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Research Article

Potential application of High Modulus Asphalt Concrete with TPS Additive for Asphalt Pavements in Vietnam

Thoi Duy Do[1*], Xian-Hua Chen[2], Vu-Tu Tran[1]

[1] Faculty of Civil Engineering, Ho Chi Minh City University of Technology and Education, Ho Chi Minh City, Vietnam.

[2] Department of Road Engineering, School of Transportation, Southeast University, China.

[*] Correspondence: dthoidd.ncs@hcmute.edu.vn

Abstract: Asphalt concrete (AC) pavements in Vietnam face increasing challenges due to heavy traffic loads, prolonged congestion, and extreme weather conditions, especially high temperatures and humidity. Conventional AC mixtures often suffer from rutting, cracking, and reduced durability under such conditions. This study investigates the potential of using TAFPACK-Super (TPS) as an additive to develop high modulus asphalt concrete (HMAC) mixtures for improved road performance in Vietnam. Three HMAC mixtures with different TPS contents (0.3 %, 0.5 %, and 0.7 %) were evaluated through a series of laboratory tests, including Marshall stability, wheel tracking, four-point bending fatigue, low-temperature flexural strength, and dynamic modulus. The results showed significant improvements in rutting resistance, water stability, fatigue life, and thermal cracking resistance with increasing TPS content. Quantitatively, dynamic stability increased by 458 % compared with the control mixture (893 → 4,989 cycles/mm). Notably, the mixture with 0.5 % TPS achieved a balanced enhancement across all performance criteria while maintaining practical economic feasibility through dry mixing application. Radar chart comparison revealed that TPS 0.5 % provided the most cost-effective and technically efficient solution. This study confirms the technical viability and high application potential of TPS-modified HMAC for highways and heavy-duty pavements in Vietnam, offering a promising material innovation to address current pavement distress and lifecycle performance requirements.

Keywords: High modulus asphalt concrete (HMAC), TPS additive, rutting resistance, water stability, fatigue performance, dynamic modulus

Highlights:

- TPS significantly improves rutting resistance, moisture stability, and fatigue life of HMAC.
- TPS increases dynamic modulus and reduces high-temperature softening, fitting Vietnam's hot–humid climate.
- A 0.5% TPS content provides optimal technical performance while maintaining reasonable construction cost.

1. Introduction

1.1 Research background

Asphalt concrete (AC) has been widely applied in road construction both in Vietnam and worldwide due to its superior properties, including high load-bearing capacity, smooth riding surface, and rapid construction process. However, under the increasing pressure of traffic volume, heavy axle loads, and global climate change - particularly the rising trend of ambient temperatures - the common distresses of asphalt pavements such as cracking, rutting, and surface wear have become more severe. These failures not only reduce the service quality of roadways but also significantly shorten the design life of pavement structures.

In Vietnam, field investigations indicate that rutting is the most prevalent and critical distress affecting asphalt pavements. The primary cause is attributed to the poor high-temperature stability of conventional asphalt mixtures, which fail to meet the long-term load-bearing requirements under real traffic conditions characterized by high traffic intensity, prolonged congestion, and frequent overloading(Nguyen & Le, 2016). According to Do (2017), the proportion of overloaded vehicles in Vietnam averages about 39.25 %, while traffic congestion frequently occurs at intersections and toll plazas, resulting in substantially extended load durations (Do, 2017). From a climatic perspective, summer months (June–August) record average temperatures exceeding 31 °C, with extreme heat events above 40 °C on many days. Additionally, the prolonged rainy season, with high precipitation and relative humidity levels ranging from 85–87%, further diminishes the rutting resistance and structural stability of asphalt pavements (Nhất & Thiện, 2014). In hot–humid regions, rutting is a predominant distress that rapidly degrades ride quality and network reliability under heavy axles and elevated pavement temperatures. Southeast Asian cities have experienced more frequent and intense hot extremes in recent decades and this trend is projected to continue, exacerbating heat-related deterioration of asphalt surfaces. Field reports from Vietnam and regional assessments similarly note accelerated permanent deformation of conventional asphalt during warm seasons and heat waves, underscoring a resilience gap in urban corridors (Nguyen & Le, 2016). In adaptation guidance for transport, multilateral agencies recommend material-level measures - e.g., higher modulus, improved rutting resistance, and durability under heat and moisture - to sustain service levels and reduce lifecycle disruptions and emissions (Bank, 2011).

To address these challenges, various domestic studies have proposed multiple solutions, ranging from traffic management measures - such as axle load control, optimized traffic organization, construction of grade-separated interchanges, and implementation of electronic toll collection (ETC) - to improvements in pavement materials. Representative approaches include adjusting aggregate gradation with larger particle sizes (Nguyen Hoang & Le, 2018), employing polymer-modified bitumen (Deef-Allah & Mohamady, 2014), reinforcing mixtures with glass or synthetic fibers, incorporating mineral fillers with high $CaCO_3$ content, replacing traditional fillers with industrial additives such as Residue Fluid Catalytic Cracking (RFCC) powder (Le, 2022), or using anti-stripping agents to enhance the adhesion between binder and aggregates (Lu et al., 2023). While these measures have shown partial effectiveness, rutting has not been fundamentally mitigated, especially under Vietnam's harsh environmental and loading conditions.

This situation underscores the urgent need to research, develop, and implement advanced material solutions that can significantly improve the thermal stability and long-term durability of asphalt mixtures under local conditions.

1.2 Literature Review

Globally, many scholars have focused on enhancing the performance of asphalt concrete (AC) pavements, particularly in the context of climate change and increasing axle loads. One prominent trend is the development of High Modulus Asphalt Concrete (HMAC), which aims to improve mixture stiffness, load distribution capacity, and resistance to permanent deformation. According to Di Benedetto and Olard (2003), increasing the modulus of asphalt mixtures reduces tensile stress at the bottom of the surface layer and decreases plastic deformation in the asphalt course, thereby extending pavement service life (Olard et al., 2003). Similarly, some studies highlighted the effectiveness of polymer additives such as polyphosphoric acid (PPA), styrene–butadiene–styrene (SBS), and high molecular compounds in enhancing rheological behavior and rutting resistance at elevated temperatures (Huang et al., 2024; Li et al., 2021; Yan et al., 2019). Several polymer additives have been commercialized and widely applied in heavy-duty pavements, including Shell SEAM (United States), Duroflex (Germany), PR Plast S (France), and TPS (Japan). Furthermore, mixing technologies have evolved from traditional wet blending to dry mixing methods, which simplify construction while maintaining improvement efficiency (Agha et al., 2023; Radeef et al., 2021; Zhang & Muhunthan, 2019). International applications of TPS-modified asphalt have also been reported in regions with climatic conditions similar to Vietnam. In Japan, TPS-based high-viscosity binders have been widely used for expressways and urban heavy-traffic corridors, demonstrating excellent rutting and moisture resistance under hot and humid summer weather (Taiyu VietNam Co., 2024). Field sections in Malaysia and Thailand further show that TPS-enhanced mixtures perform well under tropical monsoon conditions characterized by high temperatures and intense rainfall, exhibiting improved deformation resistance and reduced stripping potential (Imjai et al., 2024; Selvadurai et al., 2021). These practical applications confirm the suitability of TPS for countries facing comparable environmental and loading stresses.

In Vietnam, research efforts to improve asphalt pavement performance have been carried out along multiple directions, most notably through the use of SBS-modified asphalt or polymer-modified bitumen (PMB) to enhance durability and aging resistance (Phan, 2024). Nguyen et al. (2019) analyzed interlayer shear stresses in asphalt layers and demonstrated that HMAC mixtures could substantially reduce contact stress, thus improving overall structural integrity (Nguyen et al., 2019). More recently, Do and Chen (2023) investigated the mechanical and rheological properties of asphalt mixtures incorporating high molecular polymer additives, indicating strong potential for their practical application in Vietnam (Do & Chen, 2023). Nevertheless, most current studies remain largely at the laboratory scale and have not sufficiently examined the influence of additives on load-bearing indices, dynamic modulus, and rutting resistance under the specific climatic and traffic loading conditions of Vietnam.

Recent global trends in pavement engineering emphasize integrating thermoplastic-modified asphalt technologies with climate adaptation and low-carbon development goals. Over the past decade, thermoplastic modifiers such as TPS, SBS/SEBS, and polyethylene-based systems have been increasingly applied to enhance high-temperature rutting resistance, moisture tolerance, and fatigue durability while offering flexible construction options such as the dry-mix method. In parallel, climate adaptation frameworks highlight the importance of material-level resilience. PIARC's International Climate Change Adaptation Framework for Road Infrastructure (Committee, 2023) outlines a staged process - from risk screening to integrating adaptation measures - emphasizing material and maintenance strategies to reduce the vulnerability of road assets, while the FHWA's report Pavement Resilience: State of the Practice (Muench et al., 2023) demonstrates that higher stiffness, rutting resistance, and fatigue life can extend service intervals and lower lifecycle emissions under intensifying climate stressors. Within this dual context of performance and sustainability, TPS-based high-modulus asphalt concrete (HMAC) aligns with current global priorities: it reduces plant energy demand through dry-mixing, extends service life by delaying structural distress, and remains compatible with circular practices such as controlled incorporation of RAP and thermoplastic recyclates. Moreover, TPS-modified mixtures are millable and re-processable at end-of-life, supporting closed-loop recycling and lower-carbon maintenance cycles. These combined perspectives frame TPS-HMAC as a resilient, recyclable, and climate-adaptive material solution for sustainable pavement design in tropical and high-load environments.

1.3 Research Gap and Objective

Although numerous international studies have demonstrated the effectiveness of polymer additives in improving the performance of asphalt concrete mixtures, the widespread application of HMAC in Vietnam remains limited. Most existing domestic research has focused on SBS modified asphalt or PMB. In contrast, high-viscosity additives such as thermoplastic polymers (TPS) - which offer advantages of convenient dry-mixing application and compatibility with existing construction equipment - have not been thoroughly evaluated under Vietnam's unique climatic conditions and heavy traffic loads.

Specifically, few systematic investigations have been carried out on the mechanical and durability properties of TPS-modified HMAC, including rutting resistance, fatigue performance, moisture susceptibility, low-temperature cracking resistance, and dynamic modulus under realistic environmental and traffic conditions. The lack of comprehensive experimental data on TPS-modified asphalt mixtures creates uncertainty regarding their long-term applicability in Vietnamese road infrastructure.

To address this gap, the present study aims to evaluate the technical performance of HMAC mixtures incorporating TPS at varying additive contents. Standard laboratory tests were employed, including the Marshall stability and moisture susceptibility test, wheel tracking test for rutting resistance, low-temperature bending test, four-point bending fatigue test, and dynamic modulus determination across multiple frequencies and temperatures. The results are expected to verify the feasibility and effectiveness of TPS in enhancing the performance of asphalt mixtures, thereby supporting its practical implementation in heavily loaded roadways in Vietnam.

2. Materials and Methods

To aid reproducibility, a schematic overview of the experimental workflow is provided (**Figure 1**), summarizing materials and dry-mixing, specimen preparation, testing - data processing, and evaluation steps.

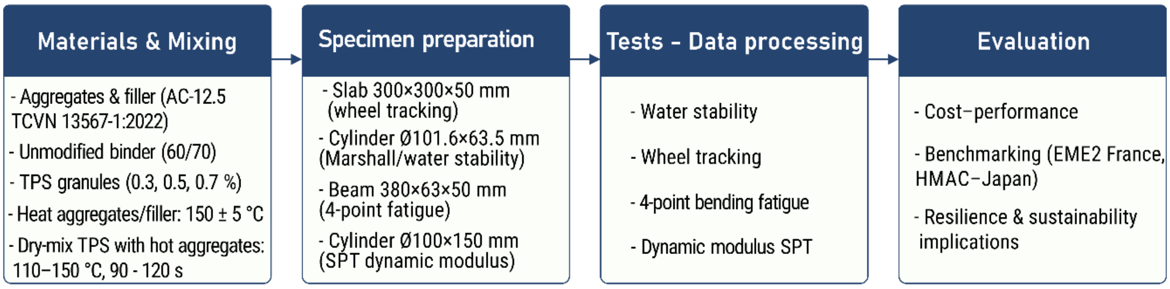

Figure 1. Experimental design flow for TPS – HMAC study

2.1. Materials

(1) Aggregates and mineral filler

The coarse and fine aggregates together with the filler employed in this study were prepared and screened in compliance with the Vietnamese national standard TCVN 13567-1:2022 (Technology, 2022). The adopted gradation corresponds to AC-12.5, a dense-graded asphalt mixture widely applied in pavement construction across Vietnam. The physical and mechanical characteristics of the aggregates and filler are summarized in **Table 1**.

Table 1. The physical and mechanical characteristics of the aggregates and filler

	Technical Index	Unit	Test Result	Requirement
Course aggregate	Crushing value	%	16.7	≤ 30
	Los Angeles abrasion value	%	23.2	≤ 28
	Apparent relative density	g/cm3	2.952	≥2.5
	Needle flake content	%	7.8	≤ 15
	Water absorption	%	0.75	≤ 2
	Adhesion degree	/	5	≥3
Fine aggregate	Washed Fines Content	%	0.6	≤ 2
	Apparent relative density	g/cm3	2.879	≥2.5
	Mud fines (<0.075 mm)	%	1.64	≤ 3
	Sand equivalent (SE)	%	72	≥60
Mineral filler	Apparent relative density	g/cm3	2.67	≥2.5
	Moisture content	%	0.6	≤ 1.0
	Hydrophilic coefficient	%	0.7	≤ 1.0

(2) Asphalt binder:

The binder used was a penetration-grade asphalt 60/70, tested in accordance with TCVN 8818-1:2011 (Technology, 2011a). All measured properties satisfied the specification limits for Type A bitumen defined in current Vietnamese standards. **Table 2** reports the detailed physical and performance-related parameters of the selected asphalt binder.

Table 2. The physical and performance-related parameters of the selected asphalt binder

Item	Test results	Technical requirement

Needle penetration at 25 °C, 0.1 mm, 5 seconds	67.5	50~70
10°C elongations (5cm/min), (cm)	71.7	≮20
Softening point TR&B, not less than (°C)	45.6	≮43
Flash point (°C)	276	≮260
Solubility (%)	99.9	≮99.5
Segregation, 48h softening point difference (°C)	0.7	≯2.5
Kinematic viscosity at 135°C, (Pa.S)	1.19	≯3
Elastic recovery 25°C (%)	90	≮80

(3) Additives:

In this study, the selected additive was TAFPACK Super (TPS), a high-viscosity modifier originating from Japan (Taiyu VietNam Co., 2024). TPS consists of a blend of thermoplastic rubber, adhesive resins, and plasticizers, which together enhance the rheological and mechanical performance of asphalt mixtures. The key physical properties of the TPS modifier are presented in **Table 3**.

Table 3. The TPS additives' physical characteristics

Items	TPS
Shape	2–3 mm granules
Appearance	Light yellow
Density	0.98g/mm
Softening point	92.5 °C

2.2. Mixture design

In this research, the asphalt mixtures were designed using the Marshall mix design procedure in compliance with TCVN 8820:2011 (Technology, 2011b). The adopted aggregate gradation followed the AC-12.5 specification, a dense-graded mixture commonly applied in Vietnam. The optimum binder content was determined through the standard Marshall testing process. **Figure 2** illustrates the gradation curve of the AC-12.5 mixture.

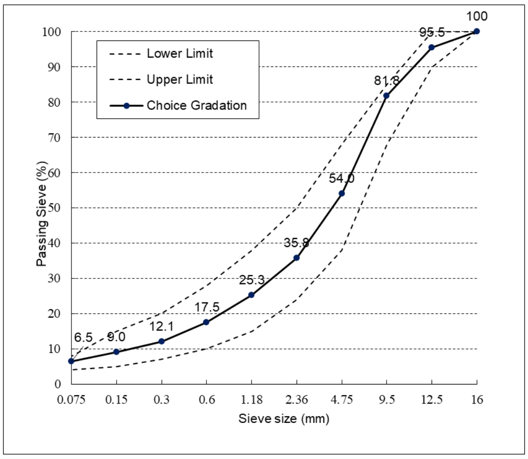

Figure 2. Gradation of AC-12.5 mixtures

High-modulus asphalt mixtures were produced by incorporating the TPS additive into the base asphalt mixture at three distinct dosage levels. The optimum binder content was determined to be 4.9%, while the TPS additive was introduced at 0.3 %, 0.5 %, and 0.7 % by weight of the mixture, respectively. In this study, the control mixture refers to the unmodified AC-12.5 asphalt mixture designed at an optimum binder content of 4.9 % (60/70 penetration grade), with no TPS additive. These variations were designed to evaluate the influence of additive content on the mechanical and rheological performance of the asphalt mixtures.

The selection of TPS dosage levels (0.3 %, 0.5 %, and 0.7 % by total mixture weight) was based on preliminary laboratory trials and existing literature on high-viscosity polymer additives for asphalt modification. Previous studies have reported that the effective dosage range for thermoplastic or rubber-based modifiers typically falls between 0.2 % and 1.0 % by weight of the mixture (Agha et al., 2023; Radeef et al., 2021; Zhang & Muhunthan, 2019).To maintain consistency with international practice while ensuring practicality for field production, the present study selected 0.3 % as the lower limit representing a minimum threshold for noticeable improvement, 0.5 % as the mid-range dosage balancing performance and cost, and 0.7% as the upper limit beyond which mixing viscosity and economic feasibility may become restrictive. This range was further confirmed by preliminary Marshall stability and viscosity screening tests, which showed that mixtures above 0.7 % TPS exhibited excessive mixing stiffness and binder agglomeration. Therefore, 0.3 %, 0.5 %, and 0.7 % were selected as representative levels for systematic performance evaluation under Vietnamese climatic and loading conditions.

2.3. Experimental Methods

2.3.1. Mixing procedure

The asphalt mixtures were prepared using the dry-mixing method recommended by the TPS manufacturer (Taiyu VietNam Co., 2024). In this process, the aggregates and mineral filler were first heated to a target temperature of 150 ± 5 °C to ensure complete drying and to facilitate uniform coating. The asphalt binder (60/70 penetration grade) was preheated separately to 145 ± 5 °C to achieve suitable fluidity prior to blending. The required quantity of TPS additive (0.3 %, 0.5 %, or 0.7 % by total mixture weight) was introduced directly into the hot aggregates and dry-mixed for approximately 90–120 seconds at a controlled temperature range of 110–150 °C until the polymer granules were evenly dispersed and partially melted. Subsequently, the preheated binder was added and mixed for another 90–120 seconds using a mechanical mixer to ensure uniform coating of all aggregate particles. The resulting mixtures were conditioned for compaction immediately after mixing.

This dry-mixing technique was adopted for its combined advantages of practicality, energy efficiency, and field adaptability. Unlike conventional wet-mix polymer modification, which requires prolonged high-temperature blending and specialized swelling equipment, the dry-mix process can be performed using standard asphalt mixing plants without any structural modification. This eliminates the need for additional heating stages, thereby reducing energy consumption and associated greenhouse gas emissions. At the same time, maintaining a controlled temperature range of 110–150 °C ensures uniform dispersion of TPS granules and stable binder–aggregate coating. Given the operational constraints of local asphalt production in Vietnam - where flexibility, cost-effectiveness, and compatibility with existing equipment are critical - the dry-mix approach offers a technically and economically viable solution for large-scale implementation of polymer-modified asphalt mixtures..

2.3.2. Wheel Tracking Test

The rutting resistance of asphalt mixtures was evaluated using the wheel tracking test in accordance with T0719-2011 (Standard, 2011). The test was performed using a LCPC-type wheel tracking apparatus equipped with a solid rubber wheel of 200 mm diameter and 50 mm width. Slab specimens with dimensions of 300 × 300 × 50 mm were compacted using a vibratory compactor to achieve the target air void content and were conditioned at 60 °C prior to testing. The tests were carried out at a temperature of 60 °C, with three replicate specimens tested for each mixture type (**Figure 3**).

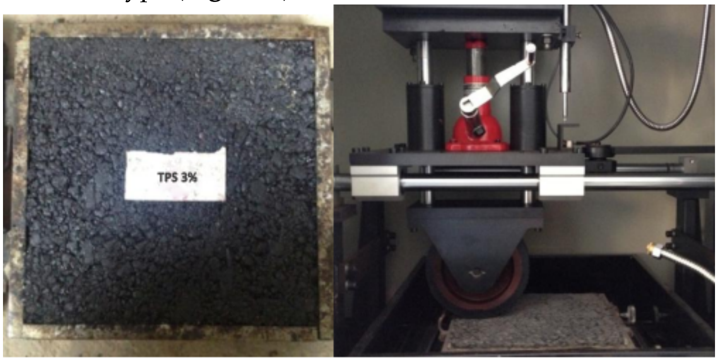

Figure 3. Asphalt Slab Specimen and Wheel Tracking Test Setup

During the test, specimens were subjected to repeated loading under a wheel load of 700 ± 10 N at a travel speed of 42 passes/min. The rut depth was continuously recorded using a linear variable displacement transducer until the total number of wheel passes reached 10000 or 60 minutes, whichever occurred first. The dynamic stability (DS), expressed as the number of load passes per millimeter of rut depth (passes/mm), was calculated to quantify the permanent deformation resistance of each asphalt mixture. The primary test results include the deformation after 45 minutes (d_1), deformation after 60 minutes (d_2), and dynamic stability (DS). DS is defined as the number of loading cycles required to produce 1 mm of rutting deformation and is calculated according to equation (1).

$$DS = \frac{(t_2 - t_1) \times N}{d_2 - d_1} \times C_1 \times C_2 \tag{1}$$

Where, C_1 and C_2 are correction factors based on the type of testing equipment and specimen configuration, respectively. For the equipment and specimen used in this study, C_1 = 1.0 and C_2 = 1.0 were applied in accordance with the standard procedure.

2.3.3. Water Stability Test

The water stability of the asphalt mixtures was evaluated using the immersed Marshall test in accordance with the Chinese specification JTG E20-2011(Standard, 2011). Cylindrical specimens with a diameter of 101.6 mm and a height of 63.5 mm were prepared and tested at a temperature of 60 °C. For the first set, specimens were kept at 60 °C without water immersion for 30–40 minutes, and the Marshall stability was recorded as MS_1. For the second set, specimens were immersed in water at 60 °C for 48 hours, and the corresponding stability was measured as MS_2. The residual stability (MS_0) was then calculated as the ratio MS_2 / MS_1, representing the retained strength after water conditioning (**Figure 4**).

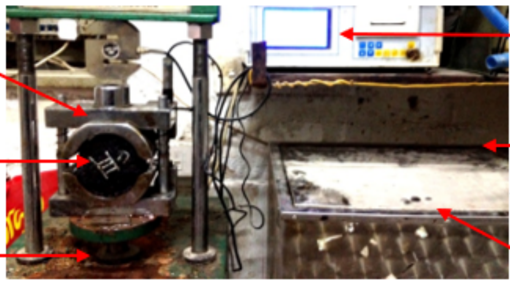

Figure 4. The Water Stability Test equipment

2.3.4. Four-Point Bending Fatigue Test

The fatigue performance of the asphalt mixtures was evaluated using the four-point bending fatigue test in accordance with AASHTO T321-07 and JTG E20-2011 (Standard, 2011). Beam specimens with dimensions of 380 × 63 × 50 mm were subjected to sinusoidal loading under controlled strain mode at 20 °C and a frequency of 10 Hz. The initial strain levels were selected as 600, 700, and 800 microstrain (με) to represent different stress conditions (Figure 5). Fatigue life (N) was defined as the number of load cycles corresponding to a 50 % reduction in the initial stiffness modulus. The test results were analyzed to establish the relationship between strain amplitude and fatigue life for each mixture type.

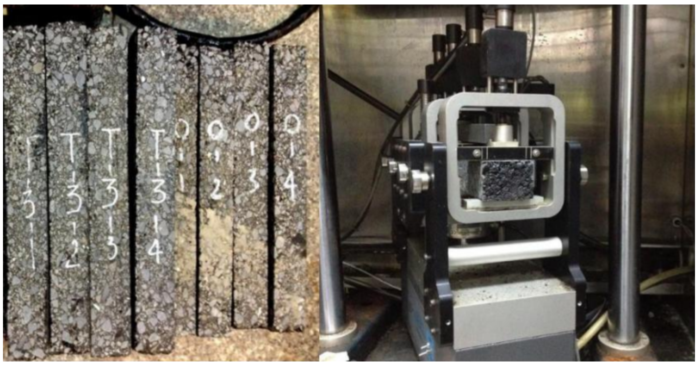

Figure 5. Four-Point Bending Fatigue Test specimen and apparatus

2.3.5. Dynamic Modulus Test

The dynamic modulus (|E*|) of asphalt mixtures was determined using the Simple Performance Tester (SPT) in accordance with AASHTO T342-11 and JTG E20-2011(Standard, 2011). Cylindrical specimens with a diameter of 100 mm and a height of 150 mm were subjected to cyclic axial loading under a sinusoidal stress waveform. The sample was installed and tested on the SPT machine as shown in **Figure 6**.

Figure 6. The sample was installed and tested on the SPT machine

Tests were performed in the unconfined mode at five loading frequencies (25, 20, 10, 5, 2, 1, and 0.5 Hz) and three temperatures (15° C, 30° C, 45 ° C, and 60° C) to capture the viscoelastic behavior of the mixtures. The SPT system was capable of capturing axial stress and strain responses in real time through an integrated data acquisition and control system. The dynamic modulus $|E^*|$ and phase angle φ of the tested HMAC specimens were calculated using equations (2) and (3). A schematic illustration of the loading configuration in the dynamic modulus test, along with the definitions of complex stress, strain, and phase angle, is presented in **Figure 7**.

$$|E^*| = \sqrt{E'^2 + E''^2} = \frac{\sigma_0}{\varepsilon_0} \tag{2}$$

$$\varphi = \frac{T_i}{T_p} \times 360° \tag{3}$$

Where, E' represents the storage modulus, which characterizes the elastic (recoverable) component of the dynamic modulus, while E'' denotes the loss modulus, reflecting its viscous (dissipative) behavior. Here, σ_0 is the amplitude of the axial (sinusoidal) stress, and ε_0 is the amplitude of the axial strain. T_i is the phase lag time between the peak stress and peak strain, and T_p is the period of the sinusoidal loading.

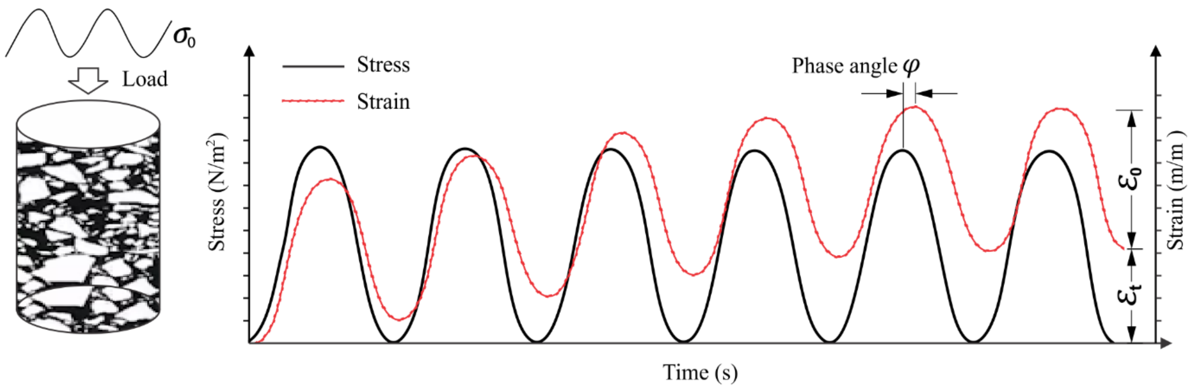

Figure 7. Schematic illustration of loading in dynamic modulus test and definition of complex stress, strain, and phase angle.

2.4. Statistical analysis and reproducibility

To ensure the reliability and reproducibility of the test results, all laboratory experiments were conducted on three replicate specimens for each asphalt mixture type and TPS dosage level. The mean and standard deviation (SD) were calculated for each measured parameter, including Marshall stability, wheel tracking deformation, fatigue life, and dynamic modulus.

The SD values were used to indicate the degree of variability among repeated tests and are presented in Tables 4–6 in the Results and Discussion section. Statistical significance among the control mixture and the TPS-modified mixtures (0.3 %, 0.5 %, and 0.7 %) was evaluated using one-way analysis of variance (ANOVA) at a 95 % confidence level ($p < 0.05$). When the differences were significant, Tukey's post hoc test was applied to identify pairwise differences between dosage levels. All statistical analyses were performed using IBM SPSS Statistics 26.0.

3. Results and Discussion

3.1 Moisture Stability

The results of the Marshall stability in dry condition (MS_1), after water immersion (MS_2), and the residual stability (MS_0) for both the base asphalt mixture and the TPS-modified high-modulus asphalt mixtures are presented in **Table 4** and **Figure 8**.

The results indicate that all TPS-modified mixtures exhibited significantly higher values of both MS_1 and MS_2 compared with the control mixture. This improvement demonstrates the effectiveness of the TPS additive in enhancing the load-bearing capacity and moisture stability of the asphalt mixtures under wet conditions. The increase in residual stability further confirms that TPS contributes to stronger adhesion between the asphalt binder and aggregates, thereby reducing the susceptibility of the mixtures to moisture-induced damage.

Table 4. Marshall stability results of the Control Mixture and three types of TPS-modified HMAC mixtures

Type	MS1(kN) ± SD	MS2(kN) ± SD	MS0(%) ± SD	Requirement (Standard, 2011)
Control Mixture	8.29 ± 0.21	7.01 ± 0.19	84.57 ± 1.91	80
HMAC TPS 0.3%	10.56 ± 0.24	9.16 ± 0.22	86.78 ± 1.84	85
HMAC TPS 0.5%	12.13 ± 0.29	10.56 ± 0.27	87.02 ± 1.75	85
HMAC TPS 0.7%	13.35± 0.33	11.63 ± 0.31	87.12 ± 1.69	85

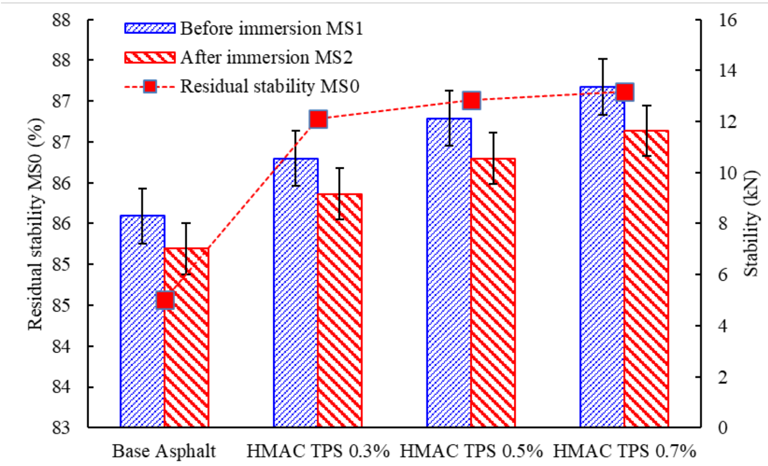

Figure 8. Comparison of dry Marshall stability, post-immersion stability, and residual stability index of the control mixture and TPS-modified HMAC mixtures

Statistical analysis was performed using one-way ANOVA to evaluate differences among the four mixtures (Control, TPS 0.3 %, 0.5 %, and 0.7 %). The results showed a statistically significant effect of TPS dosage on all moisture stability parameters (MS_1, MS_2, and MS_0) at a 95 % confidence level ($p < 0.05$). This results confirm that the addition of TPS has a measurable and statistically reliable influence on the strength and moisture resistance of asphalt mixtures.

The MS_1 value of the control mixture was 8.29 kN, whereas the TPS-modified HMAC mixtures achieved 10.56 kN, 12.13 kN, and 13.35 kN, respectively, as the TPS content increased from 0.3 % to 0.7 %. Similarly, the MS_2 values also exhibited a consistent rise with increasing TPS dosage, ranging from 9.16 kN to 11.63 kN, while the control mixture reached only 7.01 kN.

Notably, the residual stability (MS_0) of the control mixture was 84.57 %, satisfying the minimum requirement specified in JTG E20-2011 (≥ 80 %) (Standard, 2011), yet still lower than that of the TPS-modified HMAC mixtures. All TPS-modified mixtures exceeded the minimum criterion of 85 %, with the highest value of 87.12 % obtained at the 0.7 % TPS content.

Figure 8 illustrates the uniform increasing trend of MS_1, MS_2, and MS_0 with higher TPS dosages. This clearly demonstrates that the incorporation of TPS not only enhances the initial strength of the asphalt mixture but also improves its moisture resistance - a critical factor under Vietnam's hot and humid climatic conditions with frequent rainfall. In summary, the inclusion of TPS at dosages between 0.5 % and 0.7 % proved particularly effective in improving the moisture stability of asphalt mixtures, meeting the technical requirements for pavements subjected to heavy traffic loading.

3.2 High-Temperature Stability – Rutting Resistance

The rutting resistance of the asphalt mixtures was evaluated through the wheel tracking test, using the main parameters of deformation after 45 minutes and 60 minutes, Dynamic Stability (DS), and relative deformation (δ). The detailed results are presented in **Table 5** and **Figure 9**.

Table 5. Results of wheel tracking test for control mixture and TPS-modified HMAC mixtures

Type	Modifier dosage （%）	45min def (mm) ± SD	60min def (mm) ± SD	DS （cycle/mm） ± SD	Relative def δ （%）
Control	0.0	3.822 ± 0.10	4.528 ± 0.12	893 ± 27	9.06
HMAC TPS	0.3	2.068 ± 0.05	2.277 ± 0.06	3007 ± 88	4.55
	0.5	1.716 ± 0.04	1.882 ± 0.05	3785 ± 109	3.76
	0.7	1.498 ± 0.04	1.624 ± 0.05	4989 ± 143	3.25

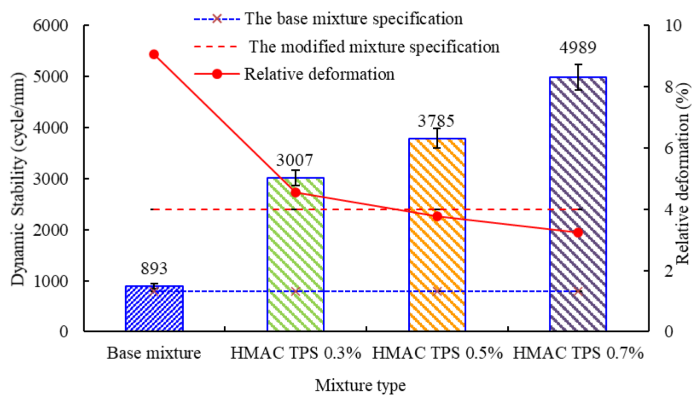

Figure 9. Comparison of rut depth, dynamic stability, and relative deformation of control and TPS-modified mixtures

Statistical analysis using one-way ANOVA confirmed that the TPS dosage had a statistically significant effect on the rutting parameters - dynamic stability (DS), deformation at 45 min and 60 min, and relative deformation - at a 95 % confidence level ($p < 0.05$). The post-hoc T-test indicated that all TPS-modified mixtures performed significantly better than the control mixture ($p < 0.01$).

As shown in **Figure 9**, the control mixture exhibited a DS value of 893 cycles/mm, which is considerably lower than the minimum requirement for modified mixtures. In contrast, the mixtures containing TPS showed a pronounced increase in DS with increasing TPS content: 3007 cycles/mm at 0.3% TPS (an improvement of approximately 236.7 %), 3785 cycles/mm at 0.5 % TPS (+323.9 %), and 4989 cycles/mm at 0.7% TPS (+458.7 %).

This consistent improvement demonstrates that TPS significantly enhances the dynamic stability of asphalt mixtures, improving their resistance to permanent deformation under repeated wheel loading at elevated temperatures. Moreover, the rut depth after 60 minutes decreased substantially - from 4.528 mm in the control mixture to only 1.624 mm for the mixture containing 0.7 % TPS. Similarly, the relative deformation (δ) decreased nearly threefold, from 9.06 % to 3.25 %, indicating that TPS-modified mixtures maintained their structural integrity more effectively with minimal rutting over time.

The obtained DS values (3007–4989 cycles/mm) not only satisfy the TCVN requirements but also exceed the minimum threshold (2000 cycles/mm) specified for EME2 high-modulus mixtures in France. According to TCVN 13567-1:2022 – Asphalt Concrete for Expressway Pavement, which adopts the wheel-tracking method and performance criteria from JTG E20-2011 (China), the minimum required DS for high-modulus or polymer-modified asphalt mixtures is ≥ 2500 cycles/mm. All TPS-modified mixtures in this study exceeded this limit, confirming full compliance with Vietnamese expressway design standards.

Overall, these findings confirm that incorporating TPS markedly improves the high-temperature stability and rutting resistance of asphalt mixtures. The enhanced mixtures not only meet but substantially exceed the technical requirements for high-modulus or polymer-modified asphalt used in expressways and heavy-traffic pavements.

3.3 Fatigue Resistance

The results of the four-point bending fatigue test reveal that the fatigue resistance of the TPS-modified HMAC mixtures was significantly superior to that of the conventional control mixture. As presented in **Table 6**, at identical strain levels (600–800 με), both the fatigue life (N) and cumulative energy dissipation (W) of the TPS-modified mixtures were markedly higher than those of the control mixture.

Table 6. Four-point bending fatigue test results

Type	Strain Level	Initial Flexural Modulus (MPa) ± SD	Fatigue Life, N (cycles) ± SD	Log(N)	Cumulative energy W (MPa) ± SD	Log(W)
Control mixture	600	3021 ± 72	11570 ± 330	4.063	26.5 ± 0.8	1.424
	700	3106 ± 79	9020 ± 280	3.955	19.1 ± 0.6	1.282
	800	3038 ± 68	4920 ± 145	3.692	10.7 ± 0.3	1.031
HMAC TPS 0.3%	600	4772 ± 103	19680 ± 520	4.294	38.6 ± 1.0	1.586
	700	4495 ± 98	14040 ± 380	4.147	32.1 ± 0.9	1.507
	800	4814 ± 112	6910 ± 190	3.839	21.1 ± 0.6	1.324
HMAC TPS 0.5%	600	4661 ± 110	25590 ± 720	4.408	61.2 ± 1.7	1.787
	700	4444 ± 107	17070 ± 470	4.232	41.5 ± 1.1	1.618
	800	4403 ± 101	10380 ± 300	4.016	33.9 ± 1.0	1.530
HMAC TPS 0.7%	600	4108 ± 95	37620 ± 1050	4.575	93.0 ± 2.6	1.968
	700	3631 ± 83	22160 ± 610	4.346	59.7 ± 1.7	1.776
	800	3302 ± 79	18470 ± 540	4.266	54.4 ± 1.6	1.736

To examine the statistical significance of the fatigue performance improvement, a one-way ANOVA was conducted for fatigue life (N) and cumulative energy dissipation (W) among the control and TPS-modified mixtures at each strain level (600, 700, and 800 με). The results indicated significant differences in both N and W values across the four mixture types at a 95 % confidence level ($p < 0.05$). Post hoc analysis using T-test showed that all TPS-modified mixtures exhibited significantly higher fatigue life and energy dissipation than the control mixture ($p < 0.01$). These findings confirm that TPS addition has a statistically reliable and consistent influence on the fatigue behavior of asphalt mixtures. The small standard deviations (generally below 3 %) across all replicates further demonstrate high reproducibility and reinforce the reliability of the observed fatigue performance trends.

At the highest strain level of 800 με, representing heavy-load conditions, the fatigue life of the control mixture was 4920 cycles, whereas the HMAC mixtures with 0.3%, 0.5%, and 0.7% TPS achieved 6910, 10380, and 18470 cycles, respectively. Notably, the HMAC with 0.7% TPS exhibited a fatigue life approximately 3.75 times greater than that of the control mixture, highlighting its outstanding ability to resist damage under repeated loading.

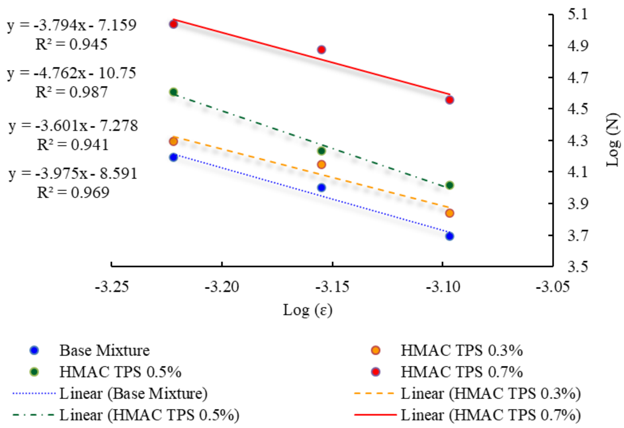

Figure 10. Regression curve of strain level versus log(N) for TPS-modified HMAC mixtures

Figure 10 shows the regression curve of strain level versus log(N), clearly illustrating this trend. The regression line for the TPS 0.7 % mixture lies highest among all, with a strong linear correlation ($R^2 \geq 0.941$), confirming a robust relationship between strain level and fatigue life within the tested range. The negative slopes of the regression equations indicate that fatigue life decreases with increasing strain; however, the smaller slope observed for TPS-modified mixtures reflects a slower rate of deterioration, implying greater stability under high-stress conditions. This behavior is also influenced by the increase in the initial flexural modulus of TPS-modified mixtures. The higher modulus indicates a stiffer and more elastic binder–aggregate system that can better distribute stresses during cyclic loading. Consequently, mixtures with higher modulus exhibit a smaller absolute slope in the fatigue regression, meaning the rate of fatigue life reduction with increasing strain becomes slower. This confirms that the improved stiffness from TPS modification contributes directly to enhanced fatigue durability.

Meanwhile, **Figure 11** depicts the relationship between strain level and cumulative energy dissipation (W). It can be observed that W increased markedly with TPS content. For example, at 800 με, the control mixture exhibited log(W) = 1.031, while the HMAC with 0.7% TPS reached log(W) = 1.736, representing an increase of more than 68%. This indicates that the TPS-modified mixtures possess a greater capacity to absorb and dissipate fatigue energy, delaying the initiation and propagation of cracks. Such energy absorption capability is a key factor contributing to improved durability under repeated traffic loading. The superior fatigue performance of TPS-modified mixtures can be explained by their enhanced viscoelastic and microstructural characteristics. The thermoplastic elastomer chains within TPS form an interconnected polymer network that increases the elastic recovery and deformation tolerance of the binder under cyclic loading. This network distributes strain more uniformly across the aggregate skeleton, delaying micro-crack initiation and propagation. Additionally, the adhesive resin component of TPS promotes stronger binder–aggregate cohesion, improving energy dissipation at the interface and reducing stress concentration. Together, these effects result in higher fatigue life and cumulative energy absorption (W), demonstrating that TPS modification enhances both the cohesive and adhesive fatigue mechanisms of the asphalt mixture.

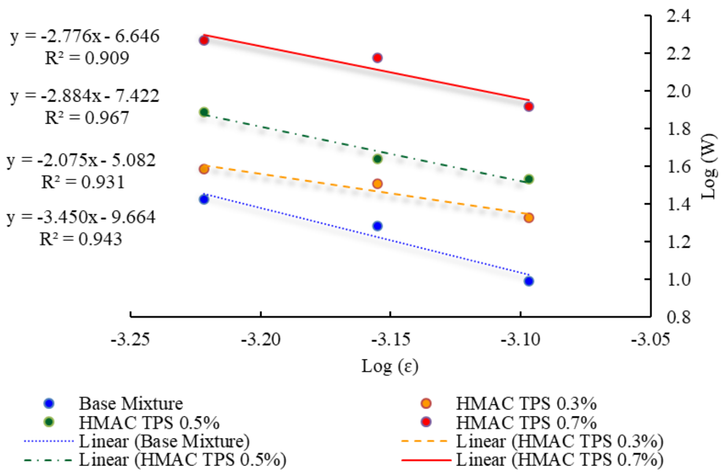

Figure 11. Regression curve of strain level versus log(W) for TPS-modified HMAC mixtures

The maximum fatigue life of the TPS-modified mixture (18,470 cycles at 800 με) is comparable to values reported for high-viscosity asphalt systems in Japan using TPS or SBS modifiers, confirming that the mixture's fatigue resistance aligns with international high-performance standards.

Overall, the combined improvement in initial flexural modulus, fatigue life, and energy dissipation capacity demonstrates that HMAC mixtures incorporating TPS - particularly at a dosage of 0.7% - exhibit excellent fatigue resistance. These mixtures show strong potential for use in heavy-duty or high-traffic pavements where long-term structural durability is critical.

3.4 Dynamic Modulus – Deformation Resistance

The results of the dynamic modulus (|E*|) test at different temperatures (15 °C, 30 °C, 45 °C, and 60 °C) and loading frequencies ranging from 0.5 Hz to 25 Hz are presented in **Figure 12**.

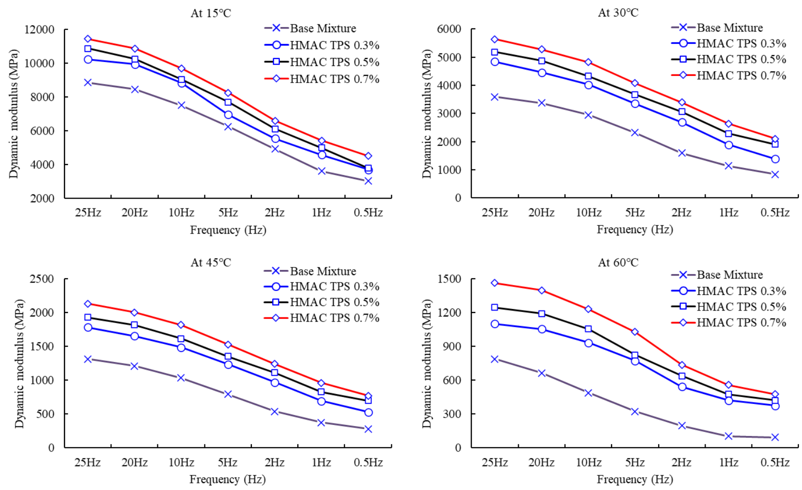

Figure 12. Relationship between loading frequency and dynamic modulus of asphalt mixtures at 15 °C, 30 °C, 45 °C, and 60 °C.

The results clearly demonstrate the pronounced influence of the TPS additive on the deformation resistance of HMAC. At all temperature and frequency levels, the TPS-modified mixtures exhibited significantly higher dynamic modulus values than the base asphalt mixture. Specifically, at 15 °C and 25 Hz, the dynamic modulus of the base asphalt was 8,848 MPa, while those of the mixtures with 0.3 %, 0.5 %, and 0.7 % TPS were 10,231 MPa, 10,873 MPa, and 11,443 MPa, respectively. This difference remained substantial even under more adverse conditions - for example, at 60 °C and 0.5 Hz, representing slow loading and high-temperature conditions - the base asphalt exhibited a modulus of only 93 MPa, whereas the TPS-modified mixtures achieved values ranging from 374 MPa to 475 MPa.

The progressive increase in TPS content from 0.3 % to 0.7 % led to a corresponding improvement in mixture stiffness, indicating that TPS effectively enhances deformation resistance under repeated loading while mitigating modulus degradation due to temperature rise. Although a full master-curve fitting was not presented, the measured |E|–frequency relationship across 15–60 °C showed a consistent upward shift with increasing TPS content. This behavior aligns with the time–temperature superposition (TTS) principle, indicating improved viscoelastic stiffness and reduced sensitivity to temperature variation.

At 15°C and 25 Hz, the measured dynamic modulus of 11,443 MPa approaches the reference range of ≥ 14,000 MPa defined in the French EME2 standard for high-modulus asphalt mixtures, demonstrating that the tested TPS-HMAC achieves stiffness levels close to those of international benchmarks. In summary, TPS incorporation enhances mixture stiffness and thermal stability, effectively improving rutting resistance and extending pavement service life.

3.5. Microstructural and rheological interpretation of TPS modification

The observed improvement in rutting resistance, moisture stability, fatigue life and deformation resistance can be attributed to the rheological modification and microstructural enhancement introduced by the TPS additive. Although detailed microstructural testing (e.g., SEM, FTIR) was beyond the scope of this study, the mechanisms are well supported by findings from previous polymer modification research and studies directly involving TPS.

Thermoplastic polymers such as TPS consist of a blend of styrene-based thermoplastic elastomers, adhesive resins, and plasticizers that physically interact with the bituminous binder. When dispersed within the asphalt matrix during mixing, TPS forms a semi-continuous polymer network that increases binder viscosity and elasticity. This network enhances the storage modulus (G′) and reduces the phase angle (δ), indicating improved elastic recovery and reduced viscous flow at elevated temperatures. Such rheological trends have been reported for TPS-modified asphalts, which exhibit higher complex modulus (|G*|) and lower δ values compared with conventional binders (Wang et al., 2025; Xiaoming & Eldouma, 2019).

SEM and DSR observations from earlier TPS studies further confirm that the polymer-rich phase strengthens binder cohesion and suppresses micro-void formation under cyclic loading (Yao et al., 2011). Similar viscoelastic reinforcement mechanisms are also consistent with the general rheological response of polymer-modified asphalts (Olard et al., 2003; Radeef et al., 2021; Yan et al., 2019).

In addition, the adhesive resin component in TPS promotes stronger binder–aggregate interfacial bonding, thereby reducing moisture susceptibility and stripping. These combined effects - enhanced elasticity, improved adhesion, and stabilized microstructure - explain the superior deformation resistance and fatigue durability observed in the present study. Overall, the behavior of TPS-modified mixtures under Vietnamese conditions aligns closely with previously documented high-viscosity polymer modification mechanisms and validates the suitability of TPS as a performance-enhancing additive.

3.6. Cost–Effectiveness Evaluation by TPS Content

To determine the most optimal material solution, it is essential to evaluate not only the technical performance indicators but also the economic feasibility. The radar chart comparing the comprehensive performance of asphalt mixtures with different TPS contents (0.3%, 0.5%, and 0.7%) against the conventional control mixture clearly illustrates an overall improvement across five key criteria: moisture stability, high-temperature rutting resistance, dynamic modulus, low-temperature cracking resistance, and fatigue performance (**Figure 13**).

Figure 13. Comprehensive Performance Comparison of Asphalt Mixtures with Varying TPS Dosages

The radar chart results show a consistent increase in the overall performance area with higher TPS content. Among them, the 0.7 % TPS mixture exhibited the largest enclosed area, indicating the highest overall technical performance. However, the performance improvement from 0.5 % to 0.7 % TPS was less pronounced compared with the gain observed from 0.3 % to 0.5% TPS. This indicates a diminishing marginal technical benefit as TPS dosage increases, whereas the additive cost continues to rise nearly linearly. To further quantify the efficiency of each dosage, a simple cost–performance ratio (CPR) was estimated by comparing the percentage increase in overall performance indices with the relative cost increment. The 0.5 % TPS mixture achieved approximately 320 % improvement in comprehensive performance with only about 15 % cost increase (CPR ≈ 21), confirming it as the most cost-effective and practically feasible option. To provide a clearer reference for economic comparison, the relative material costs were converted into absolute cost ratios based on the local market price of TPS additive and asphalt binder. When normalized to the control mixture (cost index = 1.00), the estimated total material costs for the mixtures with 0.3 %, 0.5 %, and 0.7 % TPS were approximately 1.08, 1.15, and 1.24, respectively. While the 0.7 % mixture yielded the highest overall performance, the additional 9 % cost increase beyond the 0.5 % level produced only about 12–15 % further performance gain. Therefore, from a practical cost–benefit perspective, 0.5 % TPS provides the most efficient trade-off between material expense and mechanical improvement, making it more feasible for large-scale expressway applications in Vietnam.

Specifically, the 0.5 % TPS mixture achieved the best balance between technical performance and economic efficiency. Most performance indices at this dosage either reached or closely approached the maximum observed values, while maintaining practical feasibility in material cost and field application. Moreover, the dry-mixing process used for TPS incorporation eliminates the need for specialized high-temperature blending equipment, making it more adaptable for local production facilities compared with conventional polymer-modified asphalt systems.

Based on these analyses, it is recommended that HMAC with 0.5 % TPS be adopted as the optimal solution under Vietnamese conditions. This dosage ensures superior technical performance, reasonable cost, and convenient implementation, making it suitable for heavy-duty pavements operating under harsh climatic conditions characterized by high temperatures, heavy rainfall, and sustained traffic loads.

3.7. Resilience and sustainability implications

The mechanical improvements achieved through TPS modification have broader implications for infrastructure resilience and sustainable pavement management in tropical and high-load environments such as Vietnam. The substantial increase in dynamic modulus and fatigue life directly translates into longer service intervals, reduced maintenance frequency, and lower material consumption throughout the pavement lifecycle. By extending the functional life of the surface course, HMAC (TPS modifier) helps minimize the need for periodic overlays and associated emissions from asphalt production, transport, and construction operations.

Furthermore, the enhanced moisture resistance and high-temperature stability of HMAC (TPS modifier) enable pavements to better withstand the combined stresses of heavy axle loads, frequent rainfall, and extreme heat waves, which are becoming more prevalent under regional climate change. This resilience against environmental and mechanical deterioration contributes to maintaining network-level performance and reliability of transport corridors, particularly in urban areas where pavement distress leads to congestion and higher vehicle emissions.

From a sustainability perspective, the dry-mixing process used for TPS incorporation requires no additional heating or specialized blending equipment, resulting in lower energy demand and carbon footprint compared to traditional wet polymer modification. When combined with the improved durability and reduced maintenance needs, this process aligns with low-carbon infrastructure strategies and supports the goals of resilient and sustainable urban development in Vietnam and other tropical regions. These durability gains and reduced maintenance frequency are consistent with international adaptation guidance PIARC (2023) and FHWA's pavement resilience recommendations for climate-exposed corridors, supporting low-carbon lifecycle strategies through fewer work zones and lower material use (Committee, 2023; Muench et al., 2023).

4. Conclusion

This study investigated the mechanical performance and durability of high-modulus asphalt concrete (HMAC) mixtures incorporating TAFPACK Super (TPS) additive at different dosages (0.3 %, 0.5 %, and 0.7 %) compared with a conventional control mixture. A comprehensive experimental program was conducted, including Marshall stability and moisture resistance, wheel tracking, four-point bending fatigue, and dynamic modulus tests under various temperature and loading conditions. The key findings can be summarized as follows:

(1) Moisture Stability: TPS-modified mixtures exhibited significantly higher Marshall stability values in both dry and immersed conditions compared with the control mixture. The residual stability index of all TPS-modified mixtures exceeded 85 %, demonstrating enhanced resistance to moisture-induced damage.

(2) Rutting Resistance: The Dynamic Stability (DS) values of TPS-modified mixtures increased substantially with additive content - from 3007 cycles/mm at 0.3% TPS to 4989 cycles/mm at 0.7% TPS - indicating excellent resistance to permanent deformation under high-temperature and repeated loading conditions.

(3) Fatigue Resistance: Results from the four-point bending fatigue test revealed that the fatigue life (N) and cumulative energy dissipation (W) of TPS-modified mixtures were markedly higher than those of the control mixture. At 0.7 % TPS, the fatigue life was approximately 3.75 times that of the control mixture, confirming TPS's ability to delay fatigue cracking and extend service life.

(4) Dynamic Modulus: Across all temperatures (15–60 °C) and frequencies (0.5–25 Hz), TPS-modified mixtures exhibited higher dynamic modulus values than the control mixture, with improvements up to 400–500 % under severe conditions (60 °C, 0.5 Hz). TPS effectively stabilized the modulus against temperature-induced softening, enhancing deformation resistance in hot climates.

(5) Cost–Effectiveness: Although increasing TPS content improved performance in all aspects, the marginal benefit between 0.5% and 0.7% TPS was relatively small compared to the cost increment. The 0.5% TPS mixture achieved the optimal balance between performance enhancement and economic feasibility, making it a practical and cost-effective choice for field implementation using the dry-mixing method.

Overall, the findings demonstrate that TPS is an effective high-viscosity additive that significantly improves the mechanical and durability characteristics of asphalt mixtures. The incorporation of 0.5 % TPS in HMAC is recommended as the optimal solution for heavy-duty pavements in Vietnam, offering improved moisture stability, rutting resistance, and fatigue performance under hot and humid climatic conditions. This research provides a technical basis for the broader adoption of TPS-modified HMAC in sustainable pavement design and construction. Beyond laboratory validation, these findings have direct implications for sustainable infrastructure management and long-term maintenance planning. By extending service life and reducing maintenance frequency, TPS–HMAC supports low-carbon pavement strategies and resource-efficient asset management. Furthermore, the demonstrated mechanical and environmental advantages provide a sound technical foundation for the potential inclusion of TPS-modified HMAC in Vietnam's expressway pavement design and maintenance guidelines (e.g., TCVN 13567-1:2022), aligning national infrastructure development with global resilience and sustainability goals.

Future research may extend these findings by conducting long-term field monitoring of TPS-modified HMAC on expressways to validate laboratory performance under real traffic and climate conditions. Additional investigations on combined modification strategies, such as integrating TPS with reclaimed asphalt pavement (RAP), warm-mix additives, or alternative thermoplastic polymers, could further enhance sustainability outcomes. Advanced rheological modeling and microstructural characterization are also recommended to deepen the understanding of the mechanisms driving the improved performance observed in this study.

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