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The Influence of Polyurethane Towards The Mechanical Properties of Stone Mastic Asphalt Mixture

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Abstract

Hot mix asphalt (HMA) with a gap-graded composition is referred to as stone mastic asphalt (SMA). The coarse aggregates are the main component contributing to the stability and strength of SMA mixtures. However, due to the gap-graded nature of SMA, permanent deformation and low tensile strength have become significant concerns in the early deterioration of asphalt and the lifespan of pavements, especially for SMA. The study compares the modified SMA 20 and conventional SMA 20 by conducting laboratory tests and performance assessments. In this investigation, polyurethane (PU) is mixed with heated aggregate, and the polyurethane dosage ranges from 2% to 6%. The tests conducted were the Cantabro test, Marshall stability test, indirect tensile strength (ITS) test, and moisture susceptibility test. The results show significant improvement with the addition of 6% PU. The 6% PU-SMA is considered to have better abrasion resistance, stability, flow, stiffness, ITS and tensile strength ratio (TSR). The maximum ITS value is 308 kPa (6%) with a TSR value of 89%. The optimal amount of PU required for SMA to achieve both values was 6%, as concluded by all the tests. It can be inferred that the engineering properties of SMA can be improved by the presence of PU when it is concentrated appropriately. Therefore, the effectiveness of the SMA with the PU-modified mixture is also improved, with approximately 20% improvements in abrasion resistance, 45% in stability, and 20% in ITS.

1. Introduction

Stone mastic asphalt (SMA) is a gap-graded, skeleton-dense asphalt mixture with voids filled with a considerable amount of asphalt binder, stabiliser, and finer aggregate, resulting in a low air void content. It is an important pavement type that has been extensively used worldwide due to its outstanding road performance, ease of restoration, and comfortable driving conditions [1], [4], [7]. However, the fundamental strength of asphalt pavements can be compromised by various factors that can lead to the formation of cracks on the asphalt pavement's surface.

In contemporary asphalt pavements, high-performance asphalt mixtures are increasingly necessary at the wearing course level to withstand extreme weather conditions and heavy traffic. These conditions are becoming increasingly prevalent, necessitating the development of an innovative hot-mixture asphalt known as SMA. One such mixture is SMA, which was initially developed by Dr. Zichner in Germany during the 1960s to withstand abrasion caused by studded tyres [2]. The first utilisation of SMA mixture can be traced back to the 1960s in Germany [3], [8], [11]. Afterwards, its application expanded in many European countries, including the United States. SMA is a particular type of hot mix asphalt (HMA) that can be identified by its gap-graded composition [4], [6]. SMA is a particular mixture of materials used in the production of asphalt concrete. The composition consists of two components: a coarse aggregate and a cement mixture that is combined with bitumen. The cement mixture comprises bitumen, filler, and stabilising additives, which may consist of either cellulosic or mineral fibres. The asphalt mixture should have a coarse aggregate structure characterised by direct contact between the stones. Similarly, when SMA incorporates a gap-graded aggregate mix, it effectively reduces the amount of fine and medium aggregates, resulting in a very stable and structurally robust mixture [5], [18], [22]. Moreover, the strength and durability of SMA can be attributed to its coarse aggregate framework, which enhances the internal friction and shear resistance of the mixture. This enables it to withstand the corrosive effects and abrasion caused by repeated contact with studded tyres.

In another major study, SMA is a highly effective type of asphalt paving that enables roadways to endure significant vehicle loads and resist deterioration [6], [7], [25]. The utilisation of SMA showcases its capacity to withstand rutting and fatigue, and from that, it gained significant recognition in Europe, Australia, and New Zealand. In addition to its gap-graded mix and durable stone-on-stone structure, SMA also contains a high concentration of asphalt binder, filler, and additives that serve as fibres or modifiers. Modifying the binder or adding stabilisers is essential for the SMA mixture with a gap aggregate gradation and high asphalt concentration. Failure to do so can result in top-layer erosion [8], [27], [29]. However, SMA is known to have a major issue, which is binder draindown. Thus, it requires a high-performance modifier to reduce the issues related to SMA. One of the potential modifiers is polyurethane (PU), which can withstand higher loading compared to other types of modifiers.

An analysis of PU as a modified asphalt found that the excellent high-temperature performance, durability, resistance to wear, ageing resistance, and oil resistance of PU have attracted significant interest from pavement engineers and researchers [9], [14], [18]. PU is a polymer that contains urethane groups (–NHCOO–) and is produced through the reaction between isocyanate and polyol. Isocyanates and polyols are in a liquid state at room temperature, allowing them to be combined with asphalt at lower temperatures. Due to its compatibility with lower temperatures, it can effectively conserve energy by reducing the need for manufacturing, minimising CO_2 and volatile organic compound (VOC) emissions, and delaying asphalt degradation. PU-modified asphalts are characterised by enhanced cleanliness and a higher level of sustainable development. In comparison to other modified forms of asphalt.

The optimum asphalt content of PU-modified asphalt SMA 13 (SMA 13) is 5.5% [9]-[11]. The PU-modified asphalt mixture contained 85.5% aggregate, 9% limestone powder, and 5.5% PU-modified asphalt. According to the results, the PU-modified asphalt mixture exhibited good water stability, as its immersed water stability ratio and TSR were the highest (above 90%). It is feasible to demonstrate that PU-modified asphalt can withstand water-induced damage, indicating that the asphalt may be suitable for applications requiring high water resistance. Additionally, the acceptable range of PU content in asphalt mixture is between 2% and 6% [12], [19]. When the PU content is below 6%, the PU modifiers are evenly distributed in evaporated remains. This indicates that PU can enhance the strength and internal structure of the binder, resulting in improved resistance to deformation caused by high temperatures and traffic loads. Additionally, PU can enhance the flexibility and crack resistance of the asphalt, particularly in low-temperature conditions, thereby improving its fatigue resistance.

PU has the capacity to enhance the resistance of emulsified asphalt to cracking at low temperatures, stability at high temperatures. PU-modified asphalt can maintain thermal stability and storage stability at 163 °C, indicating that PU-modified asphalt exhibits good compatibility and ageing resistance, as well as mechanical properties [13], [23], [28]. The performance of modified asphalt that had been is directly affected by the process of preparation and the types of additives employed. PU is incorporated with SMA within the prescribed range of 2% to 6%. The range is established through thorough research that has identified the optimal concentration of PU in the asphalt binder. Numerous studies have attempted to explain the performance of SMA by adding a PU in the asphalt binder. The intent is to create a high-performance pavement that offers improved resistance to water, the ability to withstand water, as well as enhanced resilience to cracking, fatigue, and a longer lifespan, all while providing a range of comforts to drivers [11], [12], [24].

Previous research has shown that PU is widely used in SMA due to its high mechanical properties, durability, and fatigue resistance. The results indicate that the PU asphalt, after undergoing physical and chemical modification, has excellent resistance to deformation, ageing, fatigue, and high-temperature storage. Simultaneously, PU has the capability to enhance the thermal stability and mechanical qualities of emulsified asphalt [13], [14], [30]. Therefore, this advancement provides a highly efficient method for building durable, sustainable, and eco-friendly pavement. The necessity for routine maintenance is obviated, as this innovation effectively reduces road degradation problems such as fractures and pavement deformation.

Various techniques to enhance the road pavement performance. SMA is one of the suitable designs for pavement design to be implemented in heavily trafficked roads due to the outstanding performance of the pavement structure [2], [15], [31]. The stability and strength of the SMA mixture are mainly due to the coarse aggregates. The structure of the coarse aggregate in this asphalt mixture should be stone-on-stone and asphalt binder [3], [16]. The formation of the gap grade in the SMA mixture requires adding a substantial amount of bitumen, ranging from 5.5% to 7.5%, during the production process of this asphalt mixture.

A common problem with SMA mixture is rutting, which refers to the formation of depressions in the pavement surface caused by repeated traffic loads, increased traffic loads and unpredictable weather changes on road surfaces in Malaysia. Additionally, SMA is gap graded and due to fewer interlocking particles, it is more prone to tensile stress and cracking [4], [17]. Thus, the performance of SMA can be improved by modifying the mixture with various modifiers, such as PU, which possesses significant characteristics of strong adhesion and elasticity in SMA.

1.1 Design of Experiment

Fig. 1 illustrates the key activities employed in this investigation. This section is important because it provides a comprehensive overview of the study's experimental design, materials, and testing methods. This study provides a comprehensive explanation of the process employed to obtain the needed result or data analysis. The selected amount of PU ranges from 0% to 6% with an increment of 2%, as referenced in previous related studies [12], [16].

Fig. 1 *Design of experiment*

1.2 Materials

The bitumen has a penetration grade of 60/70, indicating that its penetration value is within the range of 60 to 70 under standard test conditions, as shown in Table 1. The experiment involved the preparation of a modified asphalt mixture through the dry modification process. In this procedure, PU powder, as shown in Fig. 2, was incorporated into the asphalt mixture, which contained 1200 g of aggregate and filler, specifically OPC. The mixture was continuously stirred to ensure a complete combination of the materials.

Table 1 *Physical properties of bitumen*

Material	Properties	Test Standard	Range	Result
60/70 PEN Bitumen	Penetration @ 25 ˚C	ASTM D5	60 – 70mm	62 mm
	Softening point (˚C)	ASTM D36	49 – 56 ˚C	53.3 ˚C

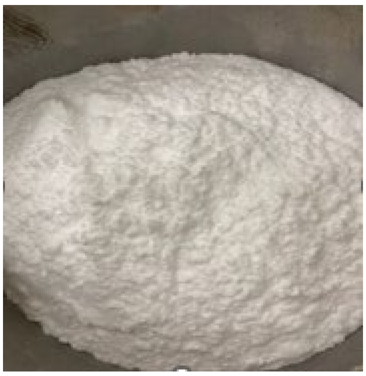

Fig. 2 *Polyurethane powder*

The particle size distribution of SMA 20 in the graph encompasses a wide range of particle sizes, spanning from 0.075 mm to 19 mm, as shown in Fig. 3. The gap-graded distribution of aggregate in the pavement allows the coarse particles to interlock, thereby enhancing the pavement's strength and longevity. Meanwhile, the fine particles fill the gaps between the coarse particles, serving as a barrier against water infiltration.

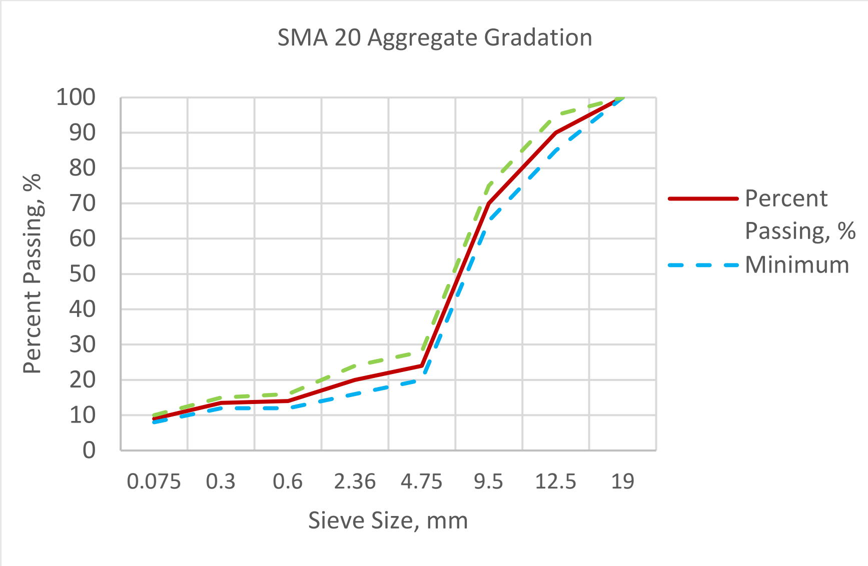

Fig. 3 *SMA 20 Aggregate gradation*

1.3 Sample Preparation

The experiments involve the formulation of modified asphalt mixtures through a dry modification method. Once the PU powder is added to the asphalt mixture, which consists of 1200 g of aggregate and OPC as the filler, the mixture is thoroughly stirred to ensure full blending of the new substance. Subsequently, the bitumen is poured into the mixture. Next, thoroughly mix the combination in a heated dish, ensuring that the temperature remains within 160°C. This temperature range ensures complete adhesion of the mixture, ensuring that bitumen leaves no portion uncoated. To ensure consistency and accuracy in the experiment results, it is essential to reduce potential sources of error by strictly following the procedure and using quality control methods when preparing samples. The consistency of mixing and compaction temperatures is crucial to ensure the consistent quality of samples prior to testing and the reliability of the results after the testing.

1.4 Experimental Procedure

1.4.1 Cantabro Loss Test

The purpose of the Cantabro test is to simulate the effects of heavy traffic and adverse weather conditions on a sample and to assess its resistance to degradation under these conditions. This test is crucial for representing the abrasion resistance of SMA under various traffic loads and surface conditions. By conducting laboratory tests on asphalt mixtures, it is possible to verify that the materials meet the implied standards and requirements for durability. This measure helps prevent premature pavement breakdowns and ensures sustained effectiveness of the roadway system. The Cantabro test is a widely used laboratory test for assessing the longevity of mix designs and evaluating SMA mixture. In the Cantabro test, the specimen is densely packed and placed in the LA abrasion machine, where it is subjected to 300 revolutions without the presence of steel balls. The sample will be weighed and returned to the machine every 100 revolutions until it reaches a total of 300 revolutions [11], [18].

1.4.2 Marshall Stability Test

The Marshall stability test is a crucial testing technique used to assess the strength and stability of an SMA mixture when subjected to traffic stresses. In this experiment, a cylindrical sample of the SMA combination is compressed using a Marshall compactor to simulate a real situation. Next, the compacted sample is placed under a vertical force in a Marshall testing machine, and the maximum load (Marshall stability) sustained by the specimen before failure, along with the corresponding deformation, is recorded. In addition, the flow value, which represents the overall deformation when subjected to the maximum load, is measured. In the case of SMA mixture, obtaining a high Marshall Stability is of the utmost importance, as it indicates the mixture's capacity to withstand deformation and rutting when subjected to intense traffic loads.

1.4.3 Indirect Tensile Strength Test

The indirect tensile strength (ITS) test is employed to evaluate the ability of an SMA mixture containing PU to resist cracking. Asphalt pavements undergo continuous strain due to factors such as vehicular movement, climatic conditions, and thermal expansion/contraction. The accumulation of these stresses may gradually lead to the formation of cracks, which can weaken the pavement's overall strength and ultimately result in potholes and other imperfections on the road surface. The ITS test enables engineers to evaluate the capacity of a mixture to withstand cracking. In general, a mixture with a higher ITS value is less susceptible to premature cracking.

In the process of asphalt mix design, it is essential to carefully select the appropriate combination of aggregates and asphalt binder, as well as determine their proportions, to create a mixture that meets the performance criteria. Hence, the ITS test is of critical importance in the selection process as it can determine the ideal equilibrium between strength, flexibility, and resistance to cracking for the intended use.

For this experiment, the sample will be positioned on the ITS apparatus, ensuring that it is centred. Next, it is necessary to correctly calibrate the sample, after which the ITS will be assessed using the Marshall compression machine. This apparatus consists of two circular loading plates that exert a diametric force on the specimen. Additionally, it is equipped with a mechanism specifically intended to measure the tensile strength of the specimen. Once the sample is prepared, the testing process will commence by hitting the start button. This apparatus operates by subjecting the specimen to progressively higher loads until it reaches the point of failure. When a weight is applied perpendicular to the plane of the specimen, it causes the asphalt mixture to experience tensile stress. Subsequently, the machine will automatically stop compression upon the appearance of the crack, at which point the data will be recorded.

1.4.4 Moisture Susceptibility Test

A moisture susceptibility test, commonly referred to as the modified Lottman test, is a laboratory process that evaluates a sample's ability to withstand damage caused by water, typically in the form of an asphalt mix. The compacted samples are placed in a conditioning chamber filled with water. The water can be maintained at a specific temperature, and the sample can be kept in the water for a predetermined dwell time. The moisture conditioning process used in this study consisted of 24 hours of dwell time at 60 °C and 1,000 cycles at 207 kPa. Every 1000 cycles takes approximately 1 hour. At the end of the conditioning process, the samples are taken out and subjected to post-condition testing, such as an ITS test. Prior to conducting the ITS test (ITS_{wet}), the samples were immersed in a water bath at 60˚C for 24 hours, followed by 1 hour at room temperature of 25˚C [20].

1.5 Results and Discussion

1.5.1 Cantabro Loss

Prior to being placed into the LA abrasion machine for the Cantabro test, the sample is weighed. For the Cantabro test, one sample is utilised per PU percentage: 0%, 2%, 4%, and 6%. The objective of the Cantabro test is to evaluate the abrasion resistance and durability of hot-mix asphalt (HMA), which is a type of compacted asphalt mixture. The test is conducted until the specimen has undergone 300 cycles; thereafter, it is required to be weighed every 100 cycles.

The data presented in Fig. 4 illustrates that the unmodified SMA mixture experiences a high value of cantabro loss, at 1.37%. In contrast, a modified SMA mixture, achieved through the addition of 6% PU, exhibited the lowest value of cantabro loss at 1.06%. This may be the result of friction between the specimen and the drum, which causes a certain level of loss in the crushed samples [19], [20], [31]. This is because the revolving drum can generate a shear stress on the sample, causing the edge surface of the sample to become rounded, even if the material is highly resistant to damage. While the overall weight reduction may be small, changes in the edge surface can influence the percentage loss. It is evident that the unmodified SMA mixture does not resist wear and tear, because the bond between aggregate particles and asphalt binder may be weaker. This makes it easier for the particles to come loose during the rolling process. In contrast, the modified SMA mixture, whereby adding PU help enhance the asphalt mixture's characteristics, such as high adhesion, which can strengthen the bond between the binder and the aggregate, and also its resistance to wear and tear, which helps keep the mixture from ravelling [21].

Additionally, the percentage of Cantabro loss varies in the case of the modified SMA mixture when a 2% to 6% additive is included in the mixture. Fig. 4 shows that the highest percentage of Cantabro loss is 1.67% for additive 2%, followed by 1.55% for additive 4%, and 1.06% for additive 6%. This demonstrates that the inclusion of 2% and 4% additives has a slight impact on the durability of the SMA mixture, resulting in a high percentage loss. Additionally, this suggests that at concentrations of 2% and 4%, the PU may not be sufficient to effectively modify the asphalt binder. It might not create a strong enough bond with the aggregates. This led to weaker interaction, where it is easier for particles to dislodge during the Cantabro test, resulting in a higher Cantabro loss. Additionally, in the lack of an adequate amount of PU, the modified SMA mixture may retain its rigid and brittle properties. This rigidity increases the likelihood of fracture when subjected to the tension encountered during the Cantabro test, thereby increasing the percentage of Cantabro loss [22]. However, the graph shows R^2 more than

0.95 for all lines, indicating a reliable relationship between those variables in interpreting the abrasion resistance of modified SMA.

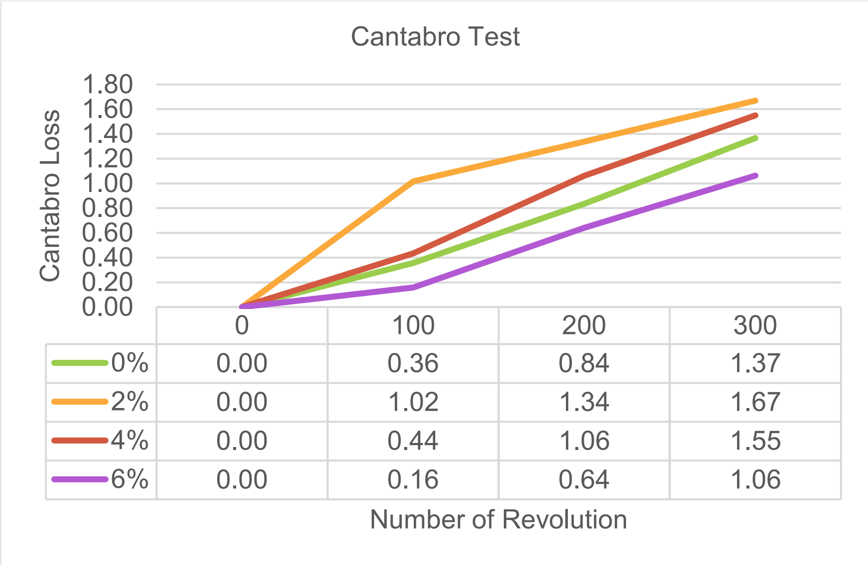

Fig. 4 *Cantabro loss*

The number of revolutions and mass loss increased as well, in line with previous related studies [23], [24]. The Cantabro loss value decreased until it reached the minimum value of 2.9% for the 60% polyurethane modified stone mastic asphalt (POC-SMA) mixture, after which the values increased. After that, the 80% POC-SMA and 100% POC-SMA show higher abrasion loss as compared to the control mixture. This is due to the porosity, surface texture and high content of the POC aggregates in the 80% POC-SMA and 100% POC-SMA. Hence, based on the minimum value, it appears that a 60% POC in SMA may be the best mix for controlling loss. The value of cantabro loss decreased until it reached a minimum value of 2.9% for a 60% SMA-POC mixture, while compared to 6% SMA-PU, the minimum value of cantabro loss achieved was 1.06%. The increased loss of abrasion of 80% POC-SMA (3.61%), 100% POC-SMA (4.32%), and 4% SMA-PU (1.5%) can be attributed to the presence of porosity, the texture of the surface, and the large amount of POC aggregates and PU [25]. Subsequently, when comparing the cantabro loss values of the POS-SMA control sample with those of the SMA-PU sample, it is observed that the POC-SMA is 3.37% greater than the SMA-PU, which is a difference of 1.37%. This is due to the palm oil clinker's size distribution and irregular shape, which differ from those of PU modifiers. Due to this irregularity, clinker particles and the asphalt matrix may not interlock well, making the POC-SMA more prone to particle displacement during the Cantabro test [26], [27].

1.5.2 Volumetric Properties

Fig. 5 illustrates the correlation between stability and flow at various levels of PU content, specifically 0%, 2%, 4%, and 6% and based on the graph, the stability values of 4% (9136 N) and 6% (12627 N) for the modified mixture, according to the standard specifications cited in JKR/SPJ/2008, have exceeded the minimum stability which is 6200 N that has designated for the SMA mixture. It is shown that the stability of the unmodified MPA mixture with a 0% PU content is 6879 N. This stability decreases to 5875 N for the modified SMA mixture, which contains a 2% PU. This is because the modified mixture has a low concentration of PU. Nevertheless, the stability of the modified SMA mixture increased significantly and rapidly to 9136 N when the PU concentration reached 4%, and this upward trend continued as the PU content grew to 6%, reaching a stability of 12627 N. The highest level of stability is observed with a PU content of 6%, corresponding to a force of 12627 N. This occurs due to the characteristics of PU, which enhance the strength of the bitumen that binds the aggregate in SMA, thereby improving compatibility and stability. A higher percentage (6%) yields a stronger and more cohesive binder layer, exhibiting enhanced resistance to deformation when subjected to pressure [28].

The flow characteristics of asphalt mixes, particularly in HMA, where bitumen is commonly used as a binder, are susceptible to being influenced by differences in the PU concentration as an additive in the asphalt mixture. Fig. 5 shows that the flow for the unmodified SMA mixture is 6.204 mm. For the modified SMA mixture with 2% PU, the flow increases slightly to 6.346mm. When the PU content is further increased to 4%, the flow increases to 6.582 mm. After that, the flow increases rapidly to 7.501 mm when the PU content reaches 6%. The flow in the graph indicates that all values fall within the range required for the SMA mixture, as specified in the Department of Public Works' standard specification for road works.

The flow in the asphalt mixture may indicate a more compaction-friendly mixture for use in construction. Thus, the addition of PU often aims to improve the adhesion between the asphalt binder and aggregate. Both stability and flow may indicate that the PU is successfully improving the internal structure of the mixture.

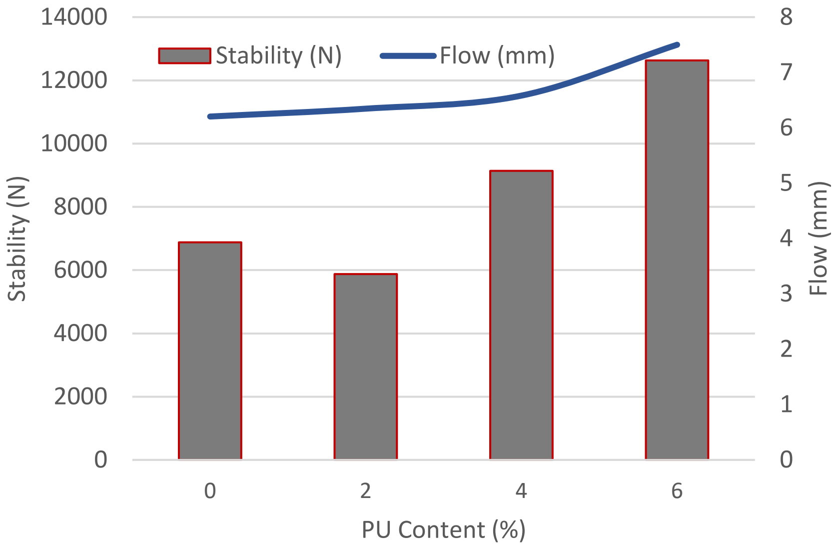

Fig. 5 *Stability vs flow*

Fig. 6 illustrates the relationship between the stability and density of SMA mixtures and the different percentages of PU, ranging from 0% to 6%. The Marshall stability test is a widely used method for measuring the ability of asphalt to withstand deformation when subjected to a load. It is often used to assess the overall quality of asphalt pavement mixtures. The graph shows that the addition of 2% PU into the asphalt mixture results in a Marshall stability of 5876N.

Subsequently, the stability progressively rises when the PU content reaches 4%, peaking at a stability of 9136N. The highest stability can be achieved at a 6% PU concentration, with a value of 12627N. This occurs due to PU's properties, which enhance compatibility and stability by strengthening the bitumen that binds the aggregate in SMA. The stability of the unmodified SMA mixture is 9841 N, which is significantly lower than the stability of the modified SMA mixture. This is because an unmodified SMA mixture depends only on its basic properties for both adhesion and internal durability, which can allow the stone to move slightly within the binder, causing depression or ruts to form over time. Hence, the addition of PU has increased the value of stability, which directly translates to enhanced rutting resistance. Rutting is the formation of permanent stress in the wheel paths caused by heavy traffic loads. This has proven that PU can effectively further enhance this pavement, leading to a road surface that can withstand heavy loads without permanent deformation. Furthermore, the presence of PU in the modified mixture can enhance stability and contribute to improved fatigue resistance, as traffic loads constantly stress the pavement. The flexibility of PU helps distribute these stresses more effectively. This reduces the possibility of fatigue cracks appearing in the asphalt over time, therefore extending the pavement's lifespan.

The density of both the unmodified and modified SMA mixture is also illustrated in Fig. 6. The density of the unmodified SMA is 2.123 g/cm^3, as demonstrated in this study. In contrast, the modified SMA mixture shows a density of 2.01 g/cm3 at a PU content of 2%. Furthermore, the modified SMA mixture has an increased density of 2.05g/cm^3 at a PU content of 4%, while the density of the modified SMA with a 6% PU content is 1.97 g/cm^3. It is advantageous to have a particular amount of voids in the SMA mixture to allow for the expansion and contraction of the asphalt binder caused by temperature changes, which can minimise cracking. Evidently, 6% PU is the optimum concentration for adding to a modified SMA mixture. Stability is enhanced by adhesion between the asphalt and the aggregate, resulting in improved resistance to deformation and fatigue resistance, which also optimises density properties at the optimum PU concentration. The mix is acceptable and allows easier compaction.

The control sample for PU content in SMA exhibits a stability of 18.9kN, whereas the sample for PU content demonstrates a stability of 6.9 kN. The addition of 2% PU to the asphalt bitumen content of stone mastic results in an increase in stability to 19.2 kN. Conversely, the stability of the mixture decreases to 5.9 kN when 2% PU is added. Furthermore, the inclusion of 4% EVA results in an increase in stability to 19.3 kN, whereas 4% PU yields a stability of 9.1 kN. Moreover, with 6% PU, stability further increases to 19.7 kN, whereas 6% PU generates a stability of 12.6 kN. It is evident that the inclusion of PU and the amount of asphalt in SMA might enhance its stability. This condition may arise due to the increased viscosity of the combination. Furthermore, modifying PU enhances the flexibility and durability of SMA. By minimising cracking resulting from heat stress and fatigue induced by driving loads, potential damage is reduced. SMA is recognised for its deformation resistance, and the inclusion of PU can augment this attribute. Hence, the incorporation of PU additive into SMA enhances the stability of the asphalt mixture in comparison to the two control samples, as demonstrated by both studies [29], [30].

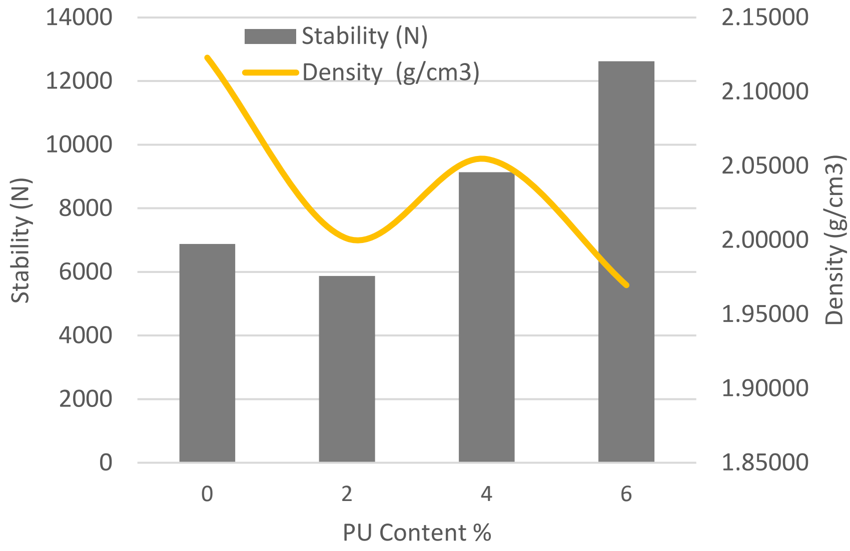

Fig. 6 *Stability vs density*

Fig. 7 shows the density and flow performance of asphalt mixtures with different PU percentages. There are two conditions for the unmodified SMA mixture and the modified SMA mixture. The density of the unmodified asphalt mixture is 2.12g/cm^3, as shown in the graph. This is because the mixture is primarily composed of mineral aggregate (stones and sand) that has been held together by asphalt cement (a binder). The density is determined by how these elements are packed, especially the aggregate. When the aggregate particles are compacted well, air spaces are reduced, resulting in a denser mixture. Regarding the modified SMA mixture, the addition of 2% PU to the SMA mixture yields a density of 2.01 g/cm^3. After that, the density value increases to 2.06 g/cm^3 when a 4% content of PU is added. With the addition of 6% PU, however, the density decreases to 1.97 g/cm^3. This may be caused by air entrapment. The presence of air voids in pavement mixtures can contribute to their enhanced workability by serving as a lubricant between aggregate particles throughout the compaction and mixing processes. This enhances the particles' movement, thereby decreasing the internal friction present in the mixture. Consequently, the mixture becomes easier to handle and compact, with reduced stiffness. This can be observed through the flow: as the density decreases, the flow increases, which can create air pockets, as illustrated in the graph. The flow of the modified SMA mixture with the addition of 6% PU is 7.50 mm, while the flow for the unmodified SMA mixture is 6.204 mm. This can be beneficial for compaction and achieving a smooth pavement surface.

Estimating the relationship between density and flow in an asphalt mixture is crucial for pavement quality control and condition assessment. The information can provide the proper strategies for the quality assurance of newly constructed pavement or the maintenance of existing pavement. Fig. 8 illustrates the stiffness and flow properties of asphalt mixtures with varying PU percentages. There are two conditions for the unmodified SMA mixture and the modified SMA mixture. As shown in the graph, the stiffness of the unmodified SMA mixture is 1108.80 N/mm. For the modified SMA mixture, the highest stiffness is achieved by adding 6% PU, resulting in a value of 1683.38 N/mm/mm. This is a significant increase in stiffness compared to the unmodified SMA mixture without PU. Thus, an increasingly stiff mixture can more effectively distribute the load of traffic over a wider area, resulting in enhanced durability against cracking and rutting. This can be particularly useful on high-traffic roads or in areas with heavy loads.

The use of PU enhances the flow characteristics of the asphalt mixtures. It clearly illustrates that the flow for the unmodified SMA mixture is 7.00 mm. In contrast to the modified asphalt mixture, the addition of 2% PU to the mixture resulted in a flow of 10.45 mm. The flow rate continues to increase following the addition of 4% PU, reaching a value of 15.16 mm. Subsequently, the flow rate increases slightly to 15.98 mm after the addition of 6% PU powder. While a low flow value suggests improved resistance to deformation, it can also result in brittleness and cracking. Therefore, a high flow indicates that the inclusion of PU powder improves the ease of handling and workability during placement, while nevertheless maintaining deformation resistance.

Thus, 6% of PU powder might still be the optimal amount for this asphalt mixture, considering both stiffness and flow. This is because it exhibits an important increase in stiffness and flow compared to the control mix, without any potential negative effects from the excessively decreased flow observed at 4% and 2% PU powder.

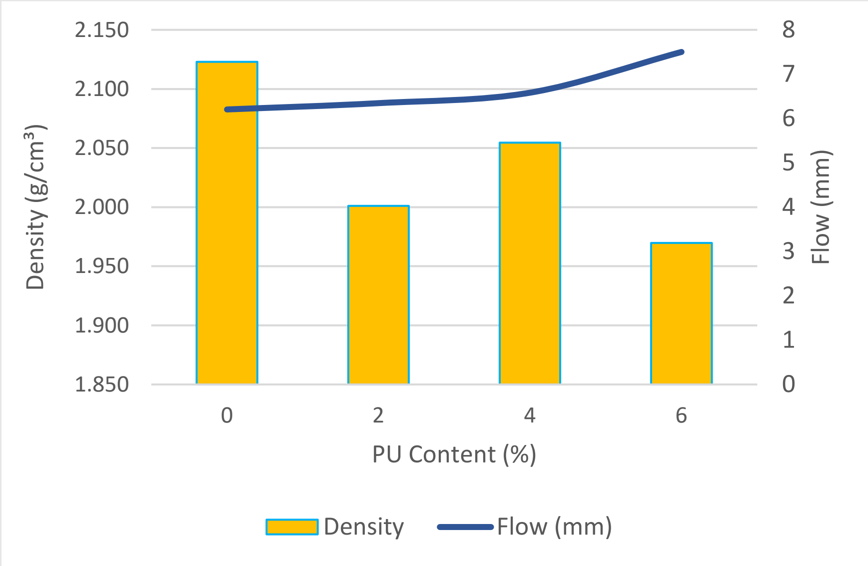

Fig. 7 *Density vs flow*

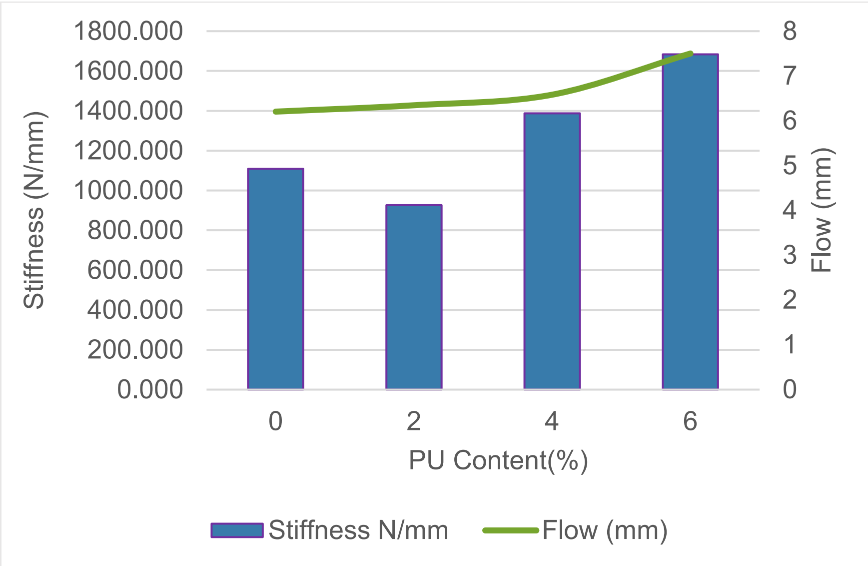

Fig. 8 *Stiffness vs flow*

The parameters measured in the Marshall stability test include the relationship between stiffness and density, as well as stability at various percentages of PU content, as shown in Fig. 9. The unmodified SMA mixture has a high stiffness value of 1108.80 N/mm. The stiffness of the modified SMA mixture, which contains 2% PU, decreases to 925.780 N/mm. This is due to the presence of a low concentration of PU in the modified mixture. However, the stiffness of the modified SMA mixture showed a substantial and rapid spike to 1388.03 N/mm/mm when the PU concentration reached 4%. This increasing trend persisted as the PU content increased to 6%, resulting in a stiffness of 1683.38 N/mm/mm. In addition to the stiffness can bolster the ability to withstand rutting by decreasing the probability of enduring deformation caused by heavy traffic loads.

The graph indicates that the unmodified asphalt mixture has a density of 2.12 g/cm^3. This is a result of the combination, which consists primarily of mineral aggregate bound together by a binder. The way these components are arranged, particularly the aggregate, determines the density. A denser mixture is created when the aggregate particles are well compacted, reducing the amount of air gaps. Regarding the modified SMA mixture, its density is 2.01 g/cm^3 after 2% PU was added. After that, adding 4% of PU causes the density value to increase to 2.06 g/cm^3. Nevertheless, the density decreases to 1.97 g/cm^3 with the addition of 6% PU. This phenomenon might be caused by air being trapped. When too many powder particles accumulate or become trapped between stone aggregates, air pockets may form. The air trapped in the mixture causes its total density to decrease, resulting in a value of 1.97 g/cm^3.

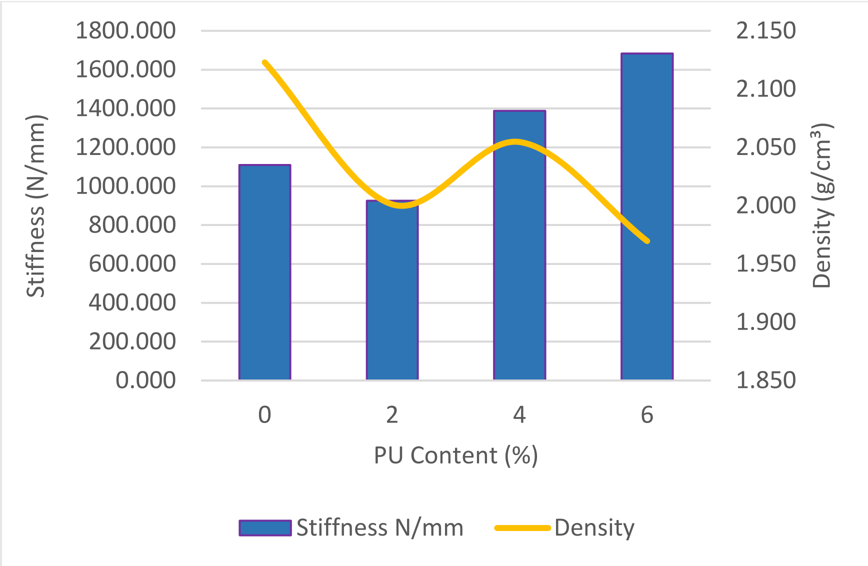

Fig. 9 *Stiffness vs density*

As a result, 4% PU appears to be the optimal content for this modified SMA mixture, given that both density and stiffness reach equilibrium at this point. This is because the added PU has increased the mixture's stiffness and improved its resistance to rutting in comparison to an unmodified SMA mixture [31]. Furthermore, the incorporation of 4% PU can increase density and stiffness, enabling the aggregates to be more compacted and packed densely, thereby further enhancing crack resistance.

The relationship between stiffness and stability at various percentages of PU content (0%, 2%, 4%, and 6%) is illustrated in Fig. 10. The graph shows that the unmodified SMA mixture exhibits a stability value of 6879 N. The stability of the modified SMA mixture, which incorporates 2% PU, decreases to 5875 N. This can be attributed to a small amount of PU (2%), which primarily functions as a lubricant, allowing PU chains to be flexible and move around, thereby reducing friction between aggregate particles and resulting in decreased stability compared to the unmodified mixture. However, when 4% PU was added to the modified SMA mixture, a substantial rise in stability was observed, reaching 9136N. This upward trajectory continued when the PU content was increased to 6%, ultimately resulting in a stability of 12627 N. When the PU concentration exceeds 2%, there's simply not enough space for the PU to move around freely. It starts to fill the gaps between other components, restricting their movement and reducing the lubricating effect, also resulting in increased contact and friction between the stones. Additionally, by increasing the proportion of PU, it can function as a binding agent, resulting in enhanced adhesion between the asphalt and the aggregates. Additionally, the enhanced structural integrity of the mixture increases its resistance to deformation and external forces, resulting in higher stability.

Fig. 10 demonstrates that the unmodified SMA mixture possesses a stiffness value of 1108.80 N/mm, indicating a high level of stiffness. When the PU concentration reached 6%, the modified SMA mixture exhibited a significant and rapid increase in stiffness, measuring 1683.38N/mm/mm. This is due to the inherent characteristic of PU, a polymer material known for its rigidity. When included in the asphalt mixture, it fills the empty spaces between the aggregate particles. These gaps are essentially empty spaces that decrease the overall rigidity of the mixture. PU not only fills the empty spaces but also forms a stronger chemical bond between the aggregate particles. This can lead to greatly enhancing its ability to resist deformation, resulting in increased stiffness [22], [32].

Based on the findings, it can be concluded that a PU content of 6% is the most suitable for this modified stone asphalt combination. This is because it results in a balanced and equal improvement in both stability and stiffness. The inclusion of PU enhances both the stability and stiffness of the asphalt mixture. Stability pertains to the ability of the mixture to withstand permanent deformation when subjected to traffic stresses, while stiffness indicates the asphalt's resistance to bending or flexing.

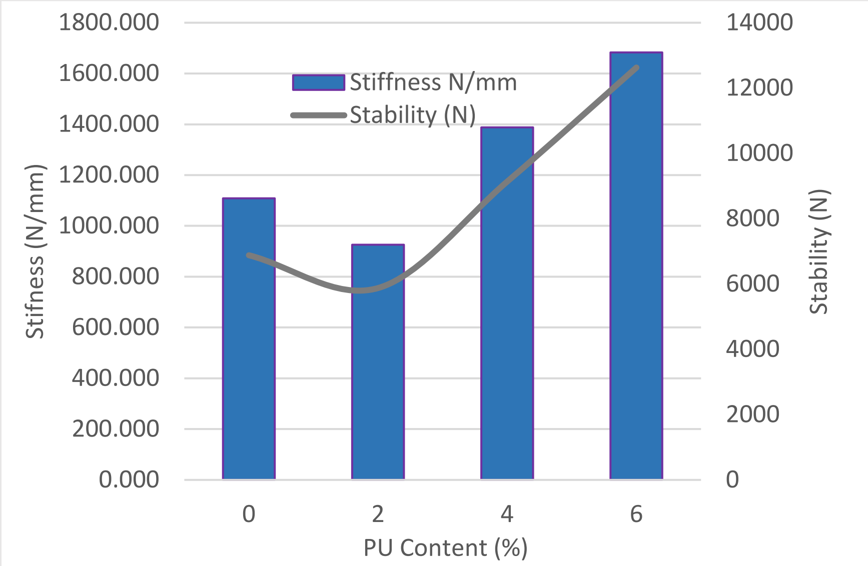

Fig. 10 *Stiffness vs stability*

1.5.3 Indirect Tensile Strength

The indirect tensile strength (ITS) test was conducted on samples with different proportions of each type of asphalt. Specifically, the unmodified SMA had a 0% percentage, whereas the modified SMA had percentages ranging from 2% to 6%. The purpose of ITS is to evaluate a material's ability to withstand cracking when subjected to opposing tensile forces, which cause it to stretch. This test is specifically conducted on HMA, which is a type of asphalt mixture compacted with 50 blows. Tests are performed via the Marshall Stability Machine. The test results are displayed in Fig. 11.

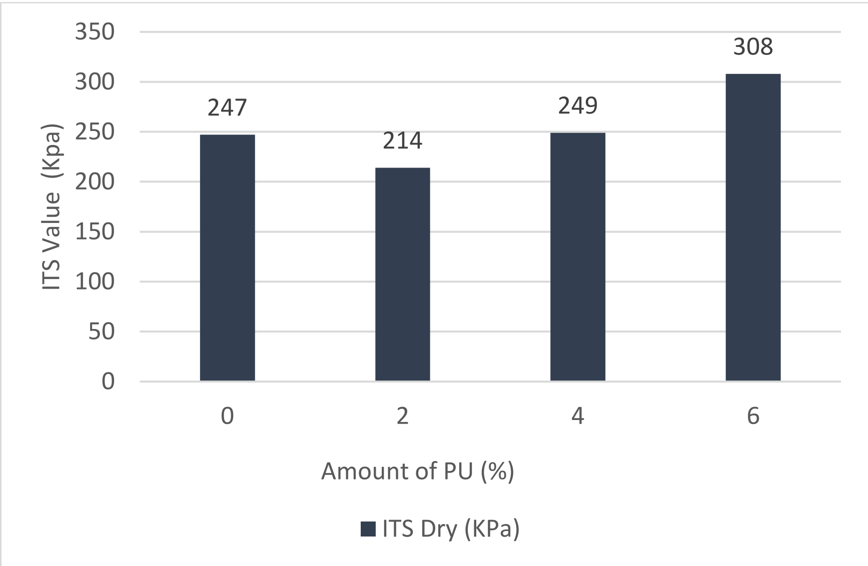

Fig. 11 *ITS vs the amount of PU*

When the amount of PU is 0%, it represents unmodified SMA. The ITS value for this mixture is 247 kPa. In contrast to the modified SMA mixture, the addition of 2% PU to the mixture results in a decrease in ITS value of 214 kPa. From this, adding 2% PU to the mixture causes a minor decrease. This may occur because the PU modifier used in the asphalt mixture was not optimised for it. As a result, the PU does not efficiently improve the characteristics of the asphalt matrix, which lowers the ITS. Next, the addition of PU content proceeded with the addition of 4% PU, where the weight of this 4% PU is 48 g. This has resulted in an increase in the ITS value of 247 kPa. In addition, the addition of 6% PU (equivalent to 72 g) to the modified SMA mixture results in a significant and continuous increase in the ITS value, reaching 308 kPa. The ITS increased with each addition of PU (2%, 4%, and 6%), as indicated by the analysis, suggesting a positive correlation between ITS and PU content. The highest strength was achieved at 6%, indicating that 6% is the optimal concentration.

Hence, the ITS value exhibited an upward trend as the proportion of PU increased from 2% to 4% and 6%. This indicates that the inclusion of PU additives functions as an adhesive, resulting in a stronger connection between the asphalt binder and the stone aggregates within the mixture. This stronger bond enhances stress distribution throughout the material, making it more resistant to cracking and tensile stresses. Additionally, it may enhance the asphalt mixture's ability to withstand rutting, a permanent deformation of the pavement caused by repetitive traffic loads. By reducing the occurrence of cracks, the pavement's overall strength and stability are improved, resulting in higher values of ITS [22], [32].

1.5.4 Moisture Susceptibility

The test results are represented in Fig. 12. The modified Lottman test provided the maximum applied load (*P*) value for each sample of SMA. The ITS_{wet} value for the unmodified SMA mixture is 310 kPa. After that, 24 g of PU content, equivalent to 2%, was added to the SMA mixture, resulting in a modified SMA mixture, and the ITS_{wet} value is 303 kPa. As can be seen, the value of ITS_{wet} for the unmodified SMA mixture is slightly higher than that of the modified SMA mixture, which contains 2% PU. This situation occurs because the PU modifier used in the asphalt mixture was not optimised for it, leading to an inefficient use of PU to improve the characteristics of the asphalt matrix, which in turn lowers the ITS.

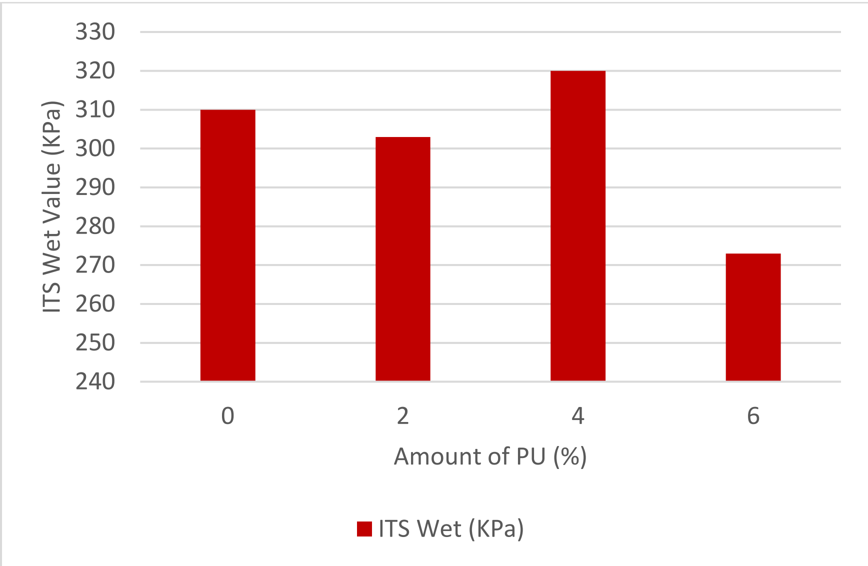

Fig. 12 *ITS_{wet} vs the amount of PU*

Furthermore, the amount of PU in the SMA mixture was increased to a concentration of 4%, equivalent to 48 g. As a result, the ITS_{wet} value increased to 320 kPa. After incorporating 6% PU, equivalent to 72 g, into the SMA mixture, the ITS_{wet} value decreased slightly to 273 kPa. This indicates that the ideal concentration of PU is 4%, resulting in a high ITS_{wet} value. When the PU is present at a concentration of 4%, it can effectively function as a useful modifier by filling gaps in the asphalt layer and establishing a more durable connection among the particles. This has the potential to result in an increased ITS_{wet} value, which is an indicator of improved tensile strength after exposure to water. Apart from that, adding too many modifiers (6% PU in this instance) could be damaging. The extra polymer may interfere with the interaction between the aggregates and asphalt, or possibly prevent the aggregates from being adequately coated by the asphalt. A weaker and more brittle composite could emerge from this, lowering the ITS_{wet} value.

Fig. 13 illustrates the comparison between ITS_{dry} and ITS_{wet} following the ITS and moisture susceptibility test. The graph illustrates that the ITS values of the dry specimens were greater than those of the wet specimens in the SMA mixture at a PU content of 6%. As can be seen, the characteristics of PU can enhance the adhesion between the asphalt binder and the aggregate particles, thereby enhancing the strength of the mixture. A stronger mixture that is resistant to cracking is also less likely to sustain permanent deformations under the pressure of traffic. Thus, PU can slightly strengthen the binder, thereby enhancing its resistance to rutting. Additionally, cracks are a considerable concern; therefore, a high ITS suggests an increased ability to resist the formation and expansion of cracks under tensile stress. PU can help the SMA mixture manage stresses more effectively, which in turn leads to a longer lifespan and fewer maintenance requirements, which is a significant concern for pavements [23], [32].

Moreover, the ITS values of the wet condition are 273 kPa for 6% SMA-PU, indicating that the modified asphalt mixture has enhanced water resistance due to PU, which forms a distributed network structure through its molecular chain [18]. Additionally, at a 6% concentration, the PU in the SMA mixture may form a water-resistant layer around the aggregate particles, thereby reducing water penetration and mitigating the weakening effect.

The potential for moisture-induced damage was also determined using the tensile strength ratio (TSR) in previous studies by Morea et al. [20], in addition to evaluating the strength of the asphalt mixture. The TSR was determined by dividing the ITS_{wet} by the ITS_{dry}. The TSR of the SMA mixture is typically required to be greater than or equal to 80%, as specified in AASTHOT 283. The TSR is a critical indicator for determining whether SMA is resistant to moisture or susceptible to it. Moisture susceptibility, alternatively referred to as moisture-induced damage or stripping, is a condition that occurs when moisture causes damage or stripping.

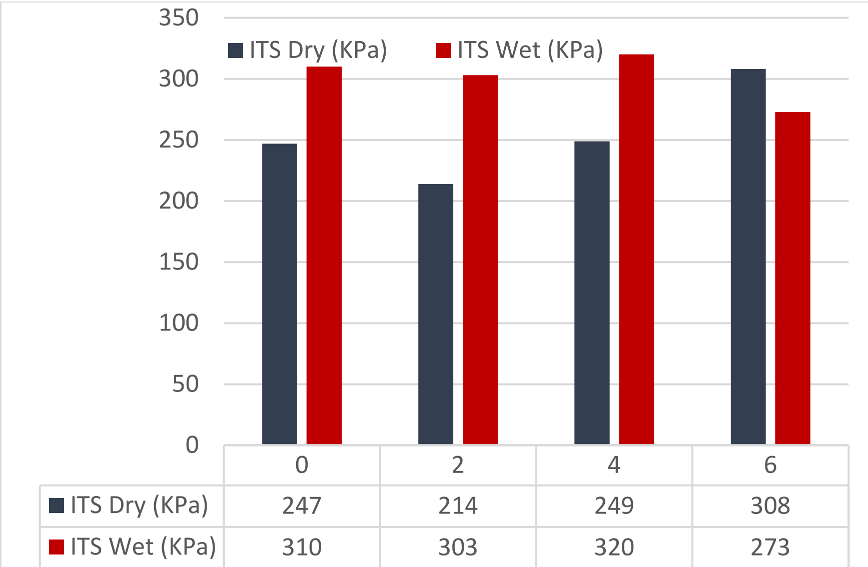

Fig. 13 *ITS_{wet} and ITS_{dry}*

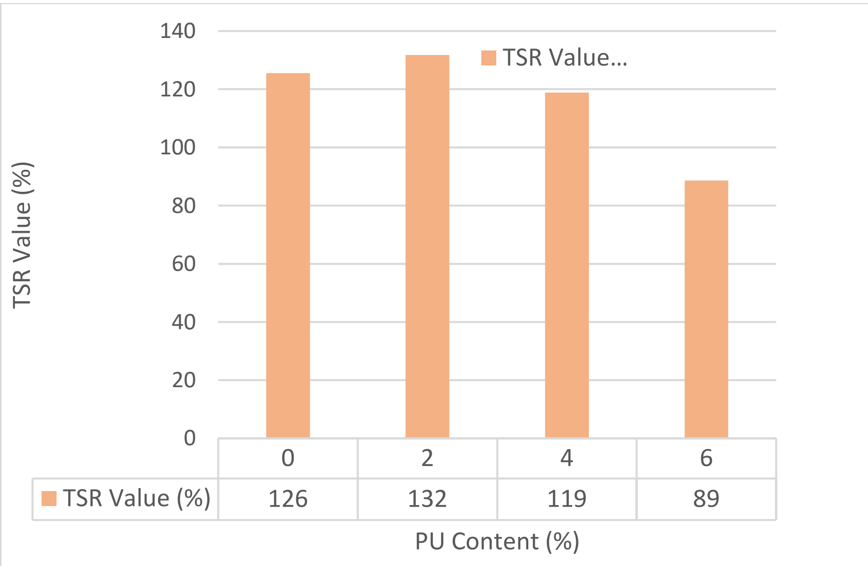

Fig. 14 *TSR vs amount of PU*

According to Fig. 14, the maximum TSR value was achieved at a 6% concentration of PU-SMA, reaching a value of 89%. Therefore, all the mixtures that were tested successfully fulfilled the criteria and demonstrated resistance to damage caused by moisture. According to the TSR value, the optimum amount of PU was determined to be 6%. Optimising the concentration of PU in SMA can significantly enhance the performance of SMA, especially in relation to its susceptibility to moisture. Adhesion is a special characteristic of PU, as it enables the efficient dispersion of PU in the SMA mixture. This adhesion occurs between the aggregate and the bitumen, resulting in a stronger and longer-lasting bond between the particles. The solubilization effect of PU in the asphalt mixture is the primary reason for the effective enhancement of asphalt adhesion when it is added. The lighter components of asphalt are absorbed by PU in asphalt, which subsequently forms a macromolecular adsorption layer on the contact surface of the phase [24]. The adsorption layer blocks the mobility of PU particles at high temperatures. Simultaneously, the macro-level adhesion of PU bitumen is enhanced by the interaction between PU particles.

1.6 Conclusions

In this paper, the PU-modified SMA mixture substantially enhances the engineering properties of the SMA mixture, as supported by the overall findings. The details are as follows:

- Durability: The addition of 6% PU content enhances the durability of the SMA mixture, as demonstrated by the Cantabro test's evaluation for its resistance to wear and tear. This improvement prevents the mixture from having ravelling.
- Rutting resistance: The stiffness, stability, and strength of the SMA mixture can be enhanced by adding 6% PU content as an additive. This can be proven in the Marshall stability test and the ITS test. Therefore, it can reduce the possibility of long-term deformation by increasing its resistance to rutting caused by heavy traffic loads.
- Fatigue resistance: PU's adhesive properties enhance the adhesion between the aggregate and bitumen in the mixture. The mixture's capacity to withstand repetitive internal stresses and strains caused by traffic loading for extended periods before cracking was due to this stronger bond. The test that can prove the fatigue resistance is the ITS, which provides a good indication of its ability to resist fatigue cracking.
- Moisture resistance: By adding PU to an SMA mixture, it can serve as an effective modifier by filling gaps in the asphalt layer and creating a stronger bond. This is due to the formation of a distributed network structure formed by the PU molecular chain. As a result, the penetration of water and the weakening effect towards the SMA mixture are reduced.

According to the classification table, determining the optimal content of PU, a PU content of 6% in the SMA mixture is preferable to a content of 0%. Thus, it may be inferred that the addition of PU improves the engineering properties of the SMA mixture. For future work, this study can be potentially expanded due to its potential applications in field trials and improved interpretation of dynamic loading for vehicles.

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Conflict of Interest

The authors declare that the work reported in this study was not affected by any conflicting financial interests or personal connections.

Author Contribution

The authors confirm their contributions to the paper as follows: ***Study conception and design:*** *Khairil Azman Masri;* ***Data collection:*** *Nuranis Sofia;* ***Analysis and interpretation of results:*** *Nuranis Sofia;* ***Draft manuscript preparation:*** *Moon Juhyuk. All authors reviewed the results and approved the final version of the manuscript.*

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