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Evaluation of Compressive Strength of Asphalt Mixture from Marshall Stability and Indirect Tensile Strength

Fatin Hadi Meqtoof[1], Haider Habeeb Aodah[2*], Ishraq Hameed Naser[3], Ameer H.M. Ali[2]

[1] Department of Kindergarten, College of Education for Women, Shatrah University, Thi-Qar 64001, Iraq
[2] College of Engineering, University of Thi-Qar, Nassiriyah 64001, Iraq
[3] College of Engineering, Al-Iraqia University, Baghdad 10054, Iraq

Corresponding Author Email: alshweily@yahoo.com

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ABSTRACT

This research includes a laboratory study that deals with the evaluation of compressive strength for three different asphalt mixtures of hot mix asphalt (HMA). First, traditional HMA was prepared, and then, two asphalt mixtures were prepared using two different polymers, namely styrene-butadiene-styrene (SBS) using 5% SBS and reactive ethylene-butyl acrylate-glycidyl methacrylate terpolymer (Ax) using three concentrations (1% Ax, 2% Ax, and 3% Ax). Polymers are used as additives to enhance the performance of mixtures by enabling the creation of blends that resist rutting and cracking. The polymer-asphalt blends and conventional mixes were assessed by examining their Marshall stability, indirect tensile strength, and compressive strength. The results indicated that the mixtures modified with Ax exhibited enhanced mechanical properties, followed by the modified blend with 5% SBS. The modified asphalt mixtures exhibit superior performance compared with unmodified asphalt, as they possess greater Marshall stability, indirect tensile strength, and compressive strength. The relationships were derived for all three asphalt mixtures (traditional HMA and the two polymer-modified mixtures). These relations were quite strong, as indicated by the high value of R^2. The empirical relations can be used to predict compressive strength in a mix based on stability and indirect tensile strength data without performing the compressive strength test. Moreover, the association between compressive strength and stability proves to be more robust than the correlation between compressive strength and indirect tensile strength.

1. INTRODUCTION

Compressive strength refers to the ability of a material to withstand compressive forces directed along its axis [1]. Compressive strength may be defined as a crucial factor in determining the appropriateness of the mixture for use as a highway paving material under specific loads and environmental conditions [2]. Although compressive strength is not a crucial parameter for pavement performance, it is frequently specified in concrete road and pavement specifications. From a structural standpoint, flexural strength is much more significant than compressive strength, and permeability is more important for the durability of the pavement. Despite its relative lack of importance, compressive strength is still specified for concrete pavements because the concrete cube tests that determine it are simple, accurate, and well-understood. In contrast, the flexural strength test is expensive, demanding, and less accurate. Compressive strength is not important alone, but it correlates with flexural strength, density, and permeability, making it a useful indicator. Consequently, compressive strength is still measured and prescribed in concrete pavements.

Moreover, the compressive strength, in addition to other physical properties of the mixture, is significantly influenced by the mixture's physical and chemical characteristics. It is a crucial factor in determining the appropriateness of the mixture for use as a highway paving material under specific loads and environmental conditions [2]. The compressive strength of the road pavement must be suitable for structural design and durability requirements. For example, extra strength can be detrimental to the performance of the concrete pavement because stronger concrete causes more drying shrinkage, curling, joint opening, loss of load transmission, and cracking, which can shorten the pavement's lifetime. Furthermore, increased traffic on the road, along with insufficient maintenance, has resulted in accelerated deterioration of the road structure in recent years. Rutting, cracking, low-temperature cracking, aging, and stripping are early signs of degradation. Thus, increased traffic and demand for greater loads have motivated the development of improved pavement performance.

There are two primary strategies for making durable pavement: the first is to utilize thicker asphalt pavement, which raises construction costs, and the second is to create an asphalt mixture with modified qualities [3]. Polymers, for example, are used as additives to enhance the performance of mixtures by enabling the creation of blends that resist rutting and cracking. Traditional asphalt has poor resistance under high temperatures and increased traffic loads. At the same time, polymers improve the physical properties of asphalt mixtures [3]. Bitumen the main component in asphalt concrete mixtures is a cement-like material with a dark brown to black color, found naturally or derived from crude oil distillation [4]. By covering the aggregate, bitumen helps bind the aggregate together. It also contributes to the road's strength. However, its water resistance is low, and thus, it is necessary to employ anti-stripping chemicals. Road surfaces with neat bitumen can exhibit bleeding in hot weather, cracking in cold weather, reduced load-bearing capacity, and can cause major damage from increased axle load, especially considering the rapid development of infrastructure. Enhancing the bitumen quality can be achieved by altering its rheological properties through the incorporation of synthetic organic polymers like rubber and plastic. Compared with pure bitumen, a polymer bitumen blend can have improved ductility, an increased softening point, and a reduced penetration value, allowing it to withstand higher temperatures and loads during construction. In instances where the aggregates are prone to stripping, modified bitumen also outperforms ordinary bitumen. The aggregate-bitumen mix coated with a polymer, featuring an excellent Marshall stability value and an adequate Marshall coefficient, is mechanically ideal for constructing flexible pavement surfaces [5].

A polymer is a chemical substance or compound mixture composed of repeating molecules [6-8]. Among the most essential physical qualities of polymers is a high tensile strength, and polymers transition from a non-conducting state to one that is sensitive to thermal expansion in various quantities and directions. Polymers also have relatively low permeability. Among the various modifiers, polymer additives were found to be particularly effective because they demonstrate enhanced performance by increasing binder stiffness at elevated temperatures while preserving flexibility at low temperatures [9-12]. Polymer-modified asphalts exhibit enhanced resistance to thermal cracking and rutting, as well as reduced fatigue damage, temperature sensitivity, and stripping [13, 14]. Furthermore, polymer additives exhibit increased creep resistance, making them suitable for prolonging the lifespan of surfaces at high-traffic intersections, bridge decks, and roundabouts. Owing to their enhanced stiffness modulus, improved fatigue life, superior creep resistance, and increased indirect tensile strength (ITS), modified bituminous mixes are appropriate for wearing courses, binder courses, and overlays on cracked and heavily trafficked surfaces. Altered binders find use in diverse crack-sealing applications like stress-absorbing membranes and stress-absorbing membrane interlayers, as well as in porous asphalt and stone matrix asphalt.

In this study, we evaluated the compressive strength of asphalt mixtures based on their Marshall stability and ITS, aiming to establish a relationship between these factors and the compressive strength. Notably, we assessed the performance of polymer-asphalt blends incorporating different polymers, namely styrene-butadiene-styrene (SBS) and a novel polymer, reactive ethylene-butyl acrylate-glycidyl methacrylate polymer (Ax).

2. MATERIALS FOR ASPHALT MIXTURE

Asphalt concrete typically consists of three main components: aggregates, bitumen, and voids. In this study, two different polymers (SBS and Ax) are added to these components to improve the overall performance.

2.1 Aggregate

To create the hot mix asphalt specimens in this study, one type of quartzite aggregate was used. This aggregate's gradation has characteristics associated with the central Iraqi surface layer. Table 1 outlines the aggregate's physical properties, and Figure 1 depicts the aggregate gradation.

Table 1. Physical aggregates properties

Property	Test Method	Iraqi Standard Limits	Test Result
Los Angeles, %	ASTM C-131	Maximum 30	22
Soundness Test, %	ASTM C-88	Maximum 12	7.5
Flakiness and Elongation Index Combined, %	ASTM D-4791	Maximum 10	3.5
Fractured Particles, %	ASTM D-5821	Minimum 90	93
Friable Particles and Clay Lumps %	ASTM C-142	Maximum 3	1.1

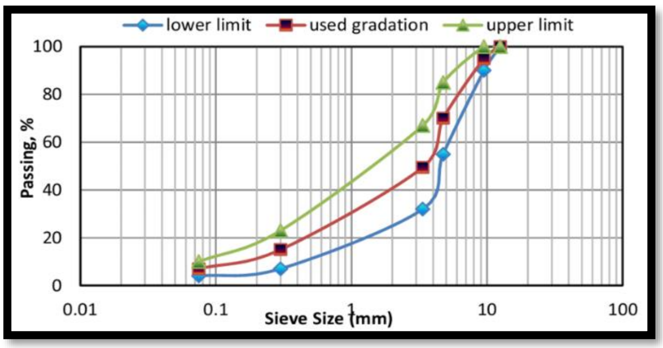

Figure 1. The surface layer's aggregate gradation at its midpoint

2.2 Bitumen

Bitumen, which is a black, viscous, and adhesive liquid or semi-solid substance, can be found in natural deposits and is a byproduct of crude oil fractional distillation. Consisting of densely packed polycyclic aromatic hydrocarbons, it is made up of 95% carbon and hydrogen (87% carbon and 8% hydrogen), with up to 5% sulfur, 1% nitrogen, and 1% oxygen content, in addition to trace metal concentrations of approximately 2000 ppm. Furthermore, bitumen is a complex chemical mixture of 400-2000 components, with an average of 600-800. It has the highest boiling point (525℃) and is the most prevalent component of crude oil. In bituminous mixtures, bitumen acts as a binding agent for aggregates. Bitumen is frequently used in the construction of flexible roads [15]. In this study, bitumen of grades 40/50 was used. The physical asphalt properties are presented in Table 2.

2.3 Polymers as modifiers

Modifiers or additives are often employed to reduce the voids present between aggregates, which improves the qualities of bituminous concrete mixes. Modifiers also bind the particles together, preventing bitumen bleeding. In this study, SBS (with a concentration of 5%) and Ax (with three different concentrations: 1% Ax, 2% Ax, and 3% Ax) as shown in Figure 2 were employed as modifiers. When used as bitumen modifiers, the selected polymers should have the following properties [15]:

- Bitumen compatibility
- Maintain stability at mixing temperatures
- Can be processed with normal mixing and laying equipment
- Determine the covering viscosity at the temperatures involved
- Retain high qualities while storing, applying, and using
- Capable of producing a uniform bitumen blend

Table 2. The physical asphalt properties

Properties	Test Result	Item Requirements
Asphalt Cement Classified According to Viscosity		
Properties	**Test Result**	**Item Requirements A-40**
Viscosity at 60℃, Poise	3800	4000±800
Viscosity at 135℃, centistoke	420	Minimum 400
Penetration 25℃, 100 g, 5 sec (1/10) mm	49	40-50
Flash point, ℃	240	232
Ductility, cm, 25℃, 5 cm/min	103	<100
Solubility in Trichloroethylene Solution, %	99.3	Minimum 99
Asphalt Cement Classified According to Penetration		
Properties	**Test Result**	**Item Requirements 50/40**
Penetration 25℃, 100 g, 5 sec (1/10) mm	49	40-50
Ductility, cm, 25 ℃, 5 cm/min	103	<100
Flash point, ℃	240	< 232
Solubility in Trichloroethylene Solution, %	99.3	< 99
Tests of the Remaining (After the Loss)		
Remaining penetration, (% of original)	84	< 55
Ductility, cm, 25℃, 5 cm/min	88	< 25

SBS is a commonly utilized polymer in bitumen modification, as its styrene-butadiene molecular composition provides outstanding rigidity and elasticity across a wide range of temperatures. Predominantly, the interaction between SBS and bitumen is physical in nature. Bitumen's smaller aromatic components penetrate SBS molecules, causing their volume to expand by approximately 3-5 times their original size. At adequate concentrations, SBS forms a 3D network that greatly improves the load-bearing capability of the modified bitumen. Additional polymers used in bitumen modification include styrene-butadiene rubber, elvaloy, ethylene vinyl acetate, and ethylene glycyl acrylate, among others. However, SBS-modified bitumen remains the leading choice in the polymer-modified bitumen market because of its superior properties and performance [16-20].

Figure 2. Polymers utilized in the study

Table 3. Physical properties of SBS

Physical Properties	Metric
Density (g/cm^3)	0.92
Tensile Strength (MPa)	10
Flexural Modulus (GPa)	0.007
Elongation at Break (%)	1000
Max. Operation Temp (℃)	50
Viscosity (cSt)	12-24
Molecular Weight (g/mol)	110-162000
Linear Mold Shrinkage (cm/cm)	0.000-0.027
Melt Flow (g/10min)	0.0100-180
Ash	0.0900-6.00%
Linear Mold Shrinkage, Transverse (cm/cm)	0.0140-0.0200

Table 4. Physical properties of Ax

Physical Properties	Value
Butyl Acrylate Content (%-wt)	25
Glycidyl Methacrylate Content (%-wt)	5
Melt Index (g/10min)	12
Melting Point (℃)	72
Density (g/cm^3)	0.93
Vicat Softening Point Temperature (℃)	<40
Flexural Modulus (MPa)	11
Elongation at Break%	860
Tensile Strength at Break (MPa)	4

Table 5. The properties of modified bitumen

Properties	Styrene-Butadiene Styrene (5% SBS)	Reactive Ethylene-Butyl Acrylate-Glycidyl Methacrylate Terpolymer (A) 1% Ax 2% Ax 3% Ax
Penetration 25℃, 100 g, 5 sec (1/10) mm	25	30 19 15
Flash point, ℃	240	240 240 240
Ductility, cm, 25℃, 5 cm/min	45	108 90 88
Solubility in trichloroethylene, %	99	99 99 99
Tests of the Remaining Candidates		
Remaining penetration (% of original)	90	92 90 90
Ductility, cm, 25℃, 5 cm/min	30	95 80 75

The physical polymer properties that use in this study are presented in Tables 3 and 4.

In order to improve the modified bitumen, an elastomer, Styrene Butadiene Styrene (SBS), was utilized. As a base bitumen, bitumen 40/50 was applied then 5% of SBS was added by weight of bitumen, most of the researchers deduced that 4 to 5% SBS is the best-adding rate [21-23].

Three ratios of the second additive (Ax), (1%Ax, 2%Ax, 3%Ax) have been suggested by the researchers for the purpose of completing the study requirements.

The mix was used to study the basic properties of bitumen as in Table 5.

3. LABORATORY TEST RESULT AND DISCUSSION

3.1 Experimental testing program

The experimental program was conducted in two phases. Initially, the Marshall stability and ITS of the asphalt mixtures without polymers were characterized to determine the baseline relationship with compressive strength. Subsequently, the modified asphalt mixtures were assessed. In this research two types of additives were used. The first one is styrene-butadiene-styrene (SBS) and the second one is reactive ethylene-butyl acrylate-glycidyl methacrylate terpolymer (Ax) it was added to asphalt as in dose from the total weight of asphalt. In the lab, mixing was done with a high-shear mixer that could control stirring speed and maintain temperature. For one hour the asphalt binder was heated to 150℃ while the mixer's speed was kept at 200 rpm. Following that, mixing was done for 1.5 hours at a speed of 500 rpm as well [24].

3.1.1 Compressive strength tests

The maximum amount of compressive stress that a material can withstand without fracturing is known as compressive strength [15]. To determine the compressive strength of the mixtures, a compression load is applied to the circular face of a circular specimen until it fails. The following equation can be used to determine the compressive strength:

$$\sigma c=(4 \text{ p max})/(\pi D^2) \qquad (1)$$

In this case, σc denotes the unconfined compressive strength, p max stands for the maximum applied compressive load, and D refers to the diameter of the sample.

To measure the compressive strength of compacted bituminous mixtures, cylinders with a diameter of 101.6 mm and a height ranging from 99.1 to 104.1 mm were used. The specimen's size has an impact on the results of the compressive strength test. Prior to incorporating the bitumen binder, the aggregate was heated to a temperature slightly higher than the required mixing temperature for the dry blending. The blending temperature never surpassed 175℃. To maintain the suitable temperature after dry mixing, the bowl and aggregate batch were preheated in an oven to a temperature that meets the aggregate specifications. Subsequently, we poured the specified amount of hot bitumen onto the heated aggregate within the bowl and promptly incorporated the bitumen into the aggregate by mixing. While blending the materials, the process was finished within a 90 to 120 second timeframe, during which the temperature was approximately 3 to 5℃ above the initial mixing temperature to allow for compaction, enabling it to start immediately. In the case of stabilized mixtures, the additives were introduced to the heated aggregate before combining with the heated bitumen [25]. To ensure consistency throughout the study, an optimal bitumen content of 5.1% (by weight of the total mix) was used in the preparation of all stabilized mixes, as determined by the Marshall control mix design. Marshall specimens were prepared for unmodified and modified mixtures with different percentages of additives. The compressive test specimens were prepared by applying a layer and compacting it with 35 blows and then applying the second layer and compacting it with 75 blows After that, the specimen was turned on the other side and compacted with 75 more blows. After taking the test samples out of the oven, they were allowed to cool down to room temperature for at least 2 hours before proceeding. Next, the specimens underwent axial compression at a consistent vertical deformation rate of 3.2 mm/min. The compressive strength is calculated by dividing the highest vertical load achieved during deformation at the specified rate by the initial cross-sectional area of the specimen, following the ASTM D 1074-09 [25]. The average compressive strength values were determined from three individual specimens in each case. Examples of the compressive strength samples are shown in Figures 3 and 4.

The relationship between the type of asphalt and Compressive (kN) and the relationship between the type of asphalt and Compressive (mPa) are shown in Figures 5 and 6.

(a) The specimen of compression (b) The mold of compression

Figure 3. The compressive sample

Figure 4. The sample after failure

Table 6. The value of Marshall stability (kN)

Type of Asphalt	40\50	5% SBS	1% Ax	2% Ax	3% Ax
Stability (kN)	10.5	12.5	12	13.7	13.5

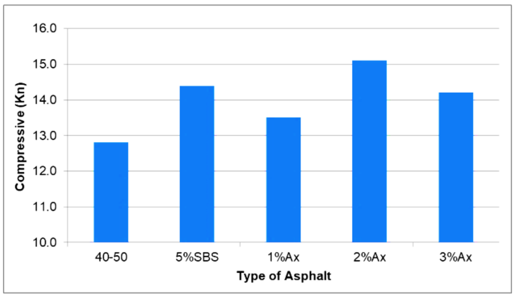

Figure 5. The relationship between the type of asphalt and compressive (kN)

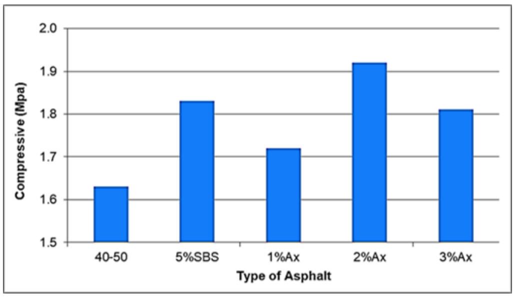

Figure 6. The relationship between the type of asphalt and compressive (mPa)

3.1.2 Marshall stability results

To calculate the optimum binder content (OBC), the Marshall technique of the mix design was used on all mixes, following ASTM D 1559 [26]. For this study, 100 mm diameter and 63.5 mm tall samples were created. Each side of the specimens received 75 strikes. According to the Asphalt Institute MS-2 series (Seventh Edition), the OBC was consistent with bitumen containing 4.0% voids. The OBC of the surface layer in this study was 5.1%. We concluded that the modifiers did not significantly affect the OBC. HMA specimens before and after stability test are shown in Figure 7.

(a) Hot mix asphalt specimens

(b) Stability test

(c) Specimen after stability test

Figure 7. Marshall test

The Marshall stability values of the five mixes were calculated and is presented in Table 6 and shown in Figure 8.

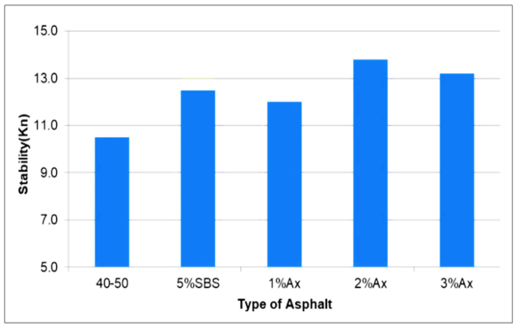

Figure 8. The relationship between the type of asphalt and stability (kN)

3.1.3 Indirect tensile strength (ITS) test

The ITS was evaluated to determine the fatigue cracking resistance of the mixtures. In this test, the samples were subjected to a consistent deformation rate of 50 mm/min by vertical ram movement. Loading persisted until the specimens experienced failure, while the maximum load was monitored and recorded throughout the process [15, 27]. The ITS was calculated using the following equation:

$$\mathrm{ITS} = (2\,P)/(\pi\,D\,\mathrm{t}) \qquad (2)$$

where,

P represents the peak load, expressed in kN.

D denotes the diameter of the specimen, measured in cm.

t refers to the thickness of the specimen, measured in cm.

The ITS values of the five mixes were calculated using Eq. (2), which are presented in Table 7. Figures 9 and 10 show the results of laboratory testing.

Table 7. The value of compressive strength

Type of Asphalt	40\50	5% SBS	1% Ax	2% Ax	3% Ax
Compressive (kN)	12.8	14.4	13.5	15.1	14.1
Compressive (mPa)	1.63	1.83	1.72	1.92	1.82

3.2 Results presentation and discussion

Tables 6 to 8 and Figures 5 to 9 indicated that the performance of mixtures prepared with polymer modified better than those of mixtures prepared without polymer, this fact is because the viscosity of the asphalt plays a significant effect on shear and compressive strength. Duggi [27] and Wayne et al. [28] also reported that binder with high viscosity has higher indirect tensile strength value. As well as it has been noticed that the mix that was modified with the polymer Reactive Ethylene-Butyl Acrylate-Glycidyl Methacrylate (Ax) with a percentile of 2% gives the maximum stability (13.7 kN) as shown in Figure 8 and Table 6, maximum compressive strength (15.1 kN) as shown in Figure 5 and Table 7, and highest comparison of the indirect tensile strength (12.8 kN) compared with other mixes then mixture prepared with the polymer styrene-butadiene-styrene (SBS) with a percentile of 5% as shown in Figure 9 and Table 8. Singh [29] reported that mixes prepared with (5% SBS) polymer has better than those of mixtures prepared without modified bitumen. At the same time, the ITS test for modified and unmodified asphalt concrete mixtures is calculated based on Eq. (2) and presented in Figures 9 and 10. It can be seen that the ITS of the mixture modified with 3% Ax has a higher value when compared with other mixes. From these values, we concluded that the improvement of asphalt mixtures in terms of compaction and stability in the case of using the (Ax) additive is better than the (SBS) additive. This is due to the difference in the physical properties of both additives, which are shown in Tables 3 and 4. Figures 11 to 16 show the relations between the asphalt types and the Marshall stability, compressive strength, and ITS.

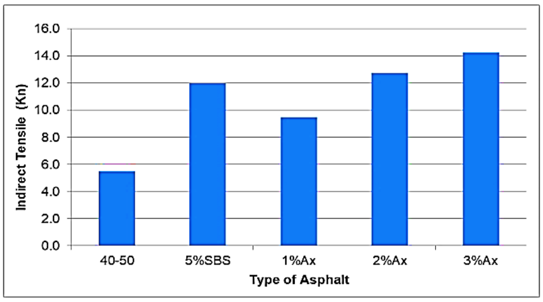

Figure 9. The relationship between the type of asphalt and indirect tensile (kN)

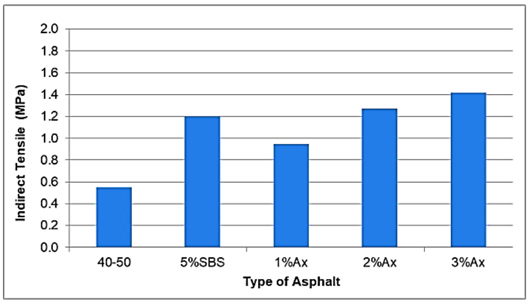

Figure 10. The relationship between the type of asphalt and indirect tensile strength (mPa)

Table 8. The value indirect tensile strength test

Type of Asphalt	40\50	5% SBS	1% Ax	2% Ax	3% Ax
Indirect Tensile (kN)	5.5	12	9.5	12.8	14.3
Indirect Tensile Strength (mPa)	0.55	1.2	0.95	1.27	1.42

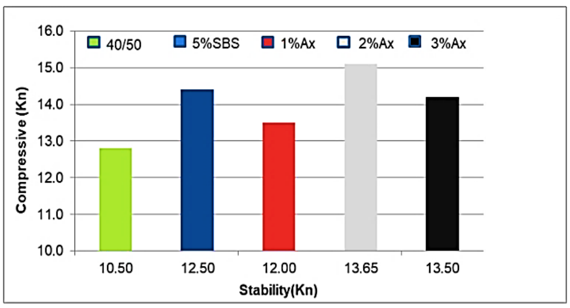

Figure 11. The relationship between compressive (kN) and Marshall stability (kN) for each type of asphalt

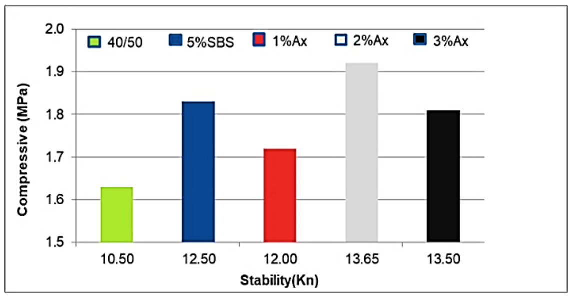

Figure 12. The relationship between compressive (mPa) and Marshall stability (kN) for each type of asphalt

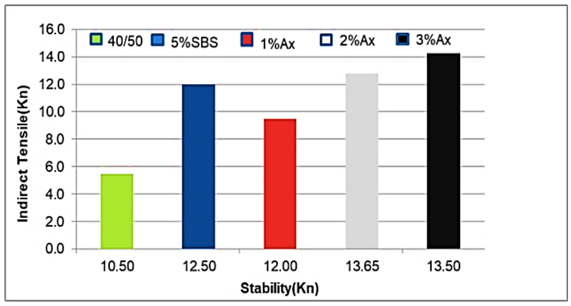

Figure 13. The relationship between indirect tensile (kN) and Marshall stability (kN) each of type of asphalt

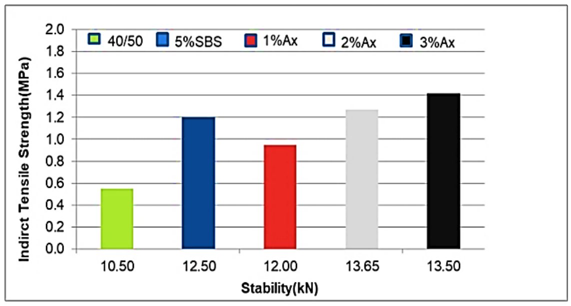

Figure 14. The relationship between indirect tensile strength (mPa) and Marshall stability (kN) for each type of asphalt

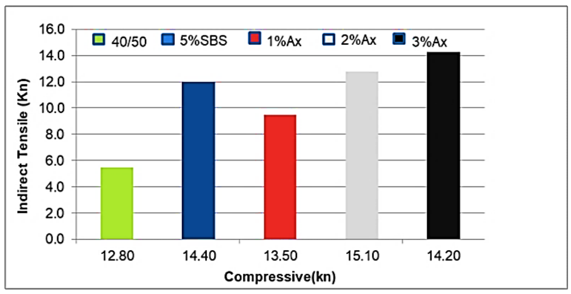

Figure 15. The relationship between indirect tensile (kN) and compressive (kN) and for each type of asphalt

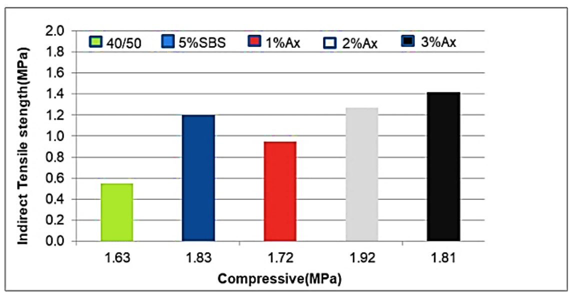

Figure 16. The relationship between indirect tensile (mPa) and compressive (mPa) for each type of asphalt

3.3 Empirical relationships

Figures 11 and 12 present the relationships between Marshall stability and compressive strength for each type of asphalt. The mixture modified with 2% Ax showed the highest values. The 3% Ax mixture showed the highest values for the relationship between Marshall stability and ITS and the relationship between compressive strength and ITS, as illustrated in Figures 13 to 16.

Figures 17 and 18 show the plots obtained for the stability test at 60℃, ITS at 25℃, and compressive strength. The findings reveal a strong correlation between stability, ITS, and compressive strength. As stability and ITS rise, compressive strength also increases. The following relationships were revealed.

$$CS=-0.01(S)^2+0.8511(S)+4.9496, (R^2 = 0.81) \quad (3)$$

$$CS=-0.0205(ITS)^2+0.6118(ITS)+9.9543, (R^2 = 0.74) \quad (4)$$

where, CS is compressive strength in kN at 25℃, S is stability in kN at 60℃, and ITS is indirect tensile strength in kN at 25℃. The empirical relations in Eqs. (3)-(4) are relatively accurate, as indicated by the high value of R^2. These relations can be used to predict compressive strength in a mix based on stability and ITS data without actually doing the compressive strength test. Additionally, the correlation between compressive strength and stability is more accurate compared with the correlation between compressive strength and ITS.

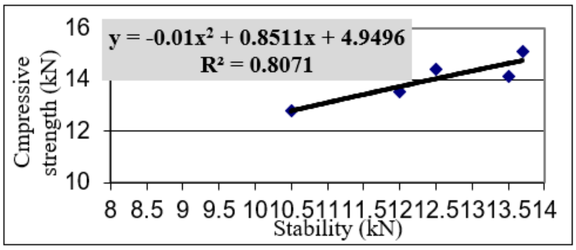

Figure 17. The relationship between stability and compressive strength

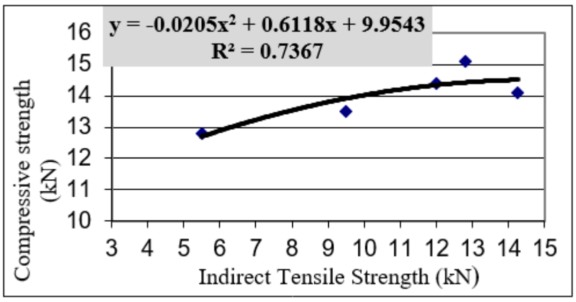

Figure 18. The relationship between indirect tensile and compressive strength

4. CONCLUSIONS AND RECOMMENDATIONS

This study aimed to evaluate the compressive strength of modified asphalt mixtures utilizing polymer additives. The impact on the properties of hot mix asphalt by adding two different polymers was investigated. Specifically, the Marshall stability, ITS, and compressive strength of each sample were experimentally determined. The addition of modifiers to pure bitumen improves its characteristics, enabling evaluation of the asphalt mixtures depending on their compressive strength, and ultimately, revealing a relationship between the compressive strength and Marshall stability. From the results and analysis, the following conclusions were determined:

a) The stability, ITS, and compressive strength values for 1% Ax, 2% Ax, 3% Ax, and 5% SBS-modified asphalt concrete mixtures were higher than the values for unmodified asphalt concrete mixtures.
b) The mix prepared with 2% Ax showed higher stability and compressive strength than other mixes but the mix prepared with 3% Ax showed higher indirect tensile strength than other mixes.
c) The empirical relations can be used to predict compressive strength in a mix based on stability and ITS data without physically performing the compressive strength test.
d) According to this study and other researches, Polymer-modified asphalt binders are a significant effect on improved rheological properties of asphalt, such as increased stiffness, reduced deformation, and enhanced durability then reduced cost of maintenance.
e) It is recommended to study the effect of the long-term performance of modified asphalt mixtures on this type of model.
f) The models developed in this study at 25℃ for surface layer aggregate gradation, it is recommended to compare these models with other models at different temperatures and different aggregate gradations.

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REFERENCES

[1] Firdaus, C.M., Wihardi, T., Muhammad, R., Johannes, P. (2016). Compressive strength of permeable asphalt pavement using domato stone (Quarzite Dolomite) and Buton Natural Asphalt (BNA) blend. International National of Engineering and Technology, 8(3): 183. https://doi.org/10.7763/IJET.2016.V6.881

[2] Gaus, A., Tjaronge, M.W., Ali, N., Djamaluddin, R. (2015). Compressive strength of asphalt concrete binder course (AC-BC) mixture using Buton granular asphalt (BGA). Procedia Engineering, 125: 657-662. https://doi.org/10.1016/j.proeng.2015.11.097

[3] Arabani, M., Mirabdolazimi, S.M., Sasani, A.R. (2010). The effect of waste tire thread mesh on the dynamic behavior of asphalt mixtures. Construction and Building Materials, 24: 1060-1068. https://doi.org/10.1016/j.conbuildmat.2009.11.011

[4] Roberts, F.L., Mohammad, L.N., Wang, L.B. (2002). History of hot mix asphalt mixture design in the United States. Journal of Materials in Civil Engineering, 14(4): 279. https://doi.org/10.1061/(ASCE)08991561(2002)14:4(279)

[5] Singhal, M., Yadav, Y., Mandal, R. (2016). Use of

modified bitumen in highway construction. International Journal for Innovative Research in Science & Technology, 2(12): 376-382.
[6] Merriam-Webster. (2021). Polymer. https://www.merriam-webster.com/dictionary/polymer.
[7] Torjoman. (2021). Polymers. https://www.torjoman.com.
[8] Merriam-Webster. (2021). Polymerization. https://www.merriam-webster.com/dictionary/polymerization.
[9] Byjus. (2021). Polymers, Types, Classification, Properties, and Uses of Polymers. https://www.byjus.com/.
[10] Geng, J., Li, H., Sheng, Y. (2014). Changing regularity of SBS in the aging process of polymer modified asphalt binder based on GPC analysis. International Journal of Pavement Research & Technology, 7(1): 77-82. https://doi.org/10.6135/ijprt.org.tw/2014.7(1).77
[11] Ghuzlan, K. A., Al Assi, M. O. (2016). Predicting the complex modulus for PAV aged asphalt binder using a master curve approach for Sasobit modified asphalt binder. Jordan Journal of Civil Engineering, 10(3): 390-402.
[12] Nega, A., Ghadimi, B., Nikraz, H. (2014). Developing master curves, binder viscosity and predicting dynamic modulus of polymer-modified asphalt mixtures. International Journal of Engineering and Technology, 7(3): 190-197. https:///doi.org/10.7763/IJET.2015.V7.790
[13] Ji, J., Yao, H., Zheng, W., et al. (2017). Preparation and properties of asphalt binders modified by THFS extracted from direct coal liquefaction residue. Applied Sciences, 7(11): 1155. https://doi.org/10.3390/app7111155
[14] Mazumder, M., Kim, H., Lee, S. (2016). Performance properties of polymer-modified asphalt binders containing wax additives. International Journal of Pavement Research and Technology, 9(2): 128-139. https://doi.org/10.1016/j.ijprt.2016.03.004
[15] Safaa, M., Farag, Kh., Ayman, O. (2017). Evaluation of mechanical properties for polypropylene modified asphalt. International Journal of Scientific Research and Management, 5(12): 7797-7801. https://doi.org/10.18535/ijsrm/v5i12.28
[16] McNally, T. (2001). Polymer Modified Bitumen: Properties and Characterization. Woodhead Publishing.
[17] Zhu, J., Birgisson, B., Kringos, N. (2014). Polymer modification of bitumen: Advances and challenges. European Polymer Journal, 54: 18-38. https://doi.org/10.1016/j.eurpolymj.2014.02.005
[18] Dinnen, A. (1985). Bitumen-thermoplastic rubber blends in road applications. In Proceedings of 3rd Eurobitume Symposium, pp. 646-651.
[19] Singh, M. (2014). Strength Characteristics of Modified Bitumen with Various Aggregates (Unpublished doctoral dissertation). Civil Engineering Department, IIT Roorkee, Roorkee, India.
[20] Mokhtari, A., Nejad, F.M. (2012). Mechanistic approach for fiber and polymer modified SMA mixtures. Construction and Building Materials, 36: 381-390. https://doi.org/10.1016/j.conbuildmat.2012.05.032
[21] Yildirim, Y. (2007). Polymer modified asphalt binders. Construction and Building Materials, 21(1): 66-72. https://doi.org/10.1016/j.conbuildmat.2005.07.007
[22] Kok, B.V., Yilmaz, M. (2009). The effects of using lime and styrene-butadiene-styrene on moisture sensitivity resistance of hot mix asphalt. Construction and Building Materials, 23(5): 1999-2006. https://doi.org/10.1016/j.conbuildmat.2008.08.019
[23] ASTM. (2002). D-1074 – 02, Standard Test Method for Compressive Strength of Bituminous Mixture.
[24] ASTM. (2006). D-6927, Resistance to Plastic Flow of Bituminous Mixtures Using Marshall Apparatus, American Society of Testing and Materials.
[25] Hozayen, H., Othman, A. (2008). Improving mechanical properties of asphalt concrete mixtures using thermoplastic polymer additives. In Gulf Conference on Transportation, Dubai, UAE.
[26] AASHTO. (2005). AASHTO designation: T322, Determining the Creep Compliance and Strength of Hot-Mix Asphalt (HMA) Using the Indirect Tensile Device, The American Association of State Highway and Transportation Officials, Washington, D. C., US.
[27] Duggi, S.V.K. (2010). Cracking and rutting characteristics of bituminous concrete mixes. Doctoral dissertation. Civil Engineering. IIT Kharagpur, India.
[28] Wayne, L.K., Gundapuneni, S.K., Singh, A. (2010). Effects of Asphalt binder grade on the performance of Rhode Island hot-mix asphalt. College of Engineering, University of Rhode Island.
[29] Singh, M. (2013). Study on subbase materials for rural road. Doctoral dissertation. Civil Engineering. IIT Roorkee, Roorkee, India.