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ORIGINAL ARTICLE

Impact of Surfactants on the Performance of Plastic Modified Bitumen: A Study on Ductility, Penetration, and Softening Point

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ABSTRACT – This study explores the effect of surfactant use, namely Sorbitan Monostearate (Span 60) and Polyethylene Glycol 400 (PEG 400), on the physical and mechanical characteristics of bitumen modified with multilayer plastic. The focus of this study is to improve the compatibility between bitumen and multilayer plastic, which often have incompatible properties, thus affecting the performance of bitumen. Methodology applied includes the preparation of bitumen samples modified with varying surfactant concentrations, followed by microscopic analysis to assess particle dispersion and distribution. The results showed that the addition of surfactants significantly improved particle dispersion, with smaller particle sizes and more even distribution. Ductility tests showed that bitumen modified with surfactants had better flexibility compared to conventional bitumen, while penetration tests showed improved elasticity properties. These findings indicate that the use of surfactants in bitumen modification can improve the physical and mechanical properties of the material, providing potential for wider applications in the construction industry. Further research is recommended to explore other surfactant combinations and their impact on bitumen properties under various environmental conditions.

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INTRODUCTION

Plastic has become one of the most popular materials in the modern world today [1, 2]. Many industries favor plastic due to its various advantages. Its lightweight and flexible nature makes plastic suitable for a wide range of shapes and applications [3, 4]. Additionally, plastic is resistant to corrosion and not easily breakable, making it an ideal choice for many products [5]. The ease of coloring and shaping plastic adds to its appeal, while its properties as a good thermal and electrical insulator make it highly useful in various contexts [6].

However, behind all these advantages, there are significant challenges that must be faced. Serious environmental issues can arise if plastic is not processed properly [7, 8]. Plastic waste has now become one of the most pressing environmental issues worldwide [9]. With the increasing production and consumption of plastic, its negative impacts on ecosystems, human health, and the sustainability of our planet are becoming more pronounced [10].

Among the various types of plastic waste, multilayer plastics are particularly challenging to recycle [11]. Generally, recycling multilayer plastics is complex because industrial recycling processes are currently unable to identify, sort, and separate the diverse layers using standard technologies [12]. Consequently, multilayer plastics often end up in landfills or are incinerated, leading into evironmental pollution [13].

One promising approach to utilizing multilayer plastic waste is to incorporate it as a blend in bitumen [14]. Bitumen is a complex mixture of hydrocarbons found in petroleum [15]. As a product of petroleum refining, bitumen has viscoelastic properties that make it ideal for use in a variety of applications [16]. Bitumen is often used as a binder in asphalt mixtures, which are a key component in the construction of roads, bridges, and other infrastructure [17].

The low compatibility between bitumen and multilayer plastics is one of the drawbacks of using multilayer plastics as bitumen blends [18]. This low compatibility can result in negative impacts, such as reduced ductility, penetration value, and softening point [19]. Therefore, special treatment is required in blending multilayer plastics with bitumen to improve their compatibility. In this study, surfactants were added to the mixture to improve the compatibility between bitumen and multilayer plastics.

Surfactants, or surface active agents, are molecules characterized by a polar head and a non-polar tail, functioning to reduce the surface tension difference between two materials within a single mixing system. The polar head exhibits hydrophilic properties (water-attracting), while the non-polar tail is hydrophobic (water-repelling) [20]. The hydrophilicity and hydrophobicity of surfactants stem from the hydrophilic and hydrophobic functional groups in their molecular structure, respectively, as illustrated in Figure 1. Consequently, surfactants are commonly used to enhance the compatibility of various products composed of materials with significantly different surface properties. They are widely applied in diverse industries such as cosmetics, textiles, detergents, food, pharmaceuticals, and others.

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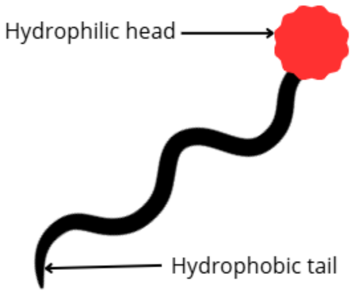

Figure 1. Surfactant structure and its relationship to hydrophilic and hydrophobic

The figure above illustrates the structure of surfactants, where the hydrophilic property is located at the polar head, while the hydrophobic property is at the non-polar tail. The head group can be anionic, cationic, zwitterionic, ampholytic, or non-ionic, whereas the tail consists of a hydrocarbon chain [21]. Generally, the ideal hydrocarbon chain length ranges from 10 to 18 carbon atoms. If the hydrocarbon chain is too long, an imbalance occurs due to either an excessive affinity for the oil group or a reduced affinity for the water group [22]

Surfactants are characterized by their charge type, which can be cationic, anionic, zwitterionic or ampholytic, or non-ionic, all of which are soluble in water. Each charge type has specific characteristics and influences the surfactant's performance and compatibility in mixing bitumen with multilayer polypropylene plastic. In this study, non-ionic surfactants were used, namely polyethylene glycol 400 (PEG 400) and sorbitan monostearate/Span 60 (SM). Non-ionic surfactants are characterized by having a neutral head group that is hydrophilic [23]. These two surfactants are suitable for high-temperature applications because they lack ionizable charged groups, making them less prone to decomposition at elevated temperatures. Additionally, non-ionic surfactants can form hydrogen bonds with water molecules, enabling them to create a homogeneous mixture with water and remain soluble at high temperatures [24].

The primary aim of this research is to evaluate the effect of surfactants on the physical and mechanical properties of bitumen modified with multilayer plastic waste, focusing on how surfactant addition influences particle size distribution, ductility, penetration, and softening point of the PMB; this study is significant as it offers a dual solution by addressing environmental plastic waste through an innovative recycling pathway while simultaneously enhancing the performance characteristics of bitumen used in road paving, providing valuable insights into sustainable material development and waste management strategies that support advancements in environmental protection.

EXPERIMENTAL METHOD

Materials and Instruments

In this study, the materials used consisted of polypropylene multilayer plastic (PPMLP) obtained from instant noodle packaging waste. This waste was collected from various sources, such as food stalls and supermarkets, then cut or chopped using a crusher machine to prepare it as raw material. In addition, the type of bitumen used was PEN 60/70, obtained from PT. Widya Sapta, in accordance with the standards set by the Directorate General of Highways, Ministry of PUPR. The surfactants used in this study were Sorbitan Monostearate, known by its trade name Span 60, and Polyethylene Glycol 400 (PEG 400). Both of these surfactants function to improve the physical and chemical properties of the resulting bitumen mixture.

Method and Procedure

This study uses bitumen with a PEN 60/70 specification as the base material for modification. Multilayer plastic waste from instant noodle packaging is used as an additive to enhance the mechanical properties of the bitumen. Nonionic surfactants, namely Sorbitan Monostearate (Span 60) and Polyethylene Glycol 400 (PEG 400), were selected as coupling agents with concentration variations of 0.1 wt.%, 0.3 wt.%, and 0.5 wt.%.

The preparation of plastic-modified bitumen (PMB) samples was carried out by mixing hot bitumen at approximately 160°C with multilayer plastic and surfactants according to the specified concentrations. After achieving a homogeneous mixture, the samples were observed under an optical microscope, and image analysis was performed using ImageJ software to quantify particle dispersion and distribution, accompanied by standard deviation as a measure of data homogeneity.

Ductility tests were conducted according to ASTM D-113-99 to measure the flexibility of the PMB. The samples were conditioned by immersion in water at 25°C for 85–95 minutes, then tested at a pulling rate of 50 mm/min until rupture. Penetration tests were performed following SNI-06-2456-1996 by inserting a penetration needle into the sample under specified temperature, load, and time conditions. The penetration value, measured in millimeters, reflects the hardness or softness of the PMB.

Softening point tests were carried out to determine the thermal properties of the PMB and the effect of surfactant concentration on the softening point. These results serve as an important comparative evaluation for material performance at high temperatures. The test data were then analyzed to assess the influence of surfactant concentration variations on the physical properties, particle dispersion, and mechanical properties of the plastic-modified bitumen. Comparisons between the control samples (without surfactant) and surfactant-treated samples provided deeper insight into the effects of nonionic coupling agents in the mixture.

RESULT AND DISCUSSION

Dispersion and Distribution

Observations using optical microscopy in this study served as a characterization method to examine the microstructure of asphalt mixtures containing coated polypropylene plastic waste. The primary purpose of these observations was to evaluate the quality of the mixture based on two crucial parameters: dispersion and distribution. As illustrated in Figure 2, the optical microscopy results on PMB samples with SM concentrations of 0.1%, 0.3%, and 0.5% demonstrate the dispersion and distribution of fine particles within the main matrix. To ensure the accuracy and objectivity of the data, ImageJ software was employed to quantify the dispersion and distribution values, accompanied by their respective standard deviation values.

Standard deviation is used to measure the extent to which data on particle dispersion and distribution deviate from their mean values. This metric is essential for determining the homogeneity and consistency of PMB mixtures. A smaller standard deviation indicates a more uniform and consistent particle dispersion. Thus, standard deviation functions as a quantitative indicator of the irregularity in particle dispersion and distribution within the samples. The following table presents the standard deviation values for the dispersion and distribution of various PMB products containing SM.

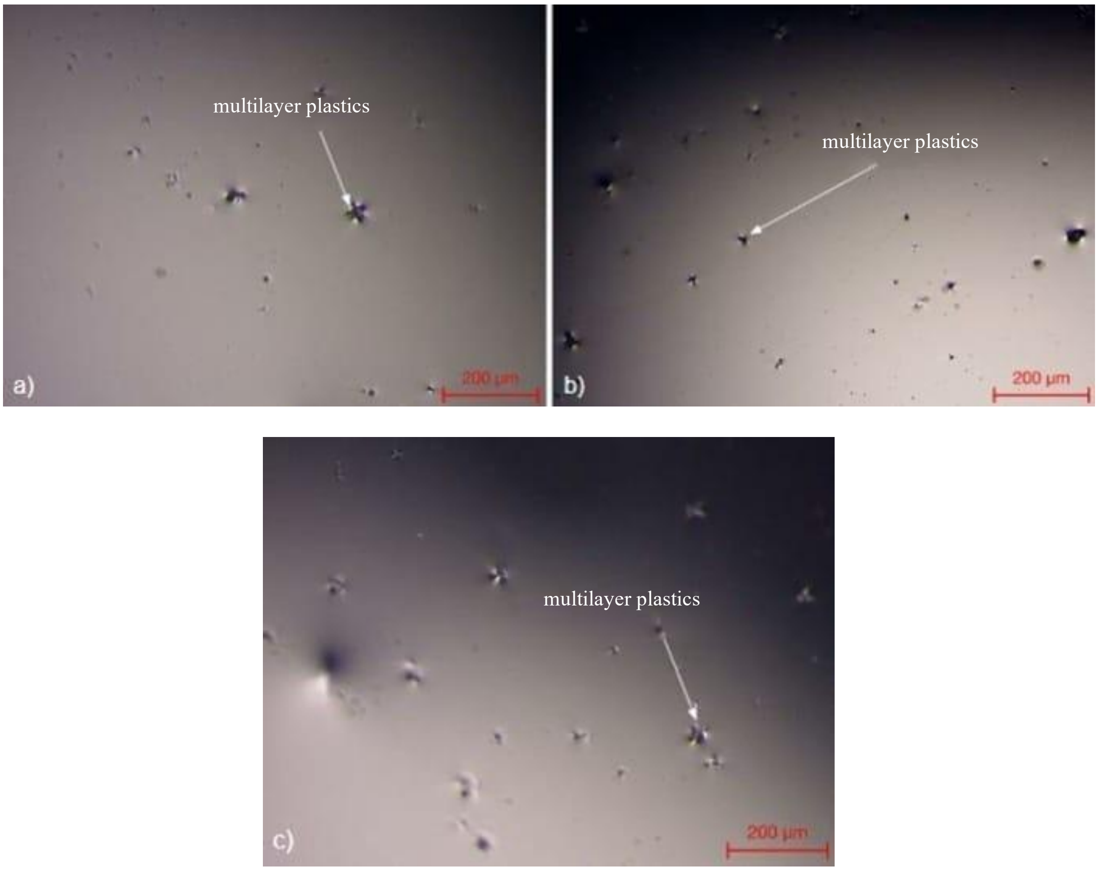

Figure 2. Results of optical microscope observations on PMB + SM samples with a) SM 0.1 wt.% b) SM 0.3 wt.% and c) SM 0.5 wt.%

The table illustrates the discrepancy in size between multilayer plastic particles in PMB + SM 0.1 wt.%, exhibiting a size disparity of 775 µm. Additionally, the distance between these particles is 175 µm. This data was obtained through the utilization of ImageJ software, a program designed for the analysis of digital images. The software was employed to interpret the microstructure image displayed in Figure 2. It is noteworthy that this analysis can be extrapolated to other concentrations of PMB + SM, including 0.3 wt.% and 0.5 wt.%. The dispersion and distribution values obtained from ImageJ software will be presented in the form of the following diagram for comparison.

Table 1. Standard deviation values of dispersion and distribution of non-surfactant PMB and PMB + SM products with concentration variations.

Sample	Standard Deviation Dispersion (μm)	Standard Deviation Distribution (μm)
PMB Non-Surfactant	948	175
PMB + SM 0,1 wt.%	775	153
PMB + SM 0,3 wt.%	781	57
PMB + SM 0,5 wt.%	878	121

Table 1 shows that the distribution value of PMB + SM 0.5 wt.% is the highest, followed by PMB + SM 0.1 wt.% and PMB + SM 0.3 wt.%. This indicates that multilayer plastic particle agglomeration occurs during mixing, causing ineffectiveness in dispersing the multilayer plastic particles. As the polymer concentration in the PMB mixture increases, the difficulty in dispersing the particles evenly also increases. This hindrance in the dispersion process results in uneven particle distribution. Irregular dispersion can cause inconsistent particle distribution in the final product, which in turn can affect the quality and performance of the product [21].

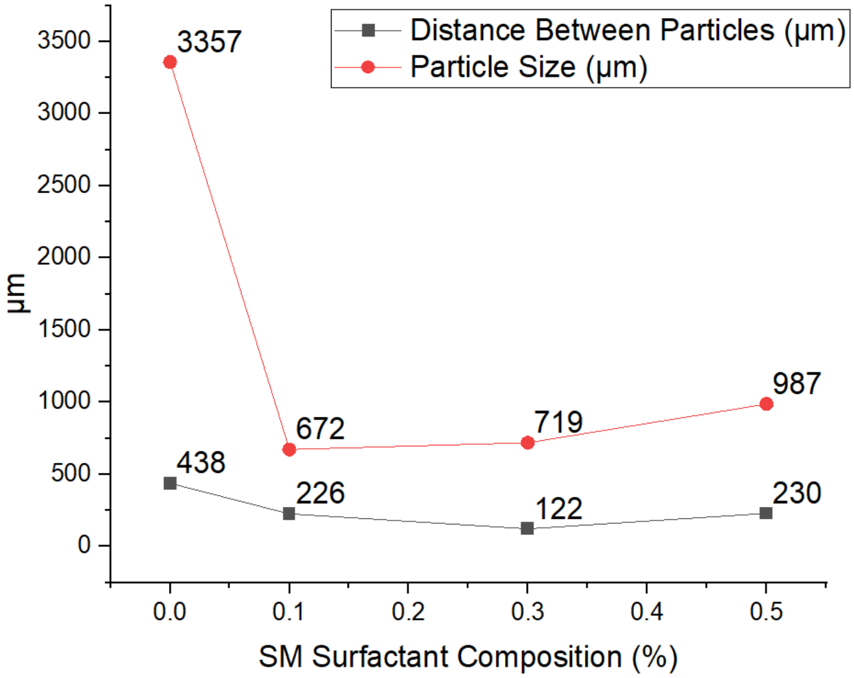

Figure 3. Dispersion and distribution graph of PMB + SM products with composition variations.

A comparative graph analyzing the dispersion and distribution of PMB+ SM products with varying compositions shows significant differences in dispersion values between PMB without surfactant and those containing surfactant, indicating that the addition of surfactant affects the dispersion of multilayer plastic particles. As illustrated in Figure 3, a detailed examination reveals that an increase in SM concentration correlates with an increase in the size of multilayer plastic particles. This trend is attributed to the solid state nature of SM, which is relatively thick compared to its liquid phase. This condition potentially causes agglomeration of SM, thereby hindering the effective dispersion of multilayer plastic particles. Furthermore, the chemical structure of SM —characterized by non-dominant hydroxyl functional groups and less polar ester and ether groups—makes it hydrophobic, promoting interactions among multilayer plastic particles that may lead to clumping.

Regarding distribution values, PMB without surfactant demonstrates the highest value due to poor dispersion resulting from aggregation within the multilayer plastic phase. However, when considering concentration variations, a different pattern emerges: PMB + SM at 0.5 wt.% exhibits the highest distribution value followed by samples with 0.1 wt.% and 0.3 wt.% concentrations respectively. This observation can be further explained by data presented in Figure 3, which indicates that the number of multilayer plastic particles in PMB + SM at 0.5 wt.% is lower than that found in PMB + SM at 0.3 wt.% sample.

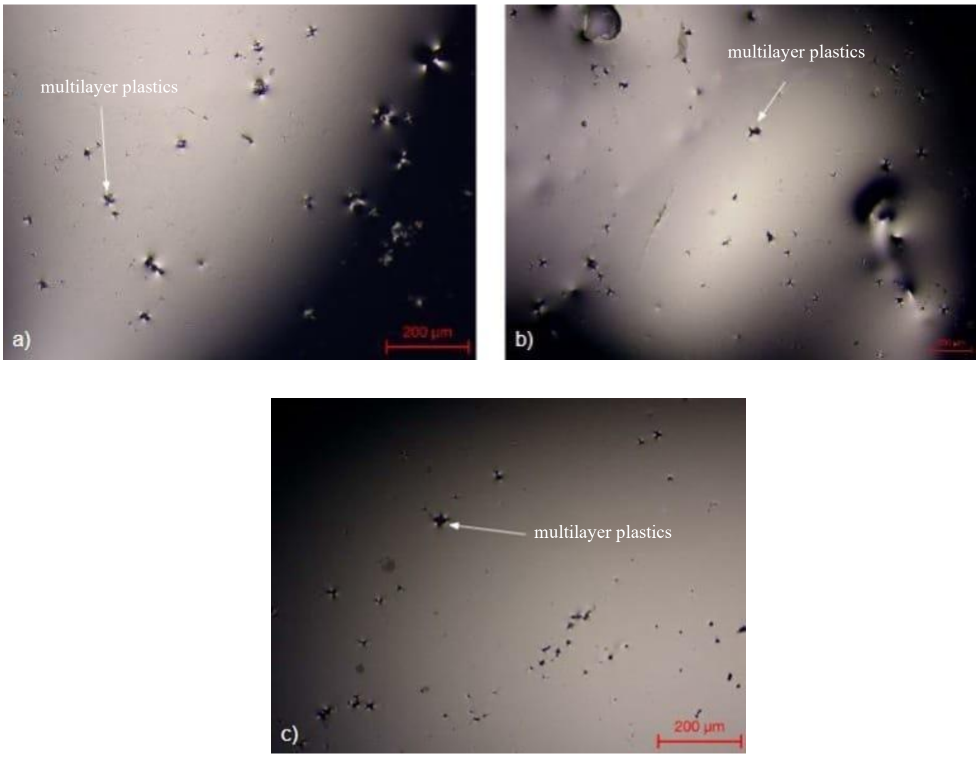

Figure 4. Results of optical microscope observations on PMB + PEG 400 samples with a) PEG 400 0.1 wt.% b) PEG 400 0.3 wt.% and c) PEG 400 0.5 wt.%.

Furthermore, the study continued with the effect of PEG 400 concentration on the dispersion and distribution of PMB products. Figure 4 shows the results of optical microscopy observations on PMB + PEG samples with concentration variations of 0.1 wt.%, 0.3 wt.%, and 0.5 wt.%. The results show that the higher the concentration of PEG 400, the multilayer plastic particle size increases.

Table 2. Standard deviation values of dispersion and distribution of non-surfactant PMB and PMB + PEG 400 products with concentration variations

Sample	Standard Deviation Dispersion (µm)	Standard Deviation Distribution (µm)
PMB Non-Surfactant	948	175
PMB + PEG 400 0,1 wt.%	382	5
PMB + PEG 400 0,3 wt.%	324	36
PMB + PEG 400 0,5 wt.%	346	93

Table 2 shows that PMB + PEG 400 products have insignificant differences in standard deviation values, indicating that the PMB + PEG 400 products with these concentration variations can be validly compared. Furthermore, the comparison of the dispersion and distribution values between non-surfactant PMB products and PMB + PEG 400 products is presented in the following graph.

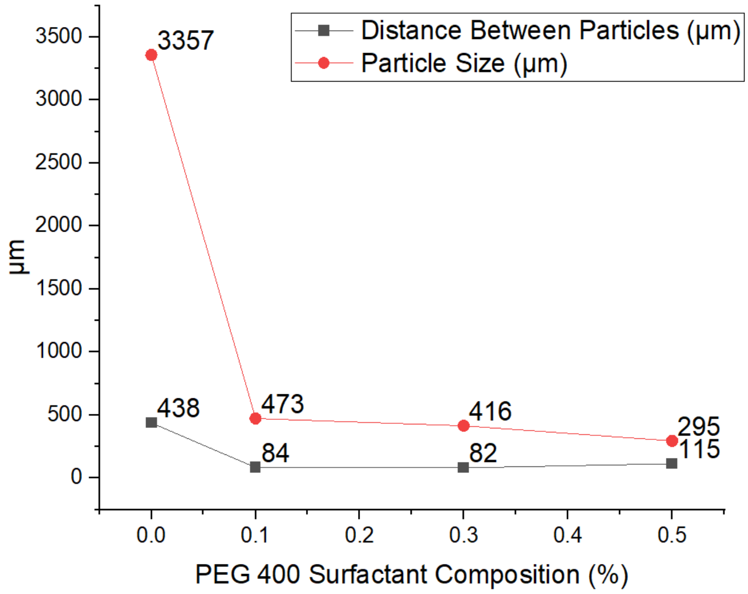

Figure 5. Dispersion and distribution graph of PMB + PEG 400 products with composition variations.

Figure 5 shows a graph comparing the dispersion and distribution of PMB + PEG 400 products of different compositions. This graph shows that there is a significant difference in the dispersion values between PMB without surfactant and PMB with surfactant, which proves that the addition of surfactant affects the dispersion of smaller particles. In the comparative analysis of dispersion based on concentration variation, it can be seen that as the concentration of PEG 400 increases, the dispersion value decreases. This is consistent with the literature, which states that the higher the surfactant concentration, the smaller the size of the lesser particles, and thus the larger the surface contact area [25]. As a result, the multilayer plastic phase becomes more mixed and better dispersed. Thus, the multilayer plastic phase and the bitumen phase can mix compatibly. In addition, the hydrophilic nature of PEG 400 is dominated by hydroxyl groups, the higher the composition of PEG 400, the more hydroxyl groups can interact with the bitumen phase, while the non-polar part of PEG 400 will interact with the multilayer plastic phase. In terms of the distribution value, PMB without surfactant has the highest value due to poor dispersion caused by the aggregation of the multilayer plastic phase. When comparing the distribution values of each concentration, there is a decrease in the distribution value of PMB + PEG 400 0.3 wt%. This is caused by the standard deviation value of the distribution of PMB + PEG 400 0.3 wt% which is higher than that of PMB + PEG 400 0.1 wt%. Thus, it can be concluded that there is a larger smaller particle size, so the distribution value is low.

The results showed that increasing the concentration of PEG 400 decreases the size of the multilayer plastic particles, thereby enhancing dispersion. The hydrophilic characteristic of PEG 400, rich in hydroxyl groups, increases interaction with bitumen phase, improving compatibility between the multilayer plastic particles and bitumen. Conversely, increasing the concentration of hydrophobic SM causes agglomeration of multilayer plastic particles, reducing the effectiveness of SM in dispersing these particles.

Ductility

Ductility testing showed that the bitumen samples modified with surfactants had better flexibility compared to non-surfactant PMB. The test results showed that bitumen containing SM and PEG 400 at certain concentrations was able to last longer before cracking when tested.

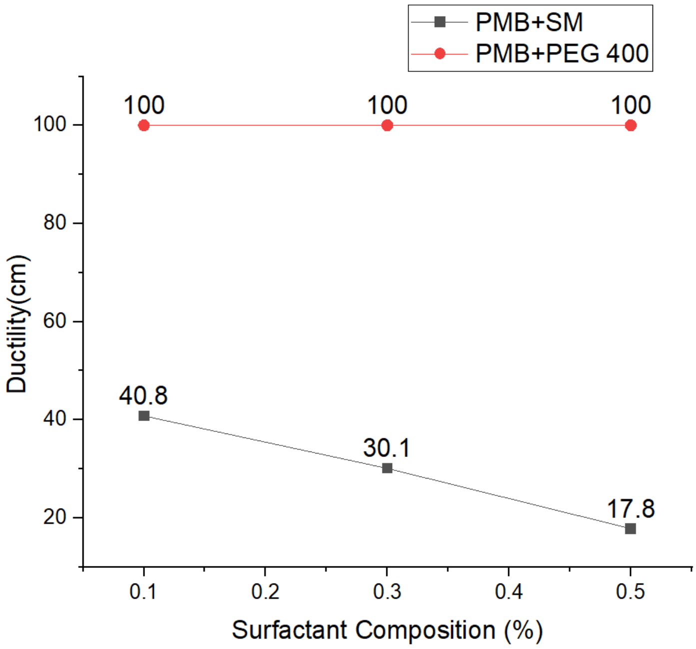

Figure 6. Ductility Test Results

The graph of the ductility test results shows that the ductility value after the addition of surfactants increased significantly compared to non-surfactant PMB. In research conducted by Manikanta [26], non-surfactant PMB exhibited a ductility value of only 28.36 cm. For PMB + PEG 400, the ductility value reached 100 cm at a concentration of 0.1 wt.%, which indicates that modification with this surfactant increases the material's resistance to deformation. In contrast, PMB + SM showed lower ductility values, namely 40.8 cm at a concentration of 0.1 wt.%, 30.1 cm at a concentration of 0.3 wt.%, and 17.8 cm at a concentration of 0.5 wt.%. This shows that PEG 400 is more effective in increasing the flexibility of bitumen compared to Sorbitan Monostearate.

Penetration

In accordance with the SNI-06-2456-1996 standard, penetration testing involves measuring the depth of penetration made by a 100-gram needle pressed into a bitumen sample for 5 seconds at a temperature of 25 °C. The penetration value is recorded in millimeters (mm). Bitumen exhibiting a penetration value between 60 and 70 mm is classified as PEN 60/70 bitumen. If the penetration value falls below this range, the bitumen demonstrates increased hardness. Conversely, if the penetration value exceeds this range, the bitumen tends to exhibit softer characteristics.

When bitumen is added with polypropylene multi-layer plastic (PPMLP), the penetration value tends to be lower. This is because PPMLP has a higher hardness value compared to bitumen. This decrease in penetration value can replace the function of bitumen modified with PPMLP, with the standard penetration value of bitumen which should be between 60 - 70 mm. If the penetration value is between 40 - 50 mm, then it can be categorized as PEN 40/50 bitumen.

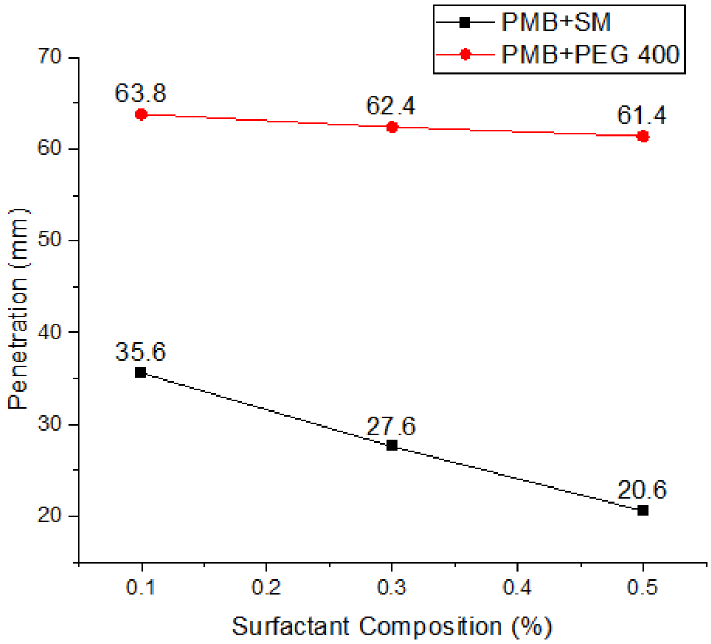

Figure 7. Penetration Test Results

According to the Bina Marga bitumen standards, the penetration value of pure bitumen typically ranges from 60 to 70 mm. In contrast, the penetration value of PMB without surfactants is significantly lower at 12.6 mm. Figure 7 illustrates the penetration test results of the PMB samples studied. The graph clearly shows that the addition of surfactants leads to a notable increase in penetration value compared to the non-surfactant PMB. This improvement is attributed to the surfactants' ability to reduce the size of multilayer plastic particles, which enhances dispersion and distribution within the bitumen matrix. These findings confirm that surfactants effectively perform their intended function in improving the penetration characteristics of PMB**.**

However, when adding SM surfactant, there is a problem because the dispersion and distribution are not good, so that the multilayer plastic phase clumps and causes the PMB product to become hard. The penetration values of PMB + SM with concentrations of 0.1 wt.%, 0.3 wt.%, and 0.5 wt.% were 35.6 mm, 27.6 mm, and 20.6 mm, respectively. The more SM concentration added, the harder the PMB.

On the other hand, in PMB + PEG 400, there was a decrease in penetration value, although the decrease was not significant. The penetration value for PMB + PEG 400 was 71.6 mm at a concentration of 0.1 wt.%, 67.6 mm at a concentration of 0.3.

Softening Point

The softening point test results indicate that the modification of bitumen with surfactants, namely SM and PEG 400, significantly influences the softening point of the material. As the concentration of SM and PEG 400 increases, the softening point of the modified bitumen also increases.

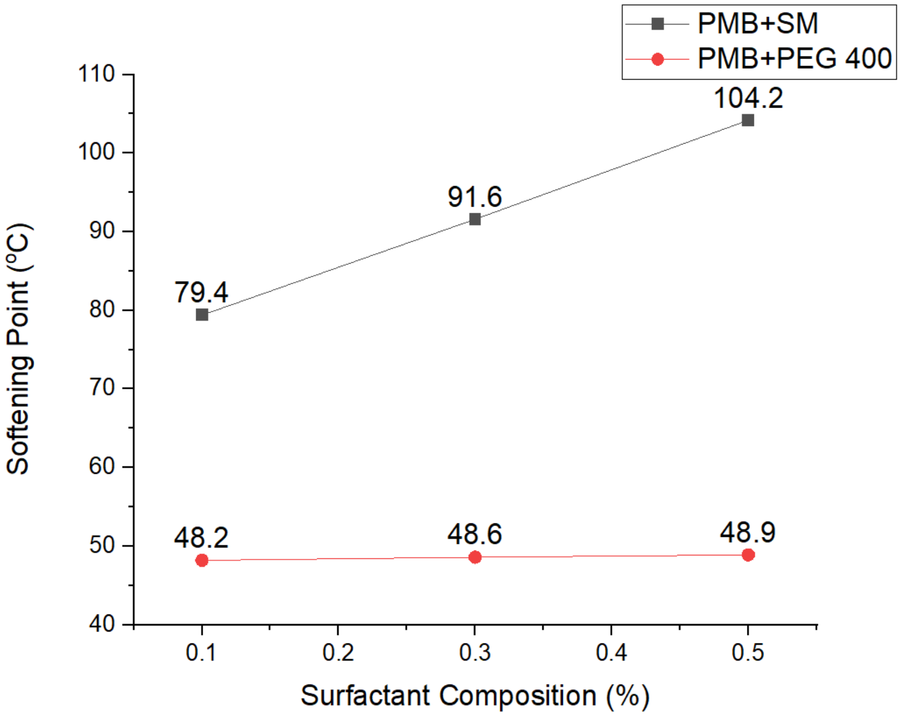

Figure 7. Softening Point Test Results.

As shown in Figure 7, the softening point values of PMB modified with SM have increased significantly. The softening point values for each SM concentration are 79.4 °C at 0.1 wt.%, 91.6 °C at 0.3 wt.%, and 104.2 °C at 0.5 wt.%. This increase is compared to the softening point values of pure bitumen and non-surfactant PMB.

This phenomenon can be explained by the dispersion and distribution behavior of the multilayer plastic phase within the bitumen. When the multilayer plastic phase tends to agglomerate, it forms clusters due to its higher melting point compared to bitumen. This agglomeration increases the overall softening point of the PMB. Therefore, as the concentration of SM increases, the degree of interaction and clustering of the multilayer plastic phase also increases, resulting in a higher softening point value.

On the other hand, for PMB modified with Polyethylene Glycol 400 (PEG 400), the softening point values obtained were 48.2 °C at a concentration of 0.1 wt.%, 48.6 °C at 0.3 wt.%, and 48.9 °C at 0.5 wt.%. These softening point values are in accordance with the bitumen standard, which sets a range between 48-58 °C [27].

CONCLUSION

This study shows that the use of surfactants, particularly SM and PEG 400, significantly affects the physical and mechanical properties of PMB. The findings indicate that adding surfactants can improve the compatibility between bitumen and multilayer plastics, which often have incompatible properties.

Further experimental results indicate that the addition of surfactants enhances particle dispersion capability, thereby improving the overall performance of the material. Reduction in particle size and increased uniformity of distribution demonstrate improved material performance. Ductility tests show that PMB modified with surfactants has better flexibility compared to conventional bitumen, while penetration tests show increased elastic properties of PMB.

Based on experimental results and data analysis, it can be concluded that both surfactants, SM and PEG 400, have positive effects on PMB performance. However, PEG 400 tends to yield better results compared to SM when observed from particle dispersion parameters, distribution, and overall mechanical stability.

This conclusion is validated by observations of the standard deviation values of particle dispersion and distribution, where PMB samples with PEG 400 show lower and more consistent values, reflecting superior particle dispersion and more homogeneous distribution. Conversely, the solid characteristics of SM and its tendency to cluster cause particle agglomeration that hinders effective dispersion.

Moreover, ductility and penetration tests show that modification with PEG 400 provides a more significant improvement in the elasticity and flexibility of PMB compared to SM. The more polar chemical structure of PEG 400 enhances the compatibility between components of the mixture more effectively.

These research findings provide an overview of the potential use of surfactants in bitumen modification for construction applications. However, further research is needed to explore other surfactant combinations and their effects on bitumen properties under various environmental conditions.

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REFERENCES

[1] Shiyu Tao, Tianhao Li, Mingyu Li, Shengxin Yang, Maocai Shen, and Hui Liu, “Research advances on the toxicity of biodegradable plastics derived micro/nanoplastics in the environment: A review,” *Sci. Total Environ.*, vol. 916, no. January, p. 170299, 2024, doi: 10.1016/j.scitotenv.2024.170299.

[2] Rodrigo A. Muñoz Meneses, Gerardo Cabrera-Papamija, Fiderman Machuca-Martínez, Luis A. Rodríguez, Jesús E. Diosa, and Edgar Mosquera-Vargas, “Plastic recycling and their use as raw material for the synthesis of carbonaceous materials,” *Heliyon*, vol. 8, no. 3, 2022, doi: 10.1016/j.heliyon.2022.e09028.

[3] Md Tanvir Hossain, Md Abdus Shahid, Nadim Mahmud, Ahasan Habib, Md Masud Rana, Shadman Ahmed Khan, and Md Delwar Hossain, “Research and application of polypropylene: a review,” *Discov. Nano*, vol. 19, no. 1, 2024, doi: 10.1186/s11671-023-03952-z.

[4] Sushant Agarwal and Rakesh K. Gupta, *Plastics in Buildings and Construction*, Second Edi. Elsevier Inc., 2017. doi: 10.1016/B978-0-323-39040-8.00030-4.

[5] Anthony L. Andrady and Mike A. Neal, “Applications and societal benefits of plastics,” *Philos. Trans. R. Soc. B Biol. Sci.*, vol. 364, no. 1526, pp. 1977–1984, 2009, doi: 10.1098/rstb.2008.0304.

[6] Andrea Cherubini, Valerio Ortenzi, Akansel Cosgun, Robert Lee, and Peter Corke, “Model-free vision-based shaping of deformable plastic materials,” *Int. J. Rob. Res.*, vol. 39, no. 14, pp. 1739–1759, 2020, doi: 10.1177/0278364920907684.

[7] Onwughara Nkwachukwu, Chukwu Chima, Alaekwe Ikenna, and Lackson Albert, “Focus on potential environmental issues on plastic world towards a sustainable plastic recycling in developing countries,” *Int. J. Ind. Chem.*, vol. 4, no. 1, p. 34, 2013, doi: 10.1186/2228-5547-4-34.

[8] Merlin N. Issac and Balasubramanian Kandasubramanian, “Effect of microplastics in water and aquatic systems,” *Environ. Sci. Pollut. Res.*, vol. 28, no. 16, pp. 19544–19562, 2021, doi: 10.1007/s11356-021-13184-2.

[9] Cayla R. Cook and Rolf U. Halden, *Ecological and health issues of plastic waste*. Elsevier Inc., 2020. doi: 10.1016/B978-0-12-817880-5.00020-7.

[10] Kim Borg, Alyse Lennox, Stefan Kaufman, Fraser Tull, Renee Prime, Luke Rogers, and Emily Dunstan, “Curbing plastic consumption: A review of single-use plastic behaviour change interventions,” *J. Clean. Prod.*, vol. 344, no. February, p. 131077, 2022, doi: 10.1016/j.jclepro.2022.131077.

[11] Geraldine Cabrera, Jixiang Li, Abderrahim Maazouz, and Khalid Lamnawar, “A Journey from Processing to Recycling of Multilayer Waste Films: A Review of Main Challenges and Prospects,” *Polymers (Basel).*, vol. 14, no. 12, 2022, doi: 10.3390/polym14122319.

[12] Katharina Kaiser, Markus Schmid, and Martin Schlummer, “Recycling of polymer-based multilayer packaging: A review,” *Recycling*, vol. 3, no. 1, 2018, doi: 10.3390/recycling3010001.

[13] Chris Matthews, Fintan Moran, and Amit K. Jaiswal, “A review on European Union’s strategy for plastics in a circular economy and its impact on food safety,” *J. Clean. Prod.*, vol. 283, p. 125263, 2021, doi: 10.1016/j.jclepro.2020.125263.

[14] Giovanni Polacco, Sara Filippi, Filippo Merusi, and George Stastna, “A review of the fundamentals of polymer-modified asphalts: Asphalt/polymer interactions and principles of compatibility,” *Adv. Colloid Interface Sci.*, vol. 224, pp. 72–112, 2015, doi: 10.1016/j.cis.2015.07.010.

[15] S. Binet, A. Pfohl-Leszkowicz, H. Brandt, M. Lafontaine, and Marcel Castegnaro, “Bitumen fumes: Review of work on the potential risk to workers and the present knowledge on its origin,” *Sci. Total Environ.*, vol. 300, no. 1–3, pp. 37–49, 2002, doi: 10.1016/S0048-9697(02)00279-6.

[16] Ehsan Behzadfar and Savvas G. Hatzikiriakos, “Viscoelastic properties and constitutive modelling of bitumen,” *Fuel*, vol. 108, pp. 391–399, 2013, doi: 10.1016/j.fuel.2012.12.035.

[17] Ian Sims, *The Shell Bitumen Handbook*, vol. 169, no. 1. 2016. doi: 10.1680/jcoma.15.00061.

[18] Jiqing Zhu, Björn Birgisson, and Niki Kringos, “Polymer modification of bitumen: Advances and challenges,” *Eur. Polym. J.*, vol. 54, no. 1, pp. 18–38, 2014, doi: 10.1016/j.eurpolymj.2014.02.005.

[19] Calvin S. A. L. Gaol, Bambang Priyono, M. Chalid, and Adam Febriyanto Nugraha, “The Effect Of Multilayer Plastic Waste Addition To Polymer Modified Bitumen Characteristics,” *OISAA J. Indones. Emas*, vol. 6, no. 1, pp. 57–64, 2023, doi: 10.52162/jie.2023.006.01.7.

[20] Nahir Dib, Cristian M. O. Lépori, N. Mariano Correa, Juana J. Silber, R. Dario Falcone, and Luis García-Río, “Biocompatible solvents and ionic liquid-based surfactants as sustainable components to formulate environmentally friendly organized systems,” *Polymers (Basel).*, vol. 13, no. 9, 2021, doi: 10.3390/polym13091378.

[21] Suman Chowdhury, Atanu Rakshit, Animesh Acharjee, and Bidyut Saha, “Novel Amphiphiles and Their Applications for Different Purposes with Special Emphasis on Polymeric Surfactants,” *ChemistrySelect*, vol. 4, no. 23, pp. 6978–6995, 2019, doi: 10.1002/slct.201901160.

[22] Bahri Ersoy and Mehmet S. Çelik, “Effect of hydrocarbon chain length on adsorption of cationic surfactants onto clinoptilolite,” *Clays Clay Miner.*, vol. 51, no. 2, pp. 172–180, 2003, doi: 10.1346/CCMN.2003.0510207.

[23] Peyman Koreh, Mostafa Lashkarbolooki, Majid Peyravi, and Mohsen Jahanshahi, “Interfacial performance of cationic,

anionic and non-ionic surfactants; effect of different characteristics of crude oil," *J. Pet. Sci. Eng.*, vol. 218, no. August, p. 110960, 2022, doi: 10.1016/j.petrol.2022.110960.

[24] Tsvetan Krasimirov Zahariev, Alia Vitali Tadjer, and Anela Nikolova Ivanova, "Transfer of non-ionic surfactants across the water-oil interface: A molecular dynamics study," *Colloids Surfaces A Physicochem. Eng. Asp.*, vol. 506, pp. 20–31, 2016, doi: 10.1016/j.colsurfa.2016.06.003.

[25] André J. P. Van Zyl, Deon De Wet-Roos, Ronald D. Sanderson, and Bert Klumperman, "The role of surfactant in controlling particle size and stability in the miniemulsion polymerization of polymeric nanocapsules," *Eur. Polym. J.*, vol. 40, no. 12, pp. 2717–2725, 2004, doi: 10.1016/j.eurpolymj.2004.07.021.

[26] M. Dines. Manikanta and M.Dinesh Kumar, "Comparative study on ductility of bitumen and plastic fiber modified bitumen," *Int. Conf. Newer Eng. Concepts Technol.*, 2025.

[27] Jiqing Zhu, Xiaohu Lu, Michael Langfjell, and Anders Gudmarsson, "Quantitative relationship of fundamental rheological properties of bitumen with the empirical Ring and Ball softening point," *Road Mater. Pavement Des.*, vol. 22, no. S1, pp. S345–S364, 2021, doi: 10.1080/14680629.2021.1900898.