Direct Tensile Test Evaluation and Characterization for Mechanical and Rheological Properties of Polymer Modified Hot Mix Asphalt Concrete

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Abstract

Using polymer to modify asphalt binder for better performance has become popular in pavement engineering, for which to evaluate the effect of polymer addition on the properties of the asphalt concrete is essential for mix design. Conventional mechanical test methods, primarily using bending of beams and indirect splitting, are not only materially and timely costly and labor intensive but also provide no direct information for the viscoelastic and rheological characteristics of the materials. This paper reports a study using direct tensile test (DTT) to evaluate the effect of polymer on both mechanical and rheological properties of modified asphalt concrete. Two types of polymers, which are Styrene-Butadiene-Styrene (SBS), and a mixture of SBS and Polyvinyl Chloride (PVC), were investigated on two mixes using fine and coarse aggregates, respectively. It has been found that SBS generates improvement for both mechanical and rheological properties of hot mix asphalt concrete. However, using a hybrid mixture of SBS and PVC shows that PVC can further improve the mechanical properties, but deteriorate the toughness of the asphalt concrete. At the end, a simple quadric polynomial model has been proposed to characterize the combined SBS and PVC effects for the sake of the guidance for mix design.

Keywords: Asphalt concrete, Polymer modification, Direct tensile test, Tensile toughness

1. Introduction

Hot mix asphalt (HMA) concrete, in general, is composed of asphalt binders, aggregates, and air voids, in which the aggregates amount up to 90-96% of total weight [1,2]. The tensile strength of HMA concrete plays a critical role deciding the performance of the asphalt concrete and constructed pavement when exposed to prevailing traffic and environmental conditions [3,4]. Improving the material properties of asphalt mixes has been a constant effort, in both pavement construction and repair, to elongate the life span of roads, which consequently helps to reduce the cost of pavement maintenance [5].

Asphalt binder modification using polymer and asphalt concrete mixture modification using mineral additive are two effective techniques popularly adopted in engineering practice and under intensive research. Adding polymer into asphalt binder was found not only enhanced the mechanical property and durability of the binder itself but also improved its binding strength with the mineral aggregates of concrete [6]. However, it was found that concrete mixes using Styrene-Butadiene-Styrene (SBS) modified asphalt have much higher optimum binder ratio than conventional mixes [7,8].

In addition to mechanical strength, the rheological characteristics of asphalt concrete also plays a critical role in the material performance to resist the deterioration of pavement in the conventional forms of rutting and cracking. Rheological characteristics decides the initiating, developing, and propagating of the distresses under the prolonged repetitive traffic loading, seasonal and daily cyclic thermal variation of environment and the aging of the material itself [9,10]. Cheng et al [11] studied the rheological properties of asphalt modified using waste polyethylene (WPE) and SBS as well as the morphology of their concrete mix. They found that penetration and softening points were increased with the rise of WPE/SBS percentage, but meanwhile ductility decreased. To enhance the ductility, they added in nano limestone dust (CaCO3) and obtained improvement. Zhang and Hu [12] studied a high viscosity modified (HVM) asphalt adding in SBS, plasticizer, and crosslinker. Examined rheological properties of modified asphalt, they found that plasticizer decreased the rutting resistance of the asphalt but accelerated the aging degradation of SBS while the crosslinker increased the aging resistance. Zhang and Hu [13] also studied the physical and rheological properties of asphalt modified using SBS and sulfur, and found that the addition of SBS and sulfur led to a thorough net-form polymer linkage, which upgraded the physical and rheological characteristics of modified asphalt under aging.

Direct evaluation and analysis of the asphalt rheological effects and mechanism contributing to the distresses are always a challenge [14] and of topical interest in asphalt concrete research [15,16,17]. Indirect tensile splitting approach is popularly adopted in pavement engineering to evaluate the crack resistance of asphalt concrete. NCHRP 9-57 project [18,19] reviewed various test approaches, they are semicircular bending test [20]; semicircular bending (Louisiana Transportation Research Centre); semicircular bending-Illinois; indirect tensile strength-CST; overlay test (OTR); bending beam fatigue test (BBF); and IDEAL cracking test. These methods are applicable for both field and laboratory tests. However, their results give out less direct information to quantify the rheological characteristics of tested materials. Compared with these methods, direct tensile test (DTT) is straighter forward, which is able to provide direct information for both the cracking resistance/tensile strength and rheological attributes. DTT is directly to apply an uniaxial tensile force on a material sample to obtain the stress-strain curve of the material, on which the basic principle properties of materials, such as tensile strength and maximal deformation/elongation, can be directly obtained [21,22], on which the viscoelastic behaviour will be easily worked out [23].

DTT in general uses a rectangular or dog bone shape sample to deliver an evenly distributed stress over the cross-section in the middle part of the sample. Align the sample's central axis in the line of the applied tensile force is also important to prevent a source of errors due to bending or twisting. DTT method has been successfully adopted to assess the performance of dense and open-graded mixes of asphalt [24], and the stiffness gradient of aged mixes of pavement from the field in terms of the measured frequency of oscillation. The objective of this work is to use the DTT method to characterize the crack resistance and rheological properties of polymer modified bituminous mixtures. It aims to find a correlation between the maximum absorbed energy and the stiffness of mix, the information employed in practice at the mix design stage for decision criteria. A novel method to evaluate and characterize the rheological property based on mechanical energy using the data from DTT has been adopted in this study.

2. Materials and Experiment

- **Materials properties and sample preparation**

A control mix using a normal asphalt was designed to have a binder content of 4.8% by total weight of mix, which was determined following the Superpave Gyratory compactor analysis, and certain void content of 4%. Figure 1 shows the gradation of the aggregates used. Other mixes were a modification on the control one. Two types of polymers were used and added into the control mix at different percentages. One is styrene-butadiene-styrene (SBS) only, which was added in by a percentage of 4, 6, and 8% of the weight of the asphalt binder, respectively. The other one is a mixture of SBS and polyvinyl chloride (PVC), which consists of 4% SBS and 1, 2, and 3% PVC, respectively, by the weight of asphalt binder. Tables 1 and 2 gives out the measured rheological properties of the control and modified binders.

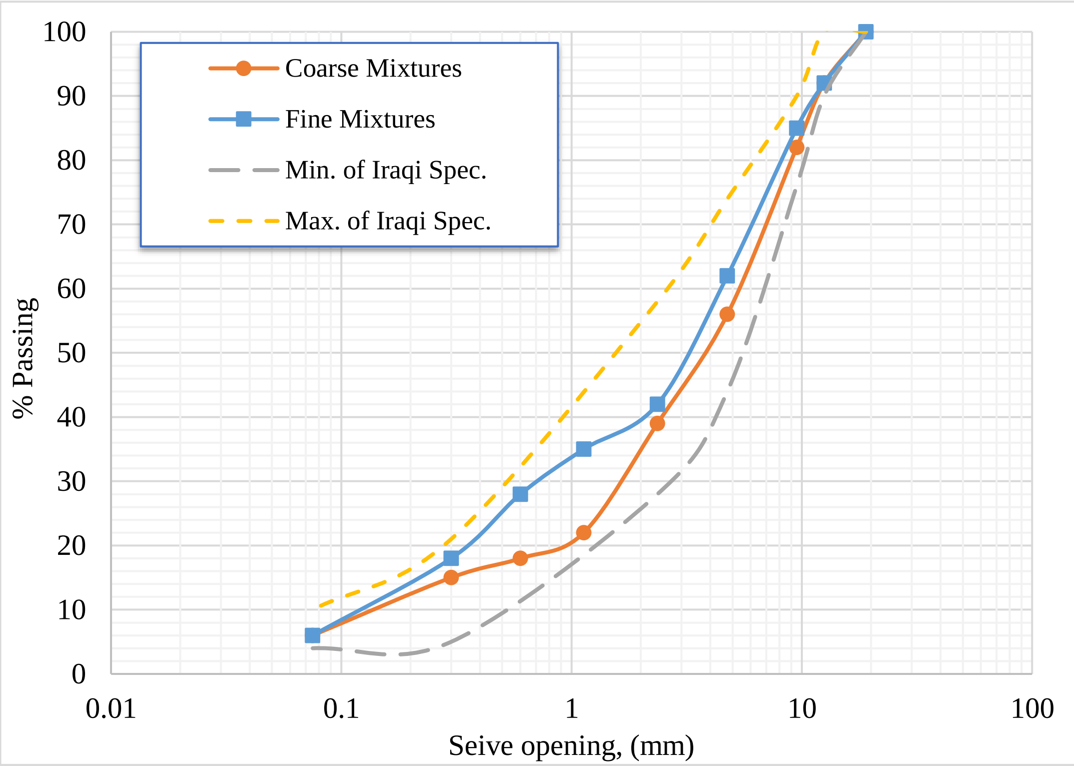

Figure 1 Selected Gradation of Combined Aggregate and Mineral Filler

The ready mixes were made into plate samples of a rectangular shape for the DTT. The dimensions of the samples are 40mm in length, 20mm in width, and 6mm in thickness. The two ends of the samples were firmly attached using epoxy with two composite heads as shown in Figure 2, which were used for the gripping of the DTT machine.

Table 1 Rheological Properties for Neat and Modified Binders

Type of Asphalt	AASHTO Designation	Control		4%SBS		6%SBS		8%SBS	
Ageing		Original		Original		Original		Original	
R.V @135 ^{O}C	TP 48	0.462		1.182		2.148		3.759	
R.V @165 ^{O}C	TP 48	0.112		0.286		0.523		0.71	
G^*/sin δ(kPa)	TP 5	@70 ^{O}C	1.73	@82 ^{O}C	1.13	@88 ^{O}C	0.86	@88 ^{O}C	1.18
Ageing		RTFO		RTFO		RTFO		RTFO	
G* /sin δ(kPa)	TP 5	@70 ^{O}C	1.92	@82 ^{O}C	1.96	@88 ^{O}C	1.54	@88 ^{O}C	2.42
Loss (%)		<1		<1		<1		<1	
Ageing		PAV		PAV		PAV		PAV	
G*. sin δ(kPa)	TP 5	@28^{O}C	4735	@28^{O}C	4782	@28^{O}C	4120	@28^{O}C	3894
Creep Stiffness (MPa)	T313	@-22^{O}C	438	@-22^{O}C	456	@-22^{O}C	478	@-22^{O}C	510
Slop m-value		@-22^{O}C	0.289	@-22^{O}C	0.269	@-22^{O}C	0.278	@-22^{O}C	0.262

Table 2 Rheological Properties of Hybrid Modified Binder

Type of asphalt	**AASHTO Designation**	**4%SBS+1%PVC**		**4%SBS+2%PVC**		**4%SBS+3%PVC**	
Ageing		**Original**		**Original**		**Original**	
R.V @135 ^{O}C	TP48	1.446		2.164		2.980	
R.V @165 ^{O}C	TP48	0.362		0.427		0.76	
G^{*} /sin δ	TP 5	@82 ^{O}C	1.12	@88 OC	2.32	@88 ^{O}C	3.32
Ageing		**RTFO**		**RTFO**		**RTFO**	
G* /sin δ	TP 5	@82 ^{O}C	2.34	@88 ^{O}C	3.68	@88 ^{O}C	4.32
Loss (%)		<1		<1		<1	
Ageing		**PAV**		**PAV**		**PAV**	
G*. sin δ	TP 5	@28^{O}C	4758	@28^{O}C	4685	@28^{O}C	4325
Creep Stiffness (MPa)	T313	@-22^{O}C	460	@-22^{O}C	524	@-22^{O}C	576
Slop m-value		@-22^{O}C	0.287	@-22^{O}C	0.293	@-22^{O}C	0.287

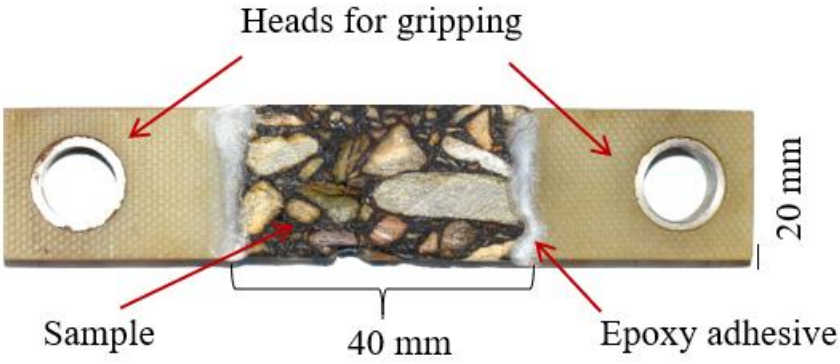

Figure 2. Sample for DTT

- **Experimental test**

All tests were performed on the INTERLAKEN Direct Tension tester (Fig. 3) under the temperature of 25^{o}C. The tensile deformation (elongation) rate was controlled at 1.01 mm/min, given the tensile force applied was controlled in the range of 40~1000N under a relax load 2N until samples broke away. Figure 4 shows a broken sample after the test.

Figure 3. DTT equipment

Figure 4. A sample after test

3. Results

- **The measurement of the stress-strain curve**

Figure 5 shows the DTT results of the SBS modified mixes and the control mix. It can be seen that there is a positive correlation between the ultimate tensile strength and the SBS addition. Meanwhile, a significant increase of the stiffness, the initial linear elastic modulus, can be noticed at the SBS contents of 6 and 8%.

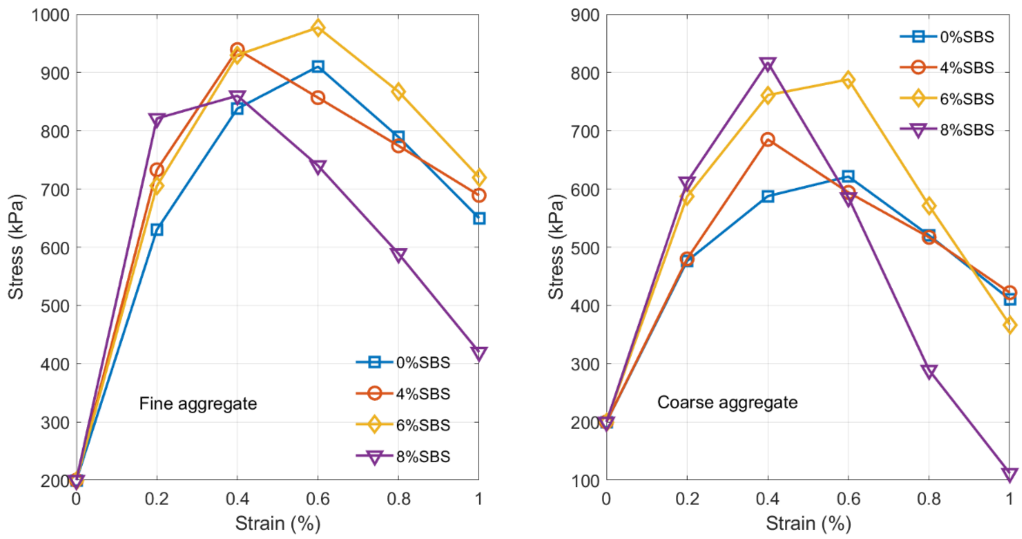

Figure 5. DTT result of the SBS modified mixtures

Figure 6 compares the DTT results of the mixes modified using the polymer mixtures of SBS and PVC. It can be seen that both ultimate tensile strength and modulus display a positive correlation with the PVC addition. A projected increment can be particularly noticed when PVC content increses from 1% to 2%.

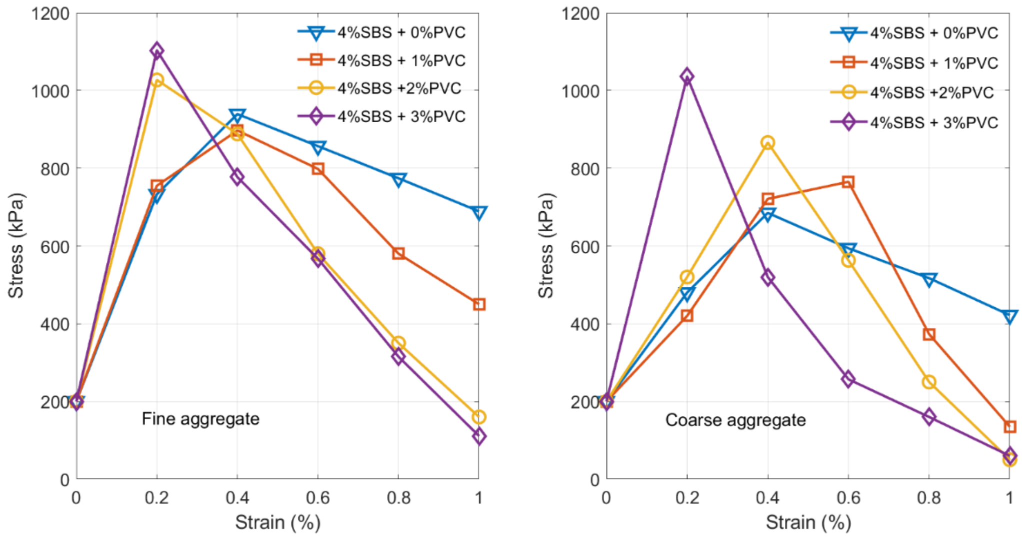

Figure 6. The DTT result of the hybrid-polymer modified mixtures

Figure 7 compares the ultimate tensile strength (UTS) of all mixes. It can be seen that the plastomer, PVC, presents a more active effect than the elastomer, SBS, because the slope of the tensile strength vs PVC percentage is more than double of that vs SBS percentage. The other advantage of plastomers is their thermal deformation resistance compared with the elastomers. The high stiffness of SBS at low temperature will make its modified asphalt mixes prone to cracking. Fig. 7 also shows that polymer effect is more pronounced on the coarse aggregate concrete. The UTS displaces a positive correlation with the SBS and PVC content on coarse aggregate concrete. Howevre, for fine aggregate concrete, 6% SBS generates an optimum tensile strength.

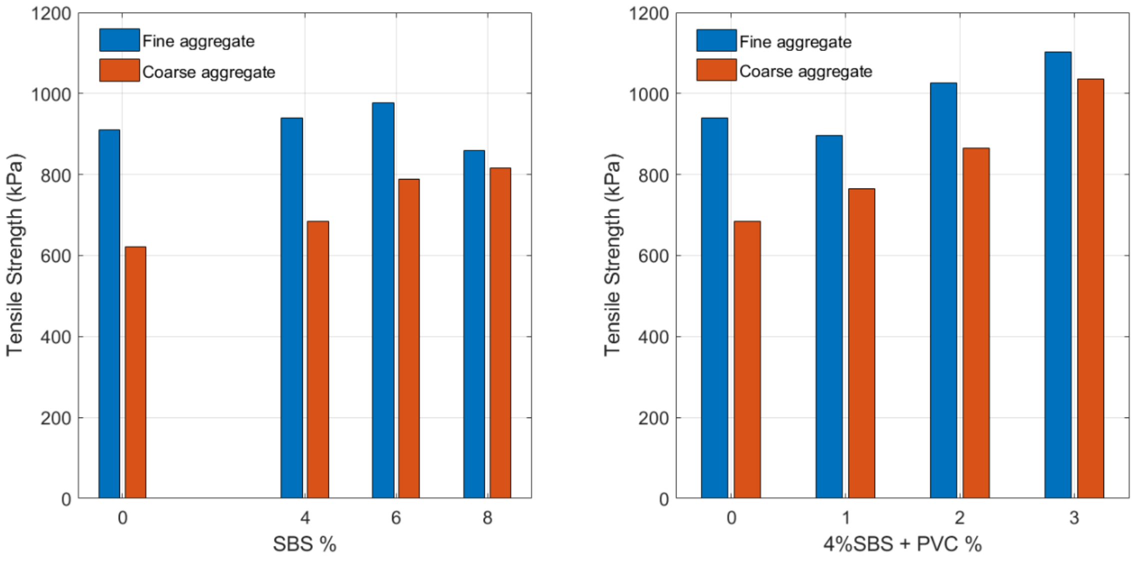

Figure 7. Polymer effect on direct tensile strength

Figure 8 shows the approximately estimated resilient modulus which simply takes the slope of 1st piece of line of the piecewise measurement curves in Figs. 5 and 6. It can be seen that both SBS and PVC demonstrate a positive correlation with the resilient modulus of the concrete, for which the effect of PVC is more pronounced on the fine aggregate concrete.

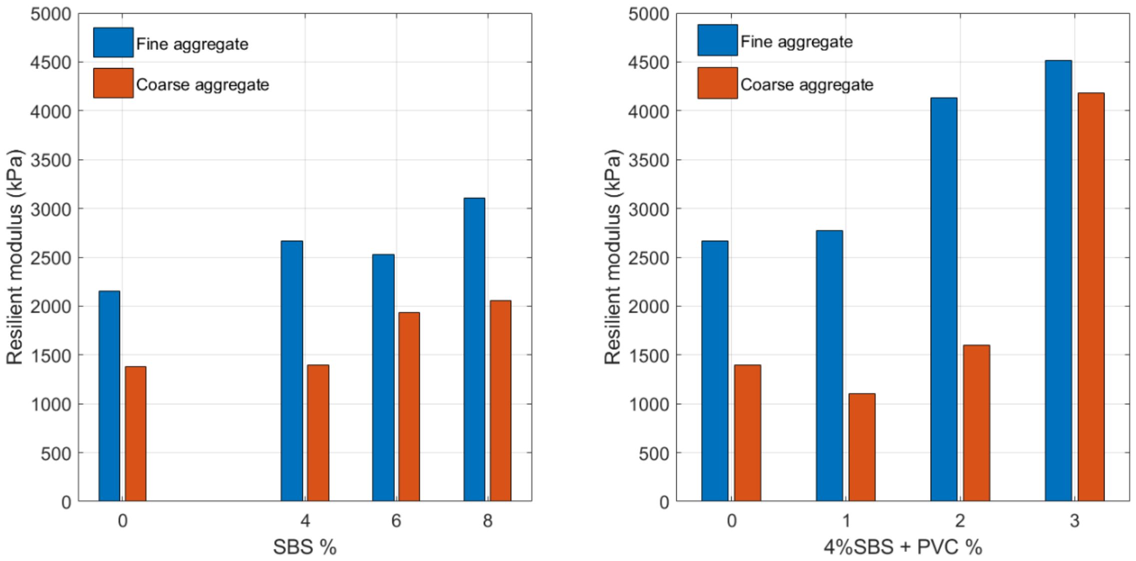

Figure 8. Polymer effect on resilient modulus

- **Toughness**

To obtain the optimum polymer mixture for asphalt concrete, in addition to the tensile strength and modulus, the further evaluation is needed for its rheological properties. As a parameter directly related to material rheological characteristics, tensile toughness is a property quantifying the energy absorbing capacity of a material undergoing plastic deformation before fracturing. It is defined as the absorbed or consumed energy per unit volume of a material before breaks up. The total energy consists of that absorbed by both elastic deformation and plastic deformation, which stands the surface area under the stress-strain curve measured directly by DTT. So the toughness can be estimated in term of the integration below:

$$E_t = \int_0^{\varepsilon_f} \sigma \times d\varepsilon \qquad \text{Eq. (1),}$$

where, E_t stands for the toughness (Jm^{-3}), σ is the stress applied (kPa) and ε is the corresponding strain, ε_f is the maximum strain measured before samples start to break. In this study, the ε_f is taken to be 1%, a value recommended by the reference [25] for deformation measurement using contact strain gauge. Owing to the low strain of asphalt concrete, failure is defined at around 1.0 per cent strain. In addition, a non-contact laser technology for strain measurement adopted by the testing machine provides more accuracy than conventional contact strain gauge. The latter could generate significant error when failure strains are lower than 3 percent.

Figure 9 shows calculated toughness according to the results in Figs. 5 and 6, which simply takes the area under each continuous piecewise curve, respectively. It can be seen that the SBS has a beneficial effect on the toughness of the modified mixes before reach a content of 6%, while PVC deteriorates toughness of mix in a linear correlation.

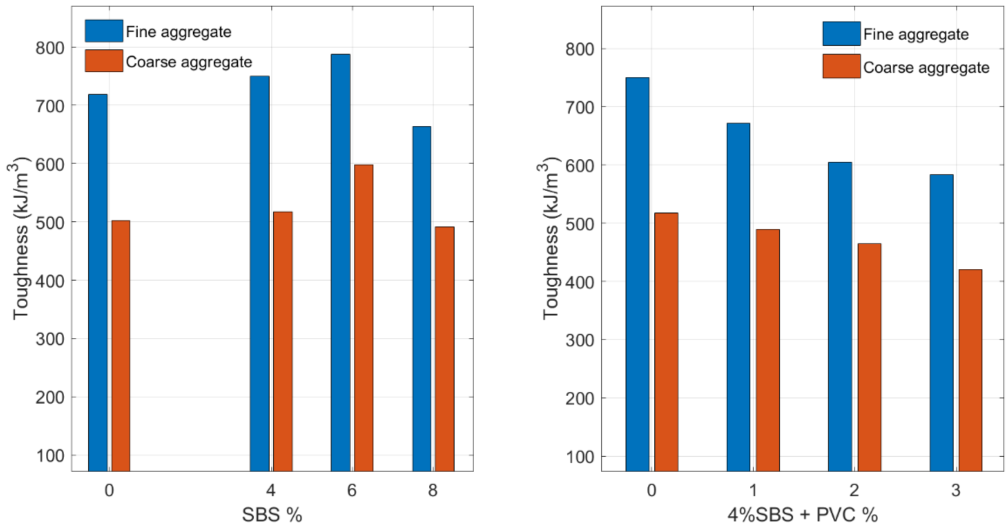

Figure 9. Polymer effect on the toughness of mixes

Figure 10 presents a characterization of the combined effect of the SBS and PVC mixture, using a quadradic polynomial surface function, Eq. (2), on the toughness, tensile strength and resilient modulus of modified asphalt concrete. The characterization model can be provide a guiding tool for the mix design for different targeted applications. Table 3 lists out the fitting parameters' value.

$$\boldsymbol{Z = c_0 + a_1 x + b_1 y + cxy + a_2 x^2 + b_2 y^2} \quad (2),$$

where Z stands for the concrete properties, toughness, tensile strength and resilient modulus, x stands the SBS content (%) and y stands PVC content (%).

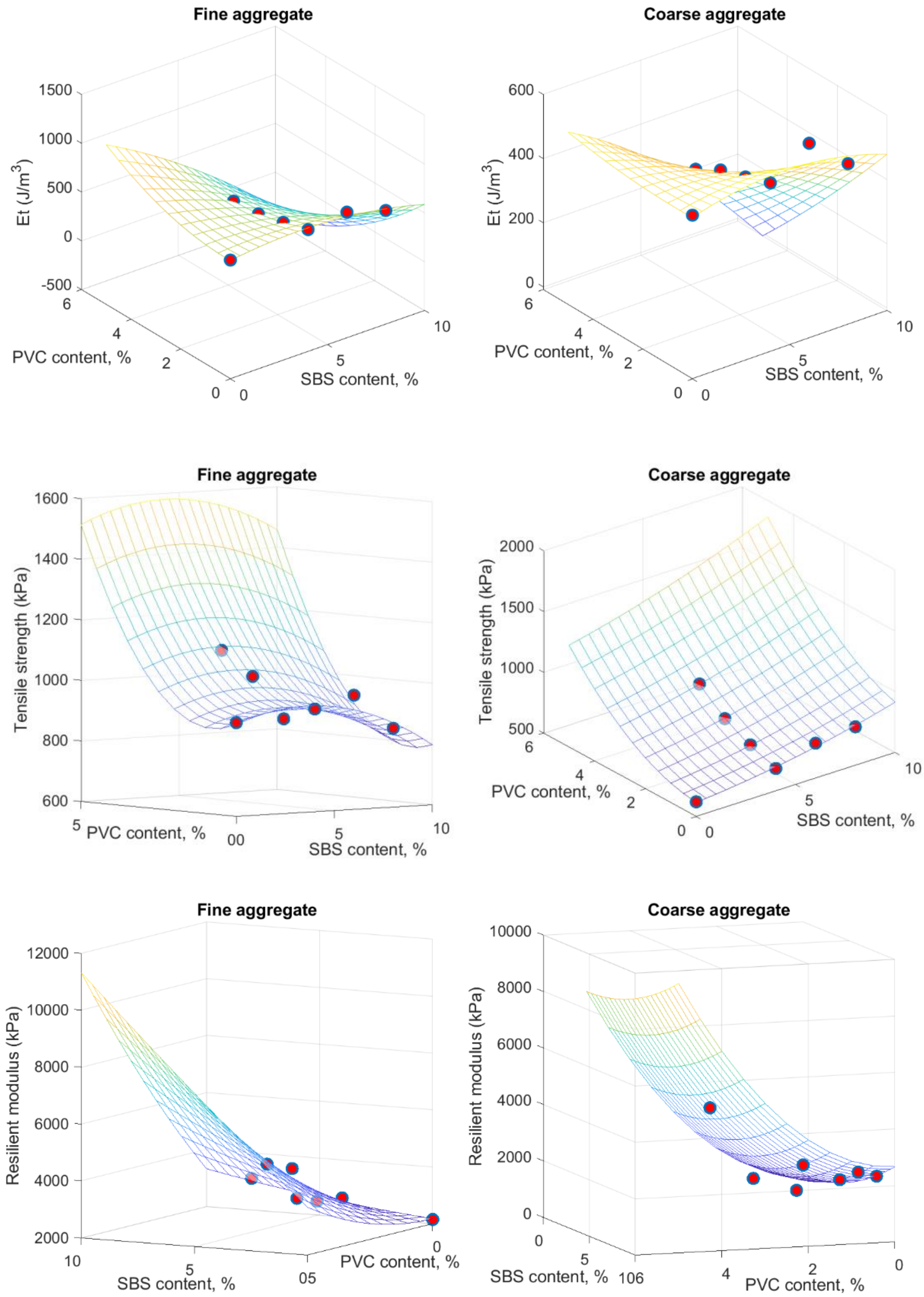

Figure. 10. 3D characterization of the polymer effects

Table 3. The fitting Parameter Data of the Eq. (2)

Property	Aggregate	c_0	a_1	b_1	c	a_2	b_2

Toughness	Fine	712.6	30.88	-6.839	-4.347	-27.36	18.33
	Coarse	494.3	19.6	-2.606	-2.122	-10.42	1.901
Tensile strength	Fine	904	26.41	-55.3	-3.708	0.9997	35.45
	Coarse	617.4	13.52	18.5	1.614	4.626	25.09
Resilient modulus	Fine	2178	67.45	1.582	4.712	129.8	59.93
	Coarse	1034	6.592e-12	5.781e-12	16.28	1.145e-12	275.5

5. Conclusions

Direct tensile test provides a straight and effective approach for the assessment of the mechanical and rheological properties of asphalt concrete. It has been found that polymer SBS will improve both the stiffness and the tensile strength of hot mix asphalt concrete. A general positive correlation exists between the SBS addition and the tensile strenagth and resilient modulus of modified coarse aggregate HMA concrete, but 6% SBS mix shows the best rheological behaviours given the highest energy absorption. For fine aggregate HMA concrete, 6% SBS presents an optimum tensile strength. A hybrid polymer mixture of SBS and PVC can generate a better improvement for the stiffness and tensile strength than SBS only. However, the PVC addition deteriorates the toughness of the modified asphalt concrete. A quadratic polynomial model is suggested to characterise the dual polymer system effect on both mechanical and reheological peroerties of modified HMA concrete. The modelling result provides a guidance for optimum polymer mixture design for asphalt modification to meet different application conditions and requirements.

Data Availability Statement

All experimental data reported in the paper are availabe by requirement.

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