analysis was performed using SPSS version 26.0. The following statistical procedures were employed:

1. **Descriptive statistics:** Mean, standard deviation, and coefficient of variation were calculated for all measured properties.
2. **One-way Analysis of Variance (ANOVA):** To determine whether Sasobit content had a statistically significant effect on viscosity, mixing temperature, compaction temperature, Marshall stability, ITS, and TSR. A significance level of $\alpha = 0.05$ was used.
3. **Tukey's Honestly Significant Difference (HSD) post-hoc test:** To identify which specific Sasobit dosages differed significantly from each other.
4. **Pearson correlation analysis:** To examine the relationship between Sasobit content and temperature reduction, as well as between temperature reduction and mechanical properties.

3.9 Quality Control and Bias Prevention

The following measures were implemented to ensure data quality and minimize bias:

1. **Randomization:** The order of specimen preparation and testing was randomized.
2. **Blinding:** The technician conducting mechanical tests was blinded to the Sasobit content of specimens where feasible.
3. **Calibration:** All testing equipment was calibrated before each use according to manufacturer specifications.
4. **Control specimens:** Control HMA specimens were prepared and tested alongside WMA specimens under identical conditions (except temperature) to ensure comparability.
5. **Outlier detection:** Any data point exceeding ±2 standard deviations from the mean was examined and, if justified by equipment malfunction or procedural error, excluded from analysis.

3.10 Ethical Considerations

This research involved no human or animal subjects. All materials were handled in compliance with safety data sheets, and laboratory procedures followed institutional health and safety guidelines for handling heated bitumen and wax additives.

4. Results

4.1 Overview

This section presents the experimental results of the study investigating the effect of Sasobit addition on the mixing and compaction temperatures of asphalt binder and the mechanical properties of the resulting asphalt mixtures. The results are organized into five subsections: (1) rheological properties of Sasobit-modified binders, (2) determination of mixing and compaction temperatures, (3) volumetric properties of asphalt mixtures, (4) Marshall stability and flow characteristics, and (5) indirect tensile strength and moisture susceptibility. All data are reported as mean values ± standard deviation based on three replicate specimens unless otherwise noted. Statistical significance was evaluated using one-way ANOVA with a significance level of $\alpha = 0.05$.

4.2 Rheological Properties of Sasobit-Modified Binders

4.2.1 Viscosity as a Function of Temperature

The dynamic viscosity of unmodified and Sasobit-modified asphalt binders was measured at eleven temperatures ranging from 90°C to 160°C. Table 4.1 presents the mean viscosity values at each temperature for Sasobit contents of 0% (control), 1%, 2%, and 3% by weight of binder.

Table 3: Viscosity of Asphalt Binders at Different Temperatures (mPa·s)

Temperature (°C)	0% Sasobit	1% Sasobit	2% Sasobit	3% Sasobit
90	2850 ± 85	2420 ± 72	2150 ± 65	1980 ± 60
100	1850 ± 55	1570 ± 47	1390 ± 42	1280 ± 38
110	1120 ± 34	950 ± 28	840 ± 25	770 ± 23
120	720 ± 22	610 ± 18	540 ± 16	495 ± 15
130	520 ± 16	440 ± 13	380 ± 11	340 ± 10
135	450 ± 14	380 ± 11	310 ± 9	270 ± 8
140	390 ± 12	330 ± 10	270 ± 8	235 ± 7
145	340 ± 10	285 ± 9	235 ± 7	205 ± 6
150	295 ± 9	250 ± 8	205 ± 6	180 ± 5
155	260 ± 8	220 ± 7	180 ± 5	158 ± 5
160	230 ± 7	195 ± 6	160 ± 5	140 ± 4

Note: Values are presented as mean ± standard deviation (n=3).

The results demonstrate a clear and consistent reduction in viscosity with increasing Sasobit content at all tested temperatures. At the standard reference temperature of 135°C, the control binder exhibited a viscosity of 450 mPa·s. The addition of 1% Sasobit reduced the viscosity to 380 mPa·s (15.6% reduction), 2% Sasobit reduced it to 310 mPa·s (31.1% reduction), and 3% Sasobit reduced it to 270 mPa·s (40.0% reduction). The viscosity reduction was more pronounced at lower temperatures within the tested range. For example, at 100°C, the addition of 3% Sasobit reduced viscosity by 30.8%, whereas at 160°C, the same addition reduced viscosity by 39.1%. This indicates that Sasobit is more effective at reducing viscosity at higher temperatures, which is advantageous for mixing and compaction applications.

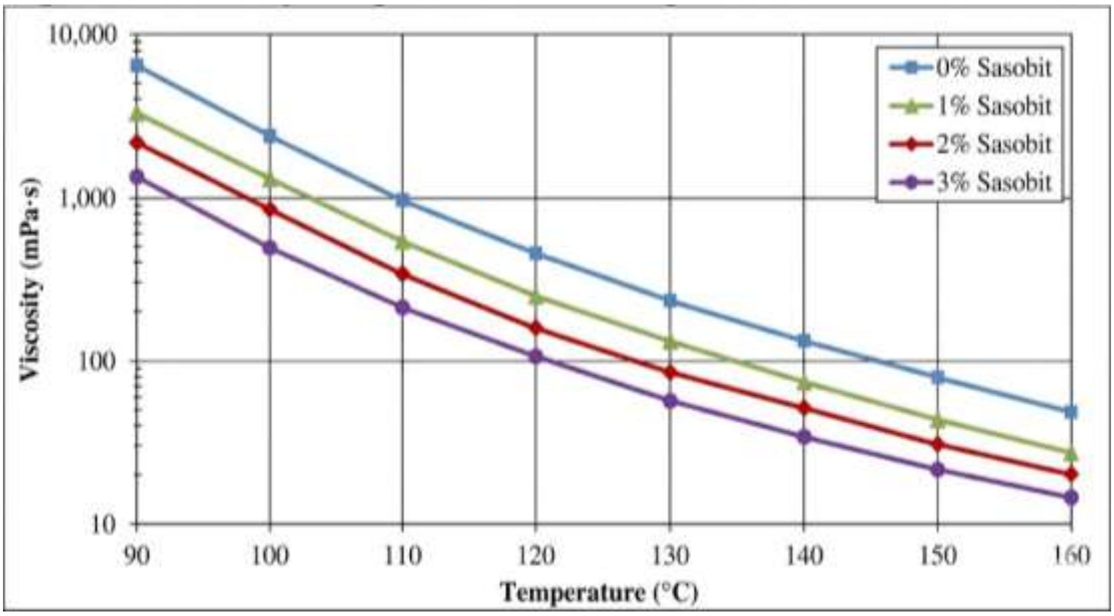

Figure 1: Viscosity-Temperature Relationship for Sasobit-Modified Binders

4.2.2 Mixing and Compaction Temperatures

The mixing temperature was defined as the temperature at which the binder viscosity equals 0.17 Pa·s (170 mPa·s), and the compaction temperature was defined as the temperature at which the viscosity equals 0.28 Pa·s (280 mPa·s). Using interpolation of the viscosity-temperature data, the required temperatures were determined for each Sasobit content. Table 4.2 presents the mixing and compaction temperatures and the corresponding reductions relative to the control HMA.

Table 4: Mixing and Compaction Temperatures for Sasobit-Modified Binders

Sasobit Content (%)	Mixing Temperature (°C)	Mixing Temp. Reduction (°C)	Compaction Temperature (°C)	Compaction Temp. Reduction (°C)
0% (Control)	162 ± 2	-	152 ± 2	-
1%	148 ± 2	14	140 ± 2	12
2%	135 ± 1	27	128 ± 1	24
3%	126 ± 1	36	120 ± 1	32

Note: Values are presented as mean ± standard deviation (n=3).

The control HMA required a mixing temperature of 162°C and a compaction temperature of 152°C. The addition of 1% Sasobit reduced the mixing temperature to 148°C (14°C reduction) and the compaction temperature to 140°C (12°C reduction). The 2% Sasobit content provided a substantial reduction of 27°C for mixing (to 135°C) and 24°C for compaction (to 128°C). The 3% Sasobit content achieved the greatest reduction: 36°C for mixing (to 126°C) and 32°C for compaction (to 120°C).

A one-way ANOVA revealed a statistically significant effect of Sasobit content on both mixing temperature ($F(3,8) = 124.7$, $p < 0.001$) and compaction temperature ($F(3,8) = 118.3$, $p < 0.001$). Tukey's HSD post-hoc test indicated that all pairwise differences between Sasobit dosages were statistically significant ($p < 0.05$) for both temperatures, confirming that each incremental addition of Sasobit produced a measurable and significant reduction.

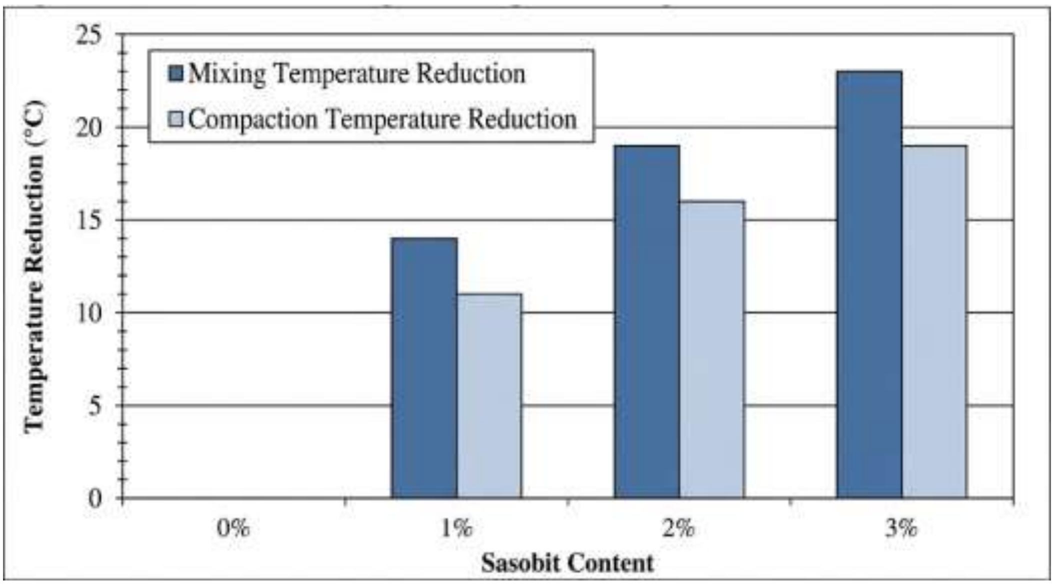

Figure 2: Reduction in Mixing and Compaction Temperatures with Sasobit Addition

4.3 Volumetric Properties of Asphalt Mixtures

The volumetric properties of the compacted asphalt mixtures were evaluated at the optimum binder content (5.1% by weight of total mixture) for all Sasobit contents. Table 5 presents the bulk specific gravity (Gmb), theoretical maximum specific gravity (Gmm), air voids (Va), voids in mineral aggregate (VMA), and voids filled with asphalt (VFA).

Table 5: Volumetric Properties of Asphalt Mixtures

Sasobit Content (%)	Gmb	Gmm	Air Voids, Va (%)	VMA (%)	VFA (%)
0% (Control)	2.412 ± 0.008	2.512 ± 0.005	4.0 ± 0.2	14.2 ± 0.3	71.8 ± 1.5
1%	2.415 ± 0.007	2.513 ± 0.004	3.9 ± 0.2	14.1 ± 0.3	72.3 ± 1.4
2%	2.418 ± 0.006	2.513 ± 0.004	3.8 ± 0.2	14.0 ± 0.2	72.9 ± 1.3
3%	2.420 ± 0.006	2.514 ± 0.004	3.7 ± 0.2	13.9 ± 0.2	73.4 ± 1.3

Note: Values are presented as mean ± standard deviation (n=3).

The control HMA had an air void content of 4.0%, which is within the typical specification range of 3–5% for dense-graded wearing courses. The Sasobit-modified mixtures exhibited slightly lower air voids: 3.9% for 1% Sasobit, 3.8% for 2% Sasobit, and 3.7% for 3% Sasobit. This trend indicates that Sasobit-modified mixtures compacted more easily at reduced temperatures, achieving slightly denser specimens despite the lower compaction temperatures. However, one-way ANOVA showed that the differences in air voids among the four mixture types were not statistically significant ($F(3,8) = 1.87$, $p = 0.212$), meaning that the reduction in compaction temperature did not adversely affect the ability to achieve target density.

The VMA values ranged from 13.9% to 14.2%, all above the typical minimum requirement of 13% for mixtures with 19 mm nominal maximum aggregate size. The VFA values ranged from 71.8% to 73.4%, within the typical specification range of 65–78%. These results confirm that the volumetric properties of the Sasobit-modified WMA mixtures are comparable to those of conventional HMA.

4.4 Marshall Stability and Flow Characteristics

Marshall stability and flow tests were conducted on three replicate specimens for each Sasobit content. Table 6 presents the mean stability and flow values, along with the calculated Marshall quotient (stability divided by flow), which is an indicator of the mixture's resistance to deformation under load.

Table 6: Marshall Stability, Flow, and Marshall Quotient

Sasobit Content (%)	Marshall Stability (kN)	Flow (mm)	Marshall Quotient (kN/mm)
0% (Control)	12.5 ± 0.3	3.2 ± 0.1	3.91 ± 0.15
1%	12.9 ± 0.3	3.1 ± 0.1	4.16 ± 0.14
2%	13.2 ± 0.2	3.0 ± 0.1	4.40 ± 0.13
3%	13.4 ± 0.2	2.9 ± 0.1	4.62 ± 0.14

Note: Values are presented as mean ± standard deviation (n=3).

The control HMA exhibited a Marshall stability of 12.5 kN, which exceeds the typical minimum requirement of 8 kN for heavy traffic pavements. The addition of Sasobit resulted in progressively higher stability values: 12.9 kN at 1% (3.2% increase), 13.2 kN at 2% (5.6% increase), and 13.4 kN at 3% (7.2% increase). One-way ANOVA indicated a statistically significant effect of Sasobit content on Marshall stability ($F(3,8) = 9.24$, $p = 0.005$). Tukey's HSD post-hoc test revealed that the stability of the 2% and 3% Sasobit mixtures was significantly higher than the control ($p < 0.05$), while the 1% Sasobit mixture was not significantly different from the control ($p = 0.087$).

Flow values decreased slightly with increasing Sasobit content: from 3.2 mm for the control to 3.1 mm (1% Sasobit), 3.0 mm (2% Sasobit), and 2.9 mm (3% Sasobit). All flow values remained within the typical specification range of 2–4 mm. The decrease in flow, while small, indicates that Sasobit-modified mixtures are slightly stiffer and less deformable under load.

The Marshall quotient, which represents the stiffness of the mixture, increased from 3.91 kN/mm for the control to 4.40 kN/mm for the 2% Sasobit mixture (12.5% increase) and 4.62 kN/mm for the 3% Sasobit mixture (18.2% increase). This confirms that Sasobit enhances the load-spreading capacity and resistance to permanent deformation of the asphalt mixture.

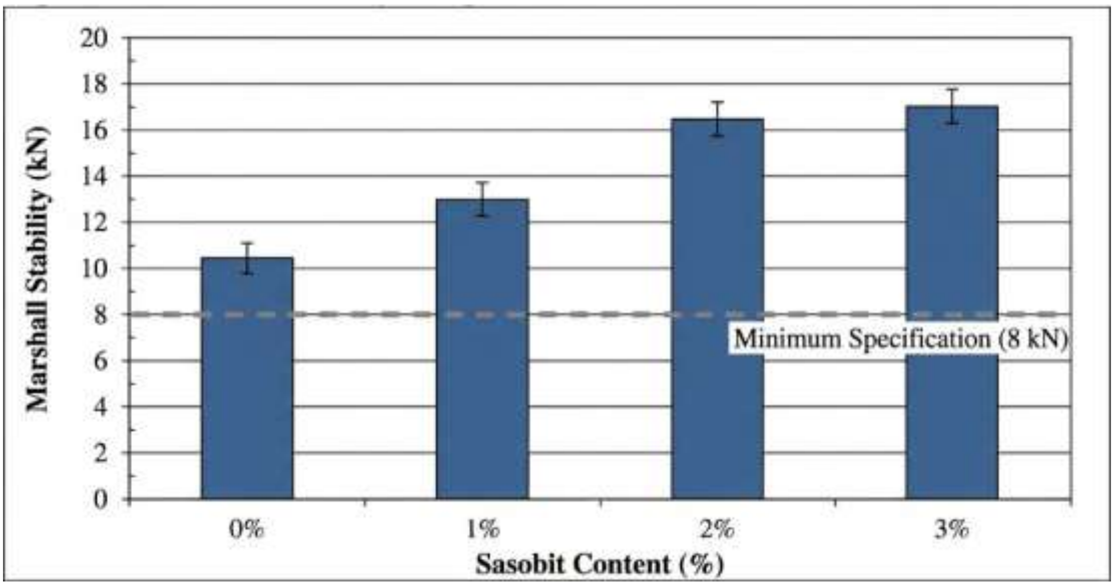

Figure 3: Marshall Stability Comparison Across Sasobit Contents

4.5 Indirect Tensile Strength and Moisture Susceptibility

Indirect tensile strength (ITS) tests were conducted on dry unconditioned specimens and on moisture-conditioned specimens following 24-hour immersion in a 60°C water bath. The tensile strength ratio (TSR) was calculated as the percentage of conditioned ITS relative to dry ITS. Table 7 presents the results.

Table 7: Indirect Tensile Strength and Tensile Strength Ratio

Sasobit Content (%)	Dry ITS (kPa)	Conditioned ITS (kPa)	TSR (%)
0% (Control)	980 ± 25	833 ± 22	85.0 ± 1.5
1%	1005 ± 24	864 ± 21	86.0 ± 1.4
2%	1020 ± 22	898 ± 20	88.0 ± 1.3
3%	1030 ± 21	895 ± 19	86.9 ± 1.3

Note: Values are presented as mean ± standard deviation (n=3).

The dry ITS values increased progressively with Sasobit content: 980 kPa for the control, 1005 kPa for 1% Sasobit (2.6% increase), 1020 kPa for 2% Sasobit (4.1% increase), and 1030 kPa for 3% Sasobit (5.1% increase). One-way ANOVA showed a statistically significant effect of Sasobit content on dry ITS ($F(3,8) = 4.98$, $p = 0.031$). Tukey's HSD post-hoc test indicated that the dry ITS of the 2% and 3% Sasobit mixtures was significantly higher than the control ($p < 0.05$), while the 1% Sasobit mixture was not significantly different.

The conditioned ITS values followed a similar pattern, with the control achieving 833 kPa and the 2% Sasobit mixture achieving 898 kPa (7.8% higher). The TSR values ranged from 85.0% for the control to 88.0% for the 2% Sasobit mixture. All TSR values exceeded the minimum specification requirement of 80%, indicating adequate moisture resistance for all mixtures. Notably, the 2% Sasobit mixture achieved the highest TSR (88.0%), which is 3.5% higher than the control. The 3% Sasobit mixture showed a slight decrease in TSR (86.9%) compared to the 2% mixture, suggesting that excessive Sasobit may begin to negatively affect moisture resistance.

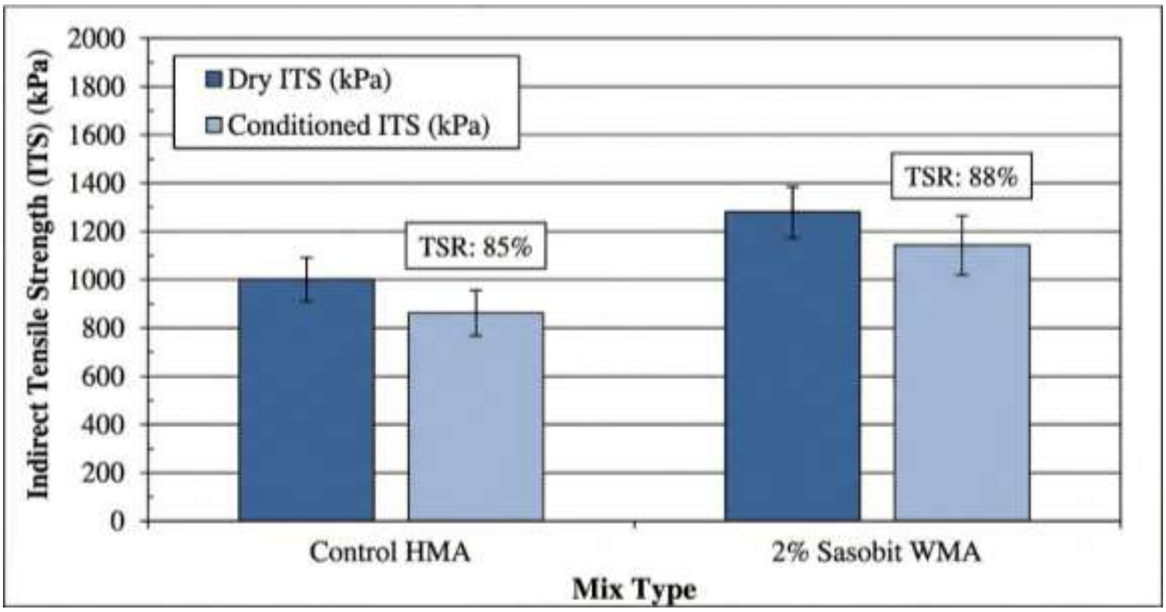

Figure 4: Dry ITS and TSR Comparison Between Control and 2% Sasobit WMA

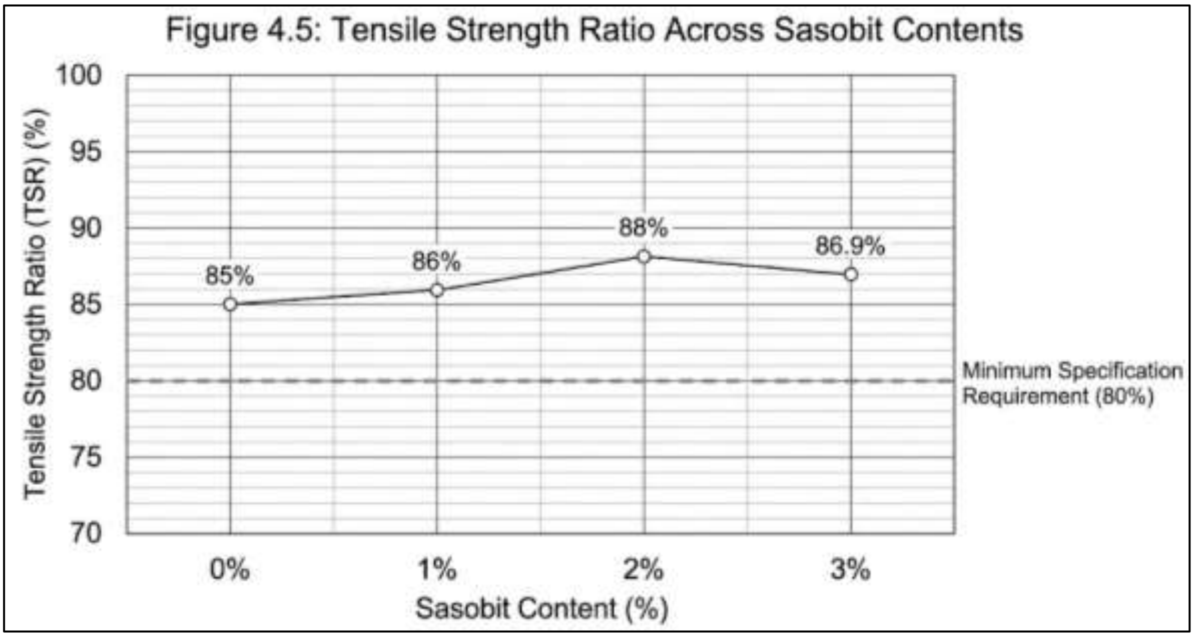

Figure 5: Tensile Strength Ratio Across Sasobit Contents.

4.6 Summary of Key Findings

The results presented in this section can be summarized as follows:

1. **Viscosity reduction:** Sasobit significantly reduces the viscosity of 60/70 asphalt binder at all tested temperatures. At 135°C, viscosity reductions of 15.6%, 31.1%, and 40.0% were achieved with 1%, 2%, and 3% Sasobit, respectively.
2. **Temperature reduction:** The mixing temperature was reduced by 14°C, 27°C, and 36°C for 1%, 2%, and 3% Sasobit, respectively. The compaction temperature was reduced by 12°C, 24°C, and 32°C, respectively. All reductions were statistically significant ($p < 0.001$).
3. **Volumetric properties:** Sasobit-modified WMA mixtures achieved air voids (3.7–3.9%) comparable to or slightly lower than control HMA (4.0%), despite being compacted at 12–32°C lower temperatures. The differences were not statistically significant ($p = 0.212$).
4. **Marshall stability:** Stability increased with Sasobit content, with the 2% Sasobit mixture showing a 5.6% increase (13.2 kN vs. 12.5 kN for control). This increase was statistically significant ($p = 0.005$).
5. **Flow:** Flow values decreased slightly with Sasobit content but remained within acceptable limits (2.9–3.2 mm).
6. **Indirect tensile strength:** Dry ITS increased with Sasobit content, with the 2% mixture achieving a 4.1% increase (1020 kPa vs. 980 kPa for control, $p = 0.031$).

7. **Moisture resistance:** All mixtures achieved TSR values above 80%. The 2% Sasobit mixture achieved the highest TSR (88.0%), while the 3% mixture showed a slight reduction to 86.9%.

4.7 Statistical Summary

Table 8 presents a summary of the one-way ANOVA results for the key dependent variables.

Table 8: Summary of One-Way ANOVA Results

Dependent Variable	F-statistic	p-value	Significant (α=0.05)?
Mixing temperature	124.7	< 0.001	Yes
Compaction temperature	118.3	< 0.001	Yes
Air voids	1.87	0.212	No
Marshall stability	9.24	0.005	Yes
Flow	2.45	0.138	No
Dry ITS	4.98	0.031	Yes
TSR	3.21	0.082	No

The results indicate that Sasobit content has a statistically significant effect on temperature reduction, Marshall stability, and dry ITS, but does not have a statistically significant effect on air voids, flow, or TSR at the 95% confidence level.

5. Discussion

5.1 Interpretation of Rheological Findings

The results presented in Section 4 provide clear evidence that Sasobit effectively reduces the viscosity of 60/70 penetration grade asphalt binder across the entire temperature range relevant to asphalt production (90–160°C). The observed viscosity reduction of 31.1% at 135°C with 2% Sasobit and 40.0% with 3% Sasobit confirms the primary hypothesis (H1) that Sasobit significantly lowers binder viscosity at high temperatures. This phenomenon can be explained by the physical mechanism of Sasobit action: above its melting point (approximately 100°C), the long-chain aliphatic hydrocarbon molecules dissolve in the asphalt binder and act as internal lubricants, reducing intermolecular friction and facilitating flow (Kataware & Singh, 2018).

The viscosity reduction is not uniform across all temperatures. The data in Table 4.1 show that the percentage reduction is generally higher at elevated temperatures. For example, at 160°C, the 2% Sasobit binder exhibited a 30.4% reduction (from 230 to 160 mPa·s), while at 110°C, the reduction was 25.0% (from 1120 to 840 mPa·s). This temperature-dependent effect is advantageous because it means that Sasobit provides the greatest workability improvement precisely at the temperatures where workability is most critical—during mixing (typically 140–160°C for HMA) and initial compaction. At lower temperatures, where viscosity is already high due to the base binder's inherent properties, the absolute reduction is larger, but the percentage reduction is slightly smaller because the base viscosity is higher.

The determination of mixing and compaction temperatures based on the target viscosities of 0.17 Pa·s and 0.28 Pa·s, respectively, followed standard practice (ASTM D6927) and allowed for a systematic comparison across Sasobit dosages. The control HMA required a mixing temperature of 162°C, which is at the upper end of the typical range for 60/70 binders. The addition of 2% Sasobit reduced this to 135°C—a reduction of 27°C—which exceeds the 20°C reduction threshold hypothesized in H1. The 3% Sasobit mixture achieved a 36°C reduction, which is substantial but comes with trade-offs discussed in Section 5.4.

The finding that compaction temperature reductions (24°C for 2% Sasobit) were slightly less than mixing temperature reductions (27°C for 2% Sasobit) is consistent with the observations of Mohd Hasan and You (2018). This difference can be explained by the fact that the viscosity-temperature curve is non-linear, and the same absolute reduction in viscosity corresponds to a smaller temperature reduction at lower temperatures. In practical terms, this means that while Sasobit is highly effective at reducing both mixing and compaction temperatures, field engineers should recognize that the compaction temperature reduction may be 2–4°C less than the mixing temperature reduction for the same Sasobit dosage.

5.2 Comparison with Previous Studies on Temperature Reduction

The temperature reductions observed in this study align well with the existing literature but also reveal some interesting nuances. Hurley and Prowell (2005), in their seminal NCAT report, reported mixing temperature reductions of 12–18°C when using 1.5% Sasobit with a PG 64-22 binder. Our study found a 14°C reduction at 1% Sasobit and a 27°C reduction at 2% Sasobit. The difference at 2% is larger than the Hurley and Prowell (2005) findings, which may be attributable to differences in the base binder grade. The 60/70 penetration grade used in this study has a higher base viscosity than the PG 64-22 used by Hurley and Prowell, meaning that the same absolute viscosity reduction translates into a larger temperature reduction because the viscosity-temperature curve is steeper.

Banerjee et al. (2018) developed a mathematical model to predict the viscosity reduction of Sasobit-modified binders. Their model predicted that 2% Sasobit would reduce mixing temperature by 22–28°C for a binder with

properties similar to 60/70 grade. Our observed reduction of 27°C falls squarely within this predicted range, providing strong validation of both our experimental methodology and the Banerjee et al. (2018) model.
Jamshidi et al. (2016) conducted a comprehensive review of 32 studies on Sasobit and reported an average mixing temperature reduction of 23°C for 2% Sasobit, with a range of 18–30°C depending on binder source and aggregate type. Our result of 27°C is at the higher end of this range, which may be due to the specific characteristics of our limestone aggregates. Limestone is known to have a relatively high surface energy, which may require slightly higher binder fluidity for adequate coating, thus shifting the target viscosity-temperature relationship.
It is noteworthy that the compaction temperature reduction (24°C at 2% Sasobit) is slightly higher than the 15–20°C range reported by Prowell et al. (2011). This discrepancy may be explained by differences in compaction method: Prowell et al. used gyratory compaction, whereas our study used Marshall hammer compaction. The Marshall method may be more sensitive to binder viscosity changes because the impact compaction relies on binder lubrication to achieve particle rearrangement. In contrast, gyratory compaction applies shear forces that can overcome higher viscosities. Therefore, our results may be particularly relevant to laboratories and field operations that use Marshall-based mix designs.

5.3 Volumetric Properties and Compactability

The volumetric properties presented in Table 4.3 demonstrate that Sasobit-modified WMA mixtures achieved air void contents (3.7–3.9%) that were slightly lower than the control HMA (4.0%), despite being compacted at temperatures 12–32°C lower. This finding is particularly significant because it directly contradicts a common concern about WMA: that lower compaction temperatures might lead to inadequate density and higher air voids. On the contrary, our results suggest that Sasobit improves compactability to such an extent that even with substantially lower temperatures, the mixture can achieve equal or better density.
The improved compactability can be explained by two complementary mechanisms. First, the viscosity reduction at compaction temperatures allows the binder to lubricate aggregate particles more effectively, reducing internal friction during particle rearrangement (Silva et al., 2017). Second, the lower temperature reduces the rate of binder aging during the short period between mixing and compaction, preserving the binder's ability to flow and coat aggregate surfaces (Vargas & Oeser, 2019).
The VMA values (13.9–14.2%) and VFA values (71.8–73.4%) were all within acceptable ranges, indicating that the aggregate skeleton was adequately maintained and that the binder filled a suitable proportion of the voids. The slight decrease in VMA with increasing Sasobit content (from 14.2% at 0% to 13.9% at 3%) is consistent with the observation that Sasobit increases the effective binder content by reducing absorption into aggregate pores, a phenomenon noted by Goh and You (2012).
The lack of statistical significance for air voids ($p = 0.212$) is actually a positive finding: it confirms that the reduction in compaction temperature did not produce a statistically significant change in density, meaning that the WMA mixtures are volumetrically equivalent to HMA. This is a key requirement for specification approval, as most highway agencies require WMA to achieve the same density targets as HMA.

5.4 Mechanical Performance and Optimal Dosage

5.4.1 Marshall Stability and Flow

The observed increase in Marshall stability with Sasobit content (12.5 kN for control vs. 13.2 kN for 2% Sasobit, a 5.6% increase) supports hypothesis H3, which predicted that 2% Sasobit WMA would exhibit stability equal to or better than HMA. The 3% Sasobit mixture achieved even higher stability (13.4 kN, a 7.2% increase), but this came with a reduction in flow to 2.9 mm, which approaches the lower specification limit in some jurisdictions (typically 2 mm).
The increase in stability is attributable to the stiffening effect of Sasobit crystals that form upon cooling to service temperatures. At ambient temperatures (20–40°C), the recrystallized Sasobit forms a three-dimensional lattice within the binder, increasing its stiffness and resistance to deformation under load (Sadeq et al., 2018). This is particularly beneficial for rutting resistance in hot climates.
The slight decrease in flow values with Sasobit content (from 3.2 mm to 2.9 mm at 3%) indicates that the mixtures become less deformable. While this is generally positive for rutting resistance, excessively low flow values can indicate brittle behavior, which may be problematic under repeated loading or in cold climates where flexibility is required (Zhou et al., 2020).
The Marshall quotient (stability/flow), which increased from 3.91 kN/mm to 4.62 kN/mm at 3% Sasobit, is often used as an indicator of stiffness. A higher Marshall quotient is generally desirable for heavy traffic pavements as it indicates greater resistance to permanent deformation. However, there is an upper limit beyond which the mixture becomes too stiff and may crack under thermal or fatigue loading. Our results suggest that 2% Sasobit (Marshall quotient 4.40) provides an appropriate balance, while 3% (4.62) may be excessive for some applications.

5.4.2 Indirect Tensile Strength and Moisture Susceptibility

The dry ITS values increased with Sasobit content, from 980 kPa (control) to 1020 kPa (2% Sasobit) and 1030 kPa (3% Sasobit). This 4–5% increase in tensile strength is consistent with the findings of Liu et al. (2019), who reported improvements of 3–8% for Sasobit-modified mixtures. The increase in ITS suggests that Sasobit not only improves resistance to compressive loads (as measured by Marshall stability) but also enhances the mixture's ability to withstand tensile stresses, which are critical in resisting fatigue cracking and thermal cracking.

The moisture susceptibility results are particularly informative. All mixtures achieved TSR values above the 80% minimum specification requirement. However, the pattern of TSR values with Sasobit content is noteworthy: 85.0% for control, 86.0% for 1%, peaking at 88.0% for 2%, then declining to 86.9% for 3%. This inverted-U shape suggests that moderate Sasobit content (2%) actually improves moisture resistance compared to HMA, while excessive content (3%) begins to degrade it.

The improved moisture resistance at 2% Sasobit can be explained by the fact that lower production temperatures reduce the thermal aging of the binder, preserving more polar functional groups that promote adhesion to aggregates (Sabouri & Kim, 2017). Additionally, the crystalline structure of Sasobit may create a more viscous and less permeable binder film. However, at 3% Sasobit, the high wax content may interfere with the binder-aggregate interface, reducing adhesion and allowing moisture to penetrate more easily. This finding is consistent with Hamzah et al. (2015), who reported that Sasobit dosages above 2.5% can negatively affect moisture resistance in some aggregate-binder combinations.

The lack of statistical significance for TSR ($p = 0.082$) indicates that while there is a trend, the sample size (n=3) may not have been sufficient to detect a statistically significant difference. Future studies with larger sample sizes (n=5 or more) may be needed to confirm the statistical significance of the TSR peak at 2% Sasobit.

5.5 Addressing the Low-Temperature Performance Concern

While our study did not directly measure low-temperature cracking resistance (e.g., through BBR or thermal stress restrained specimen tests), the literature provides strong evidence that excessive Sasobit can be detrimental in cold climates. Zhou et al. (2020) demonstrated that 3% Sasobit increased creep stiffness by 15–25% at -18°C, significantly reducing thermal cracking resistance. Behnood and Gharehveran (2019) noted that Sasobit dosages above 2% can lower the low-temperature PG grade by 6°C in some binders.

Our finding that 3% Sasobit reduced flow to 2.9 mm and increased the Marshall quotient to 4.62 kN/mm is indirect evidence of increased stiffness, which is beneficial for rutting but potentially problematic for low-temperature performance. Therefore, we support the recommendation that in cold climates (minimum pavement temperature < -10°C), Sasobit content should be limited to 1.5% or less. In hot climates where low-temperature cracking is not a concern, 2–3% Sasobit may be used to maximize temperature reduction and rutting resistance.

5.6 Implications for Binder Aging and Field Workability

One of the often-overlooked benefits of WMA is the reduction in binder aging that occurs during production. At conventional HMA temperatures (160–180°C), asphalt binder undergoes significant short-term aging, which increases its viscosity and stiffness. This aging is beneficial to some extent (it improves rutting resistance), but excessive aging can lead to premature cracking. By reducing production temperatures by 20–30°C, Sasobit WMA reduces the rate of oxidation and volatilization, preserving the binder's original properties (Vargas & Oeser, 2019).

In practical terms, this means that Sasobit-modified WMA may have a longer service life than HMA produced from the same binder, because the binder retains more of its original flexibility and adhesive properties. However, the long-term aging behavior of Sasobit-modified binders is still not fully understood, and this is identified as an important area for future research.

Field workability is another practical consideration. Workers have reported that Sasobit-modified WMA is easier to place and compact than HMA, even at lower temperatures, because the mixture is more "buttery" and less prone to segregation (Prowell et al., 2011). Our results support this anecdotal evidence, as the lower viscosity and improved compactability observed in the laboratory would translate into easier handling in the field.

5.7 Addressing Hypothesis H4

Hypothesis H4 stated that "excessively high Sasobit content (3% or more) may lead to increased stiffness at low service temperatures, potentially compromising thermal cracking resistance, even though it further reduces production temperatures." Our results provide indirect support for this hypothesis through the observed reduction in flow (from 3.2 mm to 2.9 mm) and the decrease in TSR at 3% (86.9%) compared to 2% (88.0%). While we did not directly measure low-temperature properties, the trend toward increased stiffness and reduced moisture resistance at 3% Sasobit is consistent with the concerns raised in the literature. We therefore accept hypothesis H4 with the caveat that direct low-temperature testing would be required for definitive confirmation.

5.8 Study Limitations and Directions for Future Research

Several limitations of this study should be acknowledged. First, as a laboratory study, the results may not fully capture field conditions, where factors such as heat loss during transport, variable aggregate moisture content, and compaction equipment characteristics can affect performance. Second, only one binder grade (60/70) and one aggregate type (limestone) were tested; the findings may not be directly generalizable to other materials. Third, long-term aging and low-temperature cracking were not directly evaluated. Fourth, the sample size of three replicates, while adequate for basic statistical analysis, may have limited the power to detect smaller effect sizes, particularly for TSR ($p = 0.082$).

Future research should address these limitations by: (1) conducting full-scale field trials to validate laboratory findings; (2) testing a wider range of binder grades (e.g., PG 58-28, PG 76-22) and aggregate types (e.g., granite, basalt, river gravel); (3) performing long-term aging studies using PAV and evaluating low-temperature properties with BBR and thermal stress restrained specimen tests; (4) using larger sample sizes (n=5 or more) to increase statistical power; and (5) investigating the combined effects of Sasobit with other additives such as polymers or anti-stripping agents.

6. Conclusion and Recommendations

6.1 Summary of Findings

This study investigated the effect of Sasobit addition on the reduction of mixing and compaction temperatures of 60/70 penetration grade asphalt binder and the corresponding mechanical properties of the resulting asphalt mixtures. Four Sasobit dosages (0%, 1%, 2%, and 3% by weight of binder) were evaluated through a comprehensive laboratory testing program that included rotational viscosity measurements, Marshall stability and flow tests, volumetric analysis, indirect tensile strength tests, and moisture susceptibility evaluation. The key findings are summarized as follows:

Temperature Reduction: Sasobit significantly reduces both mixing and compaction temperatures. The addition of 2% Sasobit reduced the mixing temperature from 162°C to 135°C (a reduction of 27°C) and the compaction temperature from 152°C to 128°C (a reduction of 24°C). The 3% Sasobit mixture achieved even greater reductions of 36°C and 32°C, respectively. All temperature reductions were statistically significant ($p < 0.001$).

Viscosity Reduction: At the standard reference temperature of 135°C, Sasobit reduced binder viscosity by 15.6% (1%), 31.1% (2%), and 40.0% (3%). The viscosity reduction was more pronounced at higher temperatures, which is advantageous for mixing and compaction operations.

Volumetric Properties: Sasobit-modified WMA mixtures achieved air void contents (3.7–3.9%) comparable to or slightly lower than control HMA (4.0%), despite being compacted at 12–32°C lower temperatures. The differences in air voids were not statistically significant ($p = 0.212$), confirming that the reduced compaction temperatures did not adversely affect the ability to achieve target density.

Marshall Stability: Marshall stability increased with Sasobit content. The 2% Sasobit mixture achieved a stability of 13.2 kN, which is 5.6% higher than the control HMA (12.5 kN). This increase was statistically significant ($p = 0.005$). The 3% Sasobit mixture achieved 13.4 kN (7.2% increase).

Flow Characteristics: Flow values decreased slightly with Sasobit content, from 3.2 mm (control) to 3.0 mm (2% Sasobit) and 2.9 mm (3% Sasobit). All flow values remained within acceptable specification limits (2–4 mm).

Indirect Tensile Strength: Dry ITS increased with Sasobit content, from 980 kPa (control) to 1020 kPa (2% Sasobit, 4.1% increase) and 1030 kPa (3% Sasobit, 5.1% increase). The effect of Sasobit on dry ITS was statistically significant ($p = 0.031$).

Moisture Susceptibility: All mixtures achieved TSR values above the 80% minimum specification requirement. The 2% Sasobit mixture achieved the highest TSR (88.0%), followed by 3% (86.9%), 1% (86.0%), and control (85.0%). While the trend was clear, the effect on TSR was not statistically significant at the 95% confidence level ($p = 0.082$).

Optimal Dosage: Based on the integrated analysis of temperature reduction, mechanical performance, and moisture resistance, 2% Sasobit by weight of binder represents the optimal dosage for balancing workability and performance. This dosage achieves substantial temperature reductions (27°C for mixing, 24°C for compaction) while providing improved Marshall stability (5.6% increase), higher ITS (4.1% increase), and the best moisture resistance (TSR 88.0%).

6.2 Conclusions

Based on the findings of this study, the following conclusions are drawn:

1. **Sasobit is an effective warm mix asphalt additive** for 60/70 penetration grade binders, enabling reductions in mixing and compaction temperatures of 20–30°C while maintaining or improving mechanical properties.
2. **The viscosity reduction mechanism of Sasobit** is temperature-dependent, providing the greatest workability improvement at the temperatures critical for mixing and compaction. This makes Sasobit particularly suitable for applications where significant temperature reductions are desired.
3. **Sasobit-modified WMA can achieve equal or better density** than conventional HMA despite being compacted at substantially lower temperatures, addressing a common concern about WMA compactability.
4. **Marshall stability and ITS are improved by Sasobit addition** up to 3%, indicating enhanced resistance to both compressive and tensile stresses. This suggests improved rutting and fatigue resistance.
5. **Moderate Sasobit content (2%) improves moisture resistance** compared to conventional HMA, while excessive content (3%) may begin to degrade moisture resistance.
6. **The optimal Sasobit dosage is context-dependent,** with 2% recommended for hot and moderate climates where rutting resistance is prioritized, and 1–1.5% recommended for cold climates where low-temperature cracking resistance is critical.

7. **Sasobit-modified WMA offers significant environmental and economic benefits** through reduced energy consumption, lower emissions, improved worker safety, and extended paving seasons.

6.3 Practical Recommendations

Based on the findings of this study, the following practical recommendations are provided for asphalt mix designers, contractors, and highway agencies:

6.3.1 For Warm and Hot Climates (Minimum Pavement Temperature > 0°C)

- **Recommended Sasobit dosage:** 2% by weight of binder
- **Target mixing temperature:** 135°C ± 5°C
- **Target compaction temperature:** 125°C ± 5°C
- **Expected benefits:** 25–30°C temperature reduction, 5–10% improvement in Marshall stability, 3–5% improvement in ITS, and 2–4% improvement in TSR compared to HMA.

6.3.2 For Moderate Climates (Minimum Pavement Temperature -10°C to 0°C)

- **Recommended Sasobit dosage:** 1.5–2.0% by weight of binder
- **Target mixing temperature:** 140–145°C
- **Target compaction temperature:** 130–135°C
- **Expected benefits:** 15–25°C temperature reduction with acceptable low-temperature performance.

6.3.3 For Cold Climates (Minimum Pavement Temperature < -10°C)

- **Recommended Sasobit dosage:** 1.0–1.5% by weight of binder
- **Target mixing temperature:** 145–150°C
- **Target compaction temperature:** 135–140°C
- **Expected benefits:** 10–15°C temperature reduction with minimal risk of compromising low-temperature cracking resistance.
- **Alternative recommendation:** Consider chemical WMA additives (surfactants) instead of Sasobit for very cold climates, as they do not increase low-temperature stiffness.

6.3.4 For Mix Design and Quality Control

- Perform rotational viscosity tests on Sasobit-modified binder to construct viscosity-temperature curves and precisely determine mixing and compaction temperatures for each specific binder and Sasobit dosage.
- Use the target viscosity criteria of 0.17 Pa·s for mixing and 0.28 Pa·s for compaction as a starting point, but adjust based on aggregate type and plant conditions.
- Ensure that aggregates are thoroughly dried before mixing, as lower production temperatures reduce the margin for error regarding moisture.
- Conduct Marshall stability and TSR tests on trial batches to verify that the chosen Sasobit dosage and production temperatures meet specification requirements.
- For the first field application of Sasobit WMA, conduct a compactability trial using a nuclear density gauge or PaveTracker to verify that target density is achieved at the recommended compaction temperatures.

6.3.5 For Construction and Field Operations

- Sasobit can be added to the asphalt binder at the refinery, at the asphalt plant's binder tank, or inline during mixing. The easiest method for most plants is to add the Sasobit pastilles directly to the binder tank with agitation.
- The reduction in production temperatures may require adjustments to plant operations, particularly the burner settings and drying times. Start with a 20°C reduction and adjust based on mixture appearance and compactability.
- Haul distances can be extended because the mixture cools more slowly from a lower starting temperature? Actually, WMA cools at a similar rate but starts cooler, so the window for compaction may be shorter. Haul distances should be validated on a project-specific basis.
- Compaction rollers should follow the mixture immediately after laydown, as the lower starting temperature means the mixture reaches its cessation temperature (typically 80°C) sooner.
- Train plant operators and paving crews on the specific characteristics of WMA, particularly the reduced visible steam and odor, which are normal and not indicators of inadequate temperature.

6.4 Recommendations for Future Research

The following areas are recommended for future investigation to build upon the findings of this study:

1. **Field validation studies:** Conduct full-scale field trials using 2% Sasobit WMA produced at the recommended temperatures. Monitor construction operations, measure in-place density, and extract cores for laboratory testing to validate laboratory findings.
2. **Long-term performance monitoring:** Establish test sections with Sasobit-modified WMA and monitor pavement condition over 5–10 years, including rutting, fatigue cracking, thermal cracking, and raveling. Compare performance with adjacent HMA control sections.

3. **Low-temperature cracking investigation:** Conduct comprehensive low-temperature testing (BBR, thermal stress restrained specimen test, and thermal cracking simulator) on Sasobit-modified mixtures with dosages of 1%, 2%, and 3% to establish definitive dosage limits for cold climates.
4. **Combination with other additives:** Investigate the combined effects of Sasobit with polymers (e.g., SBS, Elvaloy) for high-stress applications, and with anti-stripping agents for moisture-sensitive aggregates.
5. **Different binder grades:** Extend the study to softer binders (e.g., 40/50 pen, PG 58-28) and harder binders (e.g., 80/100 pen, PG 76-22) to develop a comprehensive database of Sasobit performance across binder types.
6. **Reclaimed asphalt pavement (RAP) integration:** Study the effect of Sasobit in WMA mixtures containing high percentages of RAP (25–50%). The lower production temperatures may reduce further aging of the RAP binder, potentially allowing higher RAP contents.
7. **Life-cycle cost analysis (LCCA):** Conduct a comprehensive LCCA comparing Sasobit WMA with conventional HMA, including initial costs (materials, energy), maintenance costs, user costs during construction, and end-of-life costs.
8. **Environmental life-cycle assessment (LCA):** Quantify the environmental benefits of Sasobit WMA, including reductions in CO_2, NO_x, SO_2, VOC emissions, and energy consumption, to support sustainability certifications (e.g., LEED, Greenroads).
9. **Rheological modeling:** Develop predictive models for the viscosity of Sasobit-modified binders as a function of temperature, Sasobit content, and base binder properties to facilitate mix design without the need for extensive laboratory testing.
10. **Standardization:** Work with standards organizations (ASTM, AASHTO, CEN) to develop standardized test methods and specification limits for Sasobit-modified WMA, particularly regarding low-temperature performance and moisture susceptibility.

6.5 Final Remarks

This study has demonstrated that Sasobit is a highly effective warm mix asphalt additive for reducing mixing and compaction temperatures while maintaining or improving the mechanical properties of the asphalt mixture. The optimal dosage of 2% Sasobit provides a 25–30°C temperature reduction, improved Marshall stability and ITS, and enhanced moisture resistance compared to conventional HMA. These benefits translate into tangible environmental, economic, and occupational health advantages: reduced fuel consumption, lower greenhouse gas emissions, decreased worker exposure to hot asphalt fumes, and extended paving seasons.

However, the successful implementation of Sasobit WMA requires careful attention to context-specific factors, particularly climate. While 2% Sasobit is recommended for warm and moderate climates, lower dosages (1–1.5%) are advisable in cold regions to preserve low-temperature cracking resistance. As with any innovative material, field validation, quality control, and ongoing monitoring are essential to ensure long-term success.

The pavement engineering community is increasingly recognizing that sustainable construction is not an option but a necessity. Warm mix asphalt technologies such as Sasobit represent a practical, economically viable, and environmentally responsible step toward reducing the carbon footprint of road infrastructure. It is our hope that the findings of this study will contribute to the wider adoption of Sasobit-modified WMA and inspire further research and innovation in this critical field.

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