How to characterize the mechanical response of Bitumen Stabilized Material?

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ABSTRACT: Material characterization and design of pavement structures with Bitumen Stabilized Material (BSM) within the context of cold in-place recycling are challenging. Diverse opinion exists related to the mechanical behavior of BSM. Few investigators have characterized BSM as granular and measured the confinement pressure dependent resilient modulus, whereas few others have characterized this material as bituminous and measured the frequency dependent dynamic modulus. It is interesting to note that BSM can exhibit both these responses depending on the mode of testing and the environmental conditions.

In this investigation, the BSM sample was subjected to resilient modulus test and dynamic modulus test at room temperature. When compared with a regular base course granular material, considerable disparity existed. The resilient modulus of BSM was found to decrease during the sequences where confinement was increased. During dynamic modulus testing, BSM exhibited similar frequency dependent characteristics when compared to a standard dense graded bituminous mixture.

1 INTRODUCTION

Cold In-place Recycling (CIR) is a method in which deteriorated pavement materials are recycled in-situ with either foamed bitumen or emulsion to produce a new stabilized base course for road rehabilitation. This technology has gained importance in the recent years due to their environmental friendly nature in terms of energy savings and maximum use of milled material. Reclaimed Asphalt Pavement (RAP) is obtained by cold milling or heating and removal of pavement layer up to a depth where the distress has transferred or from full depth removal of asphalt pavements. RAP materials treated with foamed bitumen are called as Bitumen Stabilized Material (BSM) (Asphalt Academy, 2009). BSM mixture consists of pulverized RAP material, fresh aggregates depending on the target gradation, foamed bitumen and active filler. Water is added to the pulverized material to ensure proper dispersion of foamed bitumen. Active fillers are also added to provide the initial strength to the mix and also to modify the fine fraction of aggregate gradation (Halles and Thenoux, 2009).

From the point of view of mechanical characterization in the mechanistic-empirical pavement design framework, it should be understood that the material can show a behavior similar to granular material or bituminous material. This study aims to explore the material behavior exhibited by BSM. If we consider a pavement cross section which has to be rehabilitated as shown in Figure 1, the BSM can be laid as base/binder course, after milling the pavement layers up to a depth to which the distress has permeated. The behavior of BSM mixes can be in between that of a bituminous mix and granular material (Jenkins et al., 2007). Hence when a pavement is rehabilitated with BSM layer, it is not very clear the kind of 'modulus' values to be used to carry out the design and evaluate the performance.

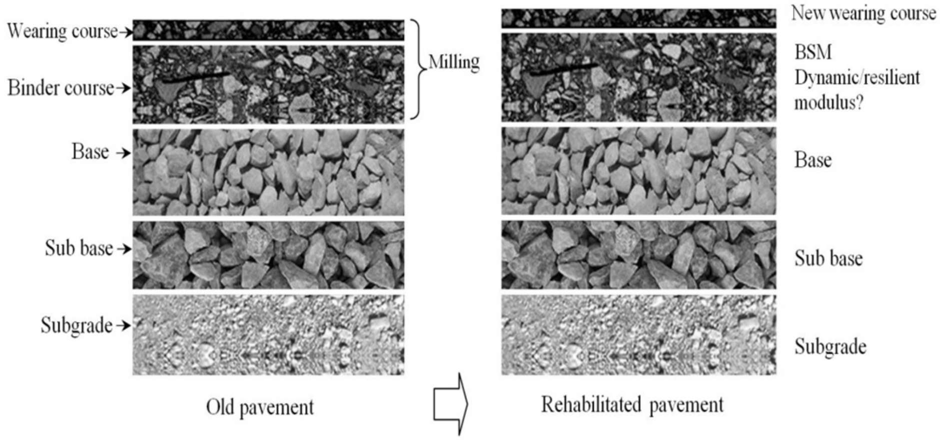


Figure 1. Cross section of a pavement (M-E PDG, 2004)

Huan et al. (2010) treated BSM as a granular material and carried out resilient modulus and unconfined compressive strength test. Khosravifar et al. (2013) reported that BSM is a partially bound material based on their stiffness. Vorobeiff (2005) developed an interim design method for pavements with BSM layers considering it as a 'bound material'. Fatigue cracking, rutting of the surface and shrinkage cracking were the three modes of distress identified in this study. Kim et al. (2009) measured the dynamic modulus of BSM at 4.4, 21.1 and 37.8^{o}C and at six different loading frequencies (25, 10, 5, 1, 0.5 and 0.1 Hz). They found out that the dynamic modulus of BSM was less sensitive to the loading frequencies compared to Hot Mix Asphalt (HMA). Since most of the testing protocols presuppose a characteristic material behavior, the mechanical response of the material will be dependent on the testing protocols. For instance, the repeated load triaxial test methods (AASHTO: T 307-99, 2007) are designed to capture the strain hardening behavior of granular material under repeated loading in the presence of confinement pressure. Hence it is possible that one can measure 'resilient modulus' or 'dynamic modulus' and use it as an input for the design of pavement structures, little realizing that such distinction does not really characterize a material.

BSM exhibit both pressure-dependent characteristics of granular materials and loading-time dependent characteristics of bituminous materials. In this investigation resilient modulus test (AASHTO: T 307-99, 2007) and dynamic modulus test (AASHTO: TP-79, 2010) were carried out on BSM. At any given temperature (in this study, room temperature), the data was analyzed to determine which of the characteristics, viz., granular or bituminous can best describe the mechanical properties of the material.

2 MATERIALS AND METHODS

2.1 Material

The properties of bitumen of grade VG10 (stipulated in IS: 73 (2013) of Indian Standards), which was used to produce foamed bitumen, are shown in Table 1.

Table 1. Properties of VG10 Binder

Properties	Value	Specification value
Penetration at 25°C, 100g, 5 s, 0.1mm	93	80 (Minimum)
Softening point, °C	45	40 (Minimum)
Absolute viscosity at 60 °C, Poise	851	800-1200
Kinematic viscosity at 135 °C, cSt	419	250 (Minimum)

The RAP was obtained from milling the Bituminous Concrete (BC) layer of National Highway 45 from Tambaram to Tindivanam in the southern part of India. The road was constructed in 2005. The thickness of the BC layer (wearing course) which was milled was 50 mm. The nominal maximum aggregate size of the BC layer was 19 mm. The thickness of the Dense Bituminous Macadam layer (binder course) was 160 mm.

2.2 Mix design

South African mix design procedure was followed to fabricate the BSM samples. A blend of 80% RAP material, 19% stone dust (fresh aggregates) and 1% cement met the grading requirements as specified in Asphalt Academy (2009). The maximum aggregate size and nominal maximum aggregate size of stone dust is 13.2 mm and 9.5 mm respectively. Indirect Tensile Strength (ITS) test was carried out on dry and wet specimen after dry and wet curing as per ASTM D 6931 (2010). In the case of BSM mixture, for a design traffic more than 6 million standard axles, the specified values for ITS_{dry} and ITS_{wet} were 225 kPa and 100 kPa respectively (Asphalt Academy, 2009). At 2% binder content, the ITS_{dry} was 248 kPa and ITS_{wet} was found to be 216 kPa. The optimum foamed bitumen content was chosen as 2%.

2.3 Sample preparation

Samples were prepared at 15% air voids using the constituents determined from the mix design procedure. The air voids was chosen as 15% as it would represent the air voids in the field at the time of laying (Weston et al., 2002). The samples were prepared using static compaction. Samples of 100 mm diameter and 200 mm height were used for repeated load triaxial tests. The cylindrical samples of 150 mm height and 100 mm diameter were sliced from original samples and was used for dynamic modulus tests.

3 TESTING

3.1 Repeated load triaxial tests

3.1.1 Testing equipment

The cyclic repeated load triaxial tests were performed using a servo-controlled cyclic triaxial testing equipment. The axial deformation was measured using two linear variable differential transducers (LVDT) placed outside the triaxial chamber diametrically opposite to each other. The applied load was measured using an external load cell with a capacity of 5 kN. Confining pressure was applied through air pressure.

3.1.2 Testing procedure

The repeated load triaxial test was performed in accordance with AASHTO T 307-99 (2007). A haversine load of 0.1 seconds and 0.9 seconds rest period was given for each cycle. Testing was performed following the loading sequence as given in AASHTO T 307-99 (2007). Preconditioning cycles were employed by applying 500 cycles of loading and unloading. The test ran up to 100 cycles for each sequence or it terminated when the permanent axial strain exceeded 5%. The data of the last 5 cycles of each loading sequence was recorded. Resilient modulus (MR) was recorded as the mean value obtained for the last 5 cycles.

3.1.3 Data analysis

Influence of confinement

For the purpose of comparison of the response of BSM and granular material, the MR data of granular material (Sparsha, 2015) was considered. Wet Mix Macadam (WMM) material of grade 2 as per Ministry of road transport and highways (MoRTH, 2001) specification for granular base was used in the study conducted by Sparsha (2015). WMM is a pavement layer where in crushed aggregates like graded course sand is mixed with water and laid as a layer. The thickness specified for WMM is 75-200mm (IRC:109-1997, 1997). The gradation of WMM and BSM are shown in Figure 2.

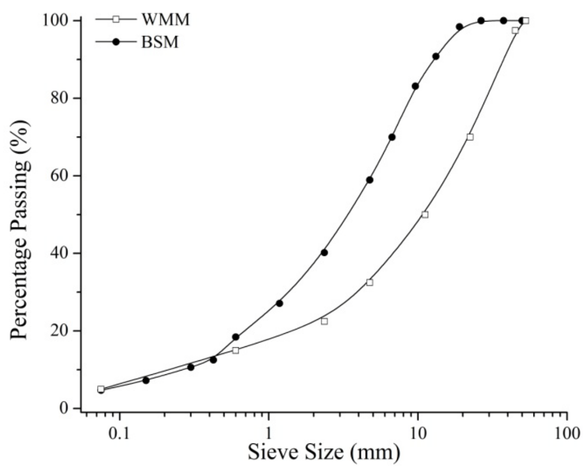


Figure 2. Gradation of BSM and WMM

The loading sequence as per AASHTO T 307-99 (2007) applied on the material is shown in Table 2. During sequence 3, the sample is subjected to a confining stress of 20.7 kPa and an axial stress of 62.1 kPa. The confinement is increased (from 20.7 to 34.5 kPa) in the next sequence and axial stress is reduced to 34.5 kPa. Similarly the confinement is increased and axial stress is reduced at Sequence 7, 10 and 13.

Table 2. Testing sequence for MR testing (AASHTO T 307-99, 2007)

Sequence No.	Confining Pressure (kPa)	Maximum Axial Stress (kPa)	Sequence No.	Confining Pressure (kPa)	Maximum Axial Stress (kPa)
0	103.4	103.4	8	68.9	137.9
1	20.7	20.7	9	68.9	206.8
2	20.7	41.4	**10**	**103.4**	**68.9**
3	20.7	62.1	11	103.4	103.4
4	**34.5**	**34.5**	12	103.4	206.8
5	34.5	68.9	**13**	**137.9**	**103.4**
6	34.5	103.4	14	137.9	137.9
7	**68.9**	**68.9**	15	137.9	275.8

In order to understand the stress-strain response of WMM and BSM during such loading, the strain response during the last 5 cycles of the 12th sequence (confining pressure of 103.4 kPa and axial stress of 206.8 kPa) and the first 5 cycles of 13th sequence (confining pressure of 137.9 kPa and axial stress of 103.4 kPa) were plotted. The strain recovery of WMM and BSM are shown in Figures 3a and 3b respectively. The percentage reduction in recoverable deformation (ε_r) during the sequences when confining pressure is increased was calculated using Equation 1 and is shown in Table 3.

$$\% \text{ Reduction in } \varepsilon_r = \sum_{i=4,7,10,13} \frac{\varepsilon_{r\,(\text{Sequence } (i))} - \varepsilon_{r(\text{Sequence } (i-1))}}{\varepsilon_{r(\text{Sequence } (i-1))}} \times 100 \tag{1}$$

It can be seen from Table 3 that WMM showed substantial strain recovery during these cycles (i.e. Sequence 4, 7, 10 and 13 of Table 2 when compared to BSM. Such variation in strain response should reflect in the calculation of MR and this is shown in Figure 4. It is seen that the MR value of WMM was found to increase as each sequence progressed (Figure 4). Typically this is the expected behavior of a granular material in which the deformation is reduced due to the increase in the confining pressure. However, the behavior of BSM is different as the confinement pressure is increased. The percentage reduction in recoverable deformation for BSM was less compared to WMM and hence there was a reduction in MR values of BSM when the confinement pressure was increased at such sequences.

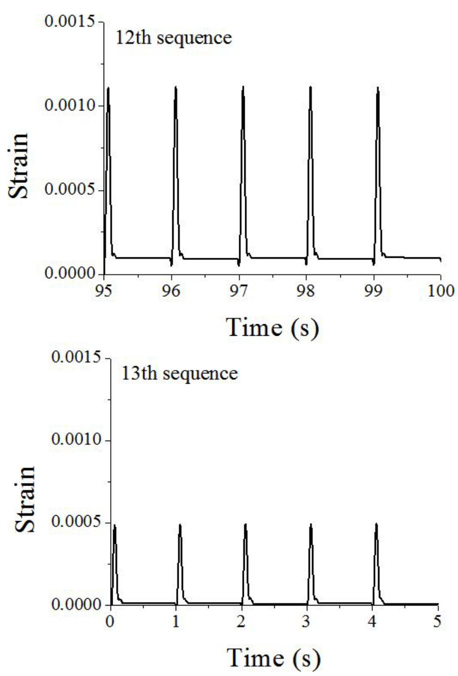


Figure 3a. Strain response during 12th and 13th sequence for WMM

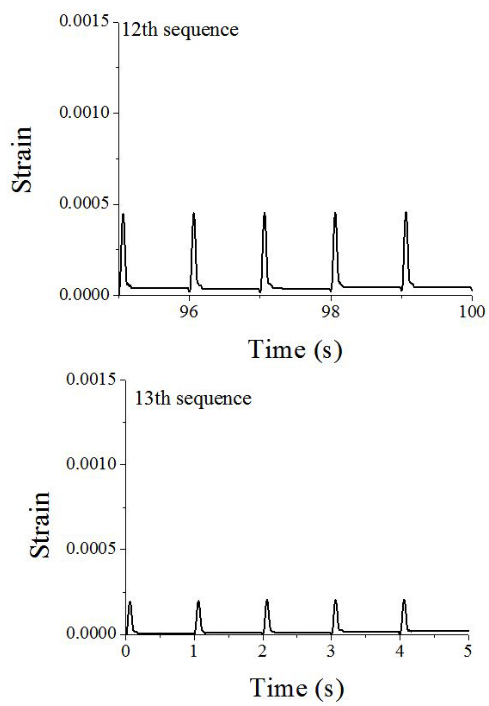


Figure 3b. Strain response during 12th and 13th sequence for BSM

Table 3. Percentage reduction in recoverable deformation

Sequence	Reduction in axial stress with respect to the previous cycle (%)	Reduction in Recoverable deformation with respect to the previous cycle (%)	
		BSM	WMM
4	44	38	53
7	33	29	51
10	66	62	71
13	50	43	53

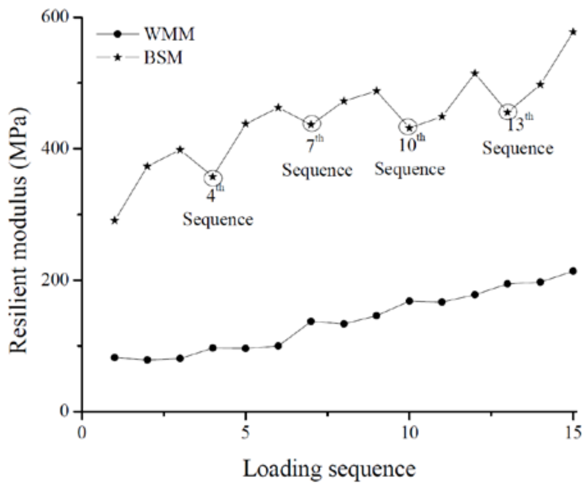
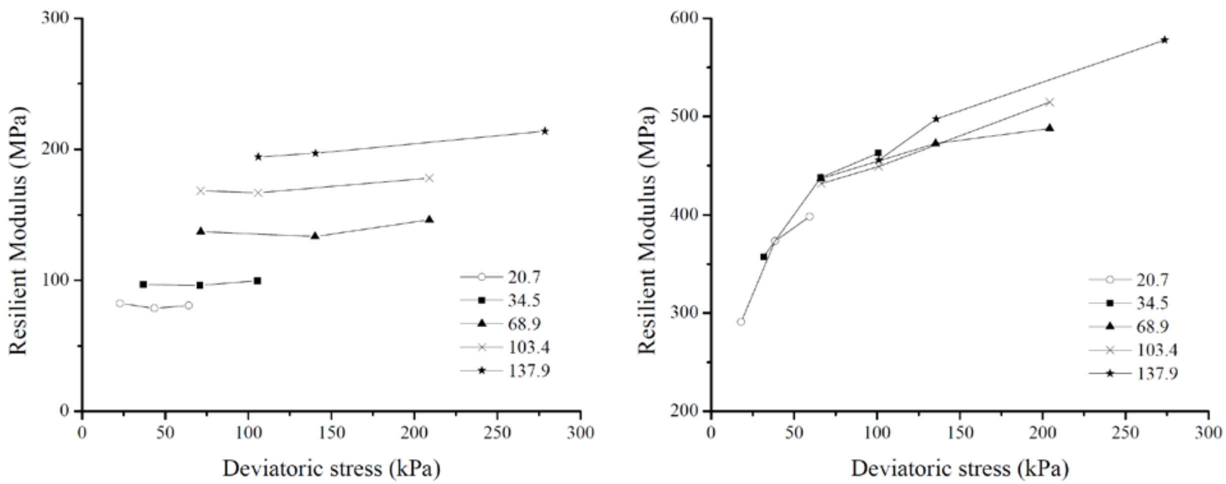


Figure 4. Resilient modulus for the entire 15 loading sequences

Influence of deviatoric stress

During repeated load triaxial testing, the deviator stress is increased (Table 2). The granular material "strain hardens" due to the increase in the bulk stress. However as known, the development of shear stresses during such loading will ensure that the MR did not increase significantly (Figure 5a). However, BSM showed significant increase in MR when deviatoric stress was increased as can be seen in Figure 5b. This can be due to the strain hardening behavior of BSM and also due to less shear stresses developed in the material due to increase in deviatoric stress.



a. WMM b. BSM

Figure 5: Resilient modulus as a function of deviator stress at various confinement pressure

Use of Resilient Modulus Models for WMM and BSM

In the literature, one comes across various models that relate MR to the stress conditions. It will be interesting to see whether one can fit a resilient modulus model to BSM. Table 4 shows the three resilient modulus models and the associated parameters for BSM and WMM. The model parameters were estimated by regression analysis using the data of 15 sequences of repeated load triaxial test. The first model is the k- θ model that was developed by Hicks and Monismith (1971) which considers the influence of only bulk stress (θ) on MR. The second model is the model due to Uzan (1999) which takes into account the shear stresses that develop in the material and it is applicable for both granular stress-hardening and cohesive stress-softening materials. The model which is used in Mechanistic-Empirical Pavement Design Guide (M-E PDG) considers bulk stress and shear stress (τ_{oct}) (M-E PDG, 2004). ρ in the Uzan's model and M-E PDG model (Table 4) is atmospheric pressure and is taken as 101.35 kPa. It can be seen in Table 4 that $k_1$and k_2 were positive in the case of BSM and WMM indicating that as bulk stress increases, MR value increases. k_3 is related to shear stress and as shear stress increases, MR tends to reduce. k_3 was found to be negative for WMM which indicates that the shear stress developed soften the material due to which MR value was reduced. Few researchers have found that k_3 value to be positive in the granular material and attributed it to the lower liquid limit of the soils (Hossain, 2010; George, 2004). k_3 for BSM was found to be positive and can be attributed to the high "cohesive" nature of BSM. As can be seen, the use of material parameters such as resilient modulus and the associated such models for BSM may not be appropriate as these models were developed to characterize typical granular material response. It is clearly seen that while BSM might have considerable amount of granular material content, due to the influence of binder and active filler in addition to the binders in RAP, the response of the material is more like a "cohesive" material and it will be interesting to compare its response to the bituminous mixtures. Such analysis is carried out in the next section.

Table 4. Model parameters for BSM and WMM

Resilient modulus models	Model parameters			R^2
	k_1	k_2	k_3	
k- θmodel $Mr = k_1(\theta)^{k_2}$	BSM : 133 WMM : 7.28	BSM : 0.21 WMM : 0.51	-	BSM : 0.8 WMM : 0.95
Uzan's model $Mr = k_1\left(\frac{\theta}{\rho}\right)^{k_2}\left(\frac{\tau_{oct}}{\rho}\right)^{k_3}$	BSM : 4.9 WMM : 0.53	BSM : 0.031 WMM : 0.71	BSM : 0.19 WMM : -0.21	BSM : 0.94 WMM : 0.98
M-E PDG model $Mr = k_1\left(\frac{\theta}{\rho}\right)^{k_2}\left(\frac{\tau_{oct}}{\rho}+1\right)^{k_3}$	BSM : 3.32 WMM : 0.82	BSM : 0.106 WMM : 0.62	BSM : 0.41 WMM : -0.41	BSM : 0.86 WMM : 0.97

3.2 Dynamic modulus test

3.2.1 Testing equipment

Dynamic modulus test was performed on BSM samples to study the influence of loading rate on the behavior of BSM. The dynamic modulus tests were performed using Asphalt Mixture Pavement Tester (AMPT). The axial deformation was measured using three LVDT attached to the specimen at a gauge length of 70 mm at 120^o apart.

3.2.2 Testing procedure

In the dynamic modulus test, sample is subjected to repeated haversine loading such that the material is within the linear viscoelastic regime. The test matrix of dynamic modulus testing is shown in Table 5.

Table 5. Test matrix of dynamic modulus test

Attribute	Value
Air voids (%)	15
Cement content (%)	1
Testing temperature (^oC)	30
Frequency (Hz)	25, 20, 10, 5, 2, 1, 0.5, 0.2, 0.1, 0.01

It is specified that the applied load should be adjusted to obtain axial peak to peak strains between 75 and 125 microstrain for unconfined tests and 85 and 115 microstrain for confined tests (AASHTO: TP-79, 2010). The underlying assumption here is that within this range the response of the material will be linear viscoelastic.

3.2.3Data analysis

Influence of frequency

For the purpose of comparison, dynamic modulus test was carried out for a dense bituminous macadam (DBM) mix. DBM is a typical HMA binder course used in the pavement. The mix follows dense gradation with a nominal maximum aggregate size of 26.5 mm and 4.5% binder content (MoRTH, 2001). The gradation of DBM compared with BSM is shown in Figure 6.

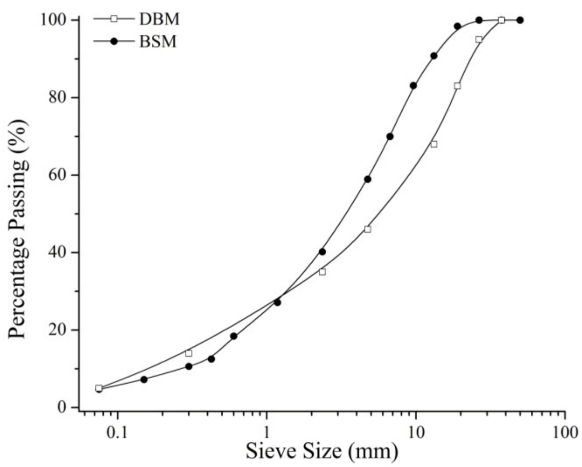


Figure 6. Gradation of BSM and DBM

The dynamic modulus as a function of frequency for BSM and DBM at 30°C is shown in Figure 7a. It can be seen that dynamic modulus of BSM is higher at lower frequencies compared to DBM. The phase lag as a function of frequency is shown in Figure 7b. The phase lag was found to decrease as frequency increased for BSM and DBM, however, the decrease is drastic for BSM. BSM was found to exhibit frequency dependent characteristics similar to that of a bituminous material.

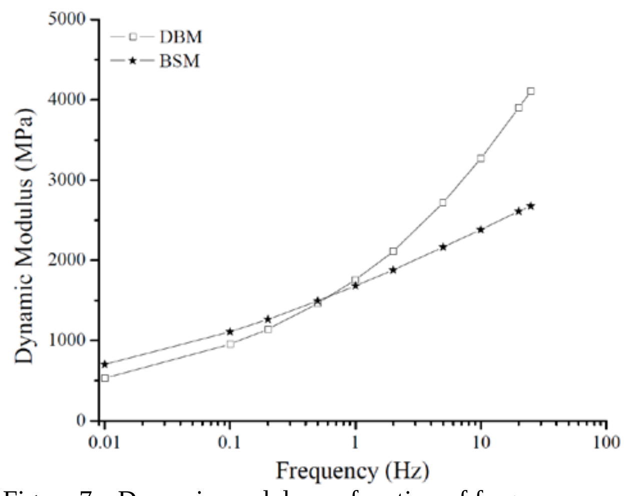


Figure 7a. Dynamic modulus as function of frequency

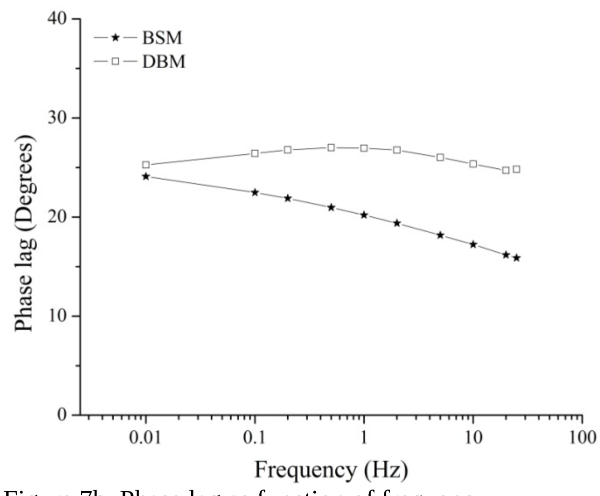


Figure 7b. Phase lag as function of frequency

Since the manner in which the strains are accumulated during loading and recover during rest periods holds the key to the precise material characterization, the normalized strain was plotted for comparing BSM with WMM and DBM. Figure 8a. and 8b. shows the strain response during MR testing and dynamic modulus testing respectively. The strain response during loading and unloading data of 100th cycle of 12th sequence (confining pressure of 103.4 kPa and axial stress of 206.8 kPa), is shown in Figure 8a. It was seen that during unloading, the strain recovery of BSM and WMM were different. Thus, it can be inferred that even though the BSM exhibits pressure dependent characteristics, the rate dependence plays a more critical role. In an attempt to compare identical loading scenario for BSM and DBM, the strain response during 10 Hz frequency of dynamic modulus testing was chosen since the loading time is 0.1 seconds. It can be seen in Figure 8b that the recovery of BSM during unloading was similar to that of the DBM material. The material shows behavior similar to bituminous material and hence any test method and the associated post-processing method which considers explicitly the rate dependent characteristics of the material can be considered to characterize BSM.

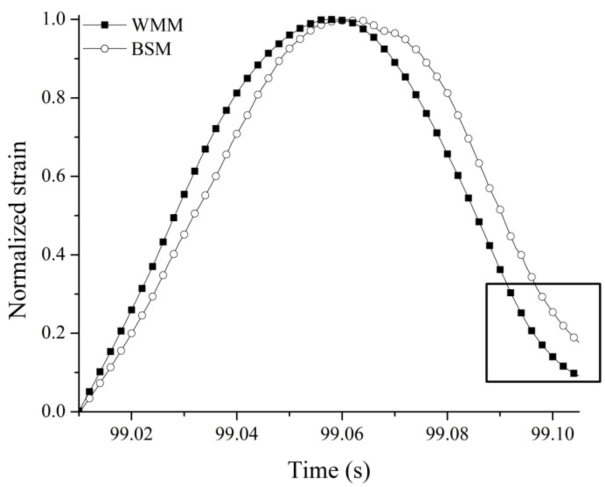


Figure 8a. Normalized strain during MR test

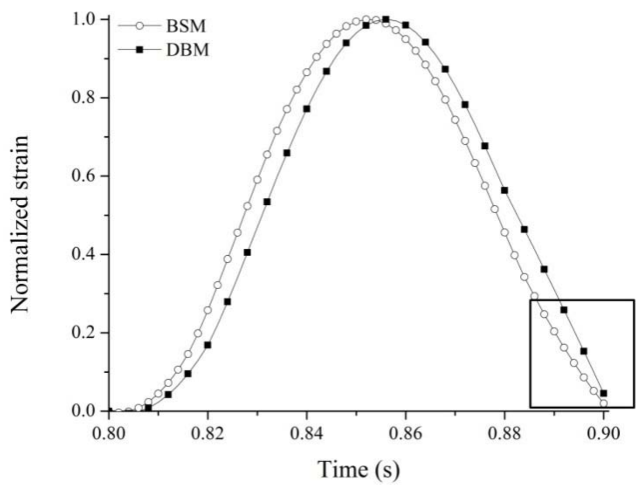


Figure 8b. Normalized strain during dynamic modulus test

4. CONCLUSIONS

The main aim of this paper is to explore the mechanical response of BSM and compare with a regular granular and HMA material. Repeated load triaxial test was carried out on BSM samples at room temperature. The manner in which the MR values changed for WMM and BSM was significantly different. The fact that the strains needed more time to recover for BSM was clearly seen. Also, the history of loading played a critical role for BSM in the sense that when the confinement pressure increased, the MR values actually decreased for the first sequence. Since the MR values did not follow the expected trend, it is not logical to use any MR models and this was demonstrated.

During dynamic modulus test, the viscoelastic characteristics of BSM, i.e. loading rate dependency, was clearly observed. The normalized strain response during unloading was found identical for DBM and BSM. While MR testing showed disparity between WMM and BSM in terms of the MR value, no such disparity was seen when BSM and DBM were compared. Hence one can conclude that the response of the BSM is predominantly similar to that of a bituminous material and appropriate testing protocols and post-processing methods are necessary.

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