Compressible behavior of bituminous mixtures in creep recovery test in confinement

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ABSTRACT: Permanent deformation in bituminous concrete occurs as a combination of densification and shear flow. There already exists standardized testing protocols like flow number and flow time tests that are focused on the shear flow mechanisms of the binder, though they are conducted in triaxial stress state. In order to characterize the permanent deformation of bituminous concrete accurately, the volumetric deformation involved in the densification process needs to be studied as well. A laboratory investigation was conducted under triaxial conditions with the main objective of observing the volumetric changes in the compressible viscoelastic behavior of bituminous concrete. Bituminous concrete cylindrical specimens which were fabricated with an unmodified binder and binders modified with crumb rubber, plastomer and elastomer were subjected to pure confinement creep and recovery tests at different confinement pressures, without applying any deviatoric stress. The response obtained showed clear dependence on the binder type and confinement pressure.

1 INTRODUCTION

Bituminous concrete is a compressible material. Significant densification has been observed to occur in addition to shear flow during the rutting process (Nelson et al. 2010). Application of confinement has also been found to drastically change the behavior of bituminous concrete in uniaxial repeated creep recovery tests (Sousa et al.1994). It is thus necessary to characterize the compressible deformation response of the bituminous concrete to three-dimensional loading.

The mechanical behavior of bituminous concrete can be nonlinear and anisotropic, and the material is necessarily inhomogeneous. However, assumptions of linearity, isotropy and homogeneity for the material have found to be reasonable and useful in predicting the mechanical behavior of this material. When these assumptions are made, the response of the material to three dimensional loading can be characterized by two material functions. The Young's relaxation modulus and time-dependent Poisson's ratio are typically the chosen functions in time domain. However, a pair of any two time-dependent or frequency-dependent material functions out of Young's modulus, Poisson's ratio, shear modulus and bulk modulus will be enough to characterize the compressible viscoelastic behavior of bituminous concrete.

Amongst the material functions, the complex Young's modulus has been extensively studied (Graziani et al. 2013, Kim et al. 2010, Lee et al. 2009, Kassem et al. 2011). The effect of temperature, mixture characteristics and other factors on this modulus parameter is well understood. While uniaxial testing is the simplest mode for measuring complex Young's modulus, measurements through several other modes of testing have been proposed in the literature by Di Benedetto et al. (2007). Some of the tests have also been standardized through specifications (Witczak et al. 2002, Zak et al. 2015). The shear modulus of bituminous concrete has been measured in the literature through torsional tests on cylinders and through simple shear tests (Sousa et al. 1991). There also exists a specification for the measurement of shear modulus using a Superpave Shear Tester (AASHTO TP7). Poisson's ratio of bituminous concrete has not been investigated to the extent of Young's modulus or even shear modulus. There have been some techniques proposed for its measurement, but the Poissons' ratio thus measured has been observed to vary over a wide range depending on the technique used (Di Benedetto et al. 2007).

Bulk modulus of bituminous concrete has received the least attention in the literature amongst the above stated material functions. But for a few studies that were conducted as a part of Superpave performance evaluation (Di Benedetto et al. 2001), hardly any experimental investigation has addressed the compressibility of bituminous concrete. A rigorous experimental investigation of the time-dependent compressible behavior of bituminous concrete would thus be valuable and this is the objective of this study. Constant hydrostatic pressure was applied in the absence of any deviatoric stress to observe the creep of volumetric strain and the pressure was suddenly removed to study the recovery. The results could be used to determine the bulk modulus of bituminous concrete if it is an applicable or relevant parameter, or it could be used to determine the limits of compressibility as observed by some researchers.

2 MATERIALS

2.1 *Aggregates*

The aggregate used in the study is crushed granite obtained from a quarry in Chennai, India. Aggregate gradation conforming to Bituminous Concrete (BC) Grade 2 as per the MORT&H specifications (Ministry of Road Transport and Highways, 2013) with a nominal maximum size of 13.2 mm, was chosen for the bituminous mixtures. The limits of BC Grade 2 gradations are presented in Table 1. Figure 1 shows the gradation of the mix.

Table 1. MORT&H specification for BC Grade 2

Sieve size (mm)	19	13.2	9.5	4.75	2.36	1.18	0.6	0.3	0.15	0.075
Lower limit	100	90	70	53	42	34	26	18	12	4
Upper limit	100	100	88	71	58	48	38	28	20	10

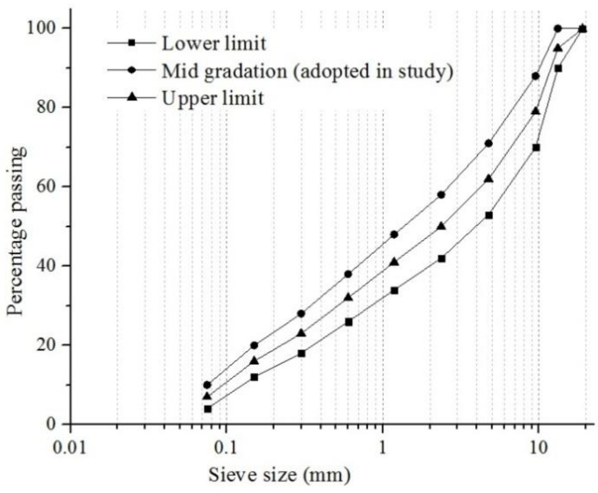


Figure 1. Gradation of the mix used for the study

2.2 *Binders*

An unmodified binder of Viscosity Grade 30 (VG-30), a styrene-butadiene-styrene modified binder (PMB-E), a polyolefin modified binder (PMB-P) and a crumb rubber modified binder (CRMB), were used for the investigation. All the binders were manufactured by M/s Hindustan Petroleum Corporation. The dosage of modifier used for each of the modified binder is presented in Table 2. The properties of the unmodified and the modified binders tested in accordance with the Indian specifications IS:73-2013 and IS 15462:2004, respectively, are presented in Table 3 and Table 4.

Table 2. Details of modified binder

Specification	Modifier	Dosage (%)
PMB-E	Styrene-butadiene-styrene	3.5
PMB-P	Polyolefin	3.25
CRMB	Crumb rubber	10

Table 3. Properties of unmodified binder (VG-30)

Specification	Properties	Methods of test
Absolute viscosity at 60 °C (Poise)	2988.71	IS 1206 (Part 2)
Kinematic viscosity at 135 °C (cSt)	514.8	IS 1206 (Part 3)
Penetration at 25 °C, 100 g, 5 s, 0.1 mm	61	IS 1203
Softening point (R&B) (°C)	52	IS 1205
Viscosity ratio at 60 °C after thin film oven test	2.01	IS 1206 (Part 2)
Ductility at 25 °C after thin film oven test	100+	IS 1208

Table 4. Properties of modified binders

Specification	Properties			Methods of test
	Plastomer	Elastomer	CRMB	
Penetration at 25 °C, 100 g, 5 s, 0.1 mm	43	46	40	IS 1203
Softening point (R&B) (°C)	69	70	69	IS 1205
Elastic recovery of half thread in ductilometer at 15 °C	41	79	72	ASTM D6084
Viscosity at 150 °C (Poise)	2.84	8.5	10.31	IS 1206 (Part 1)
Elastic recovery of half thread in ductilometer at 25 °C after thin film oven test	36	80	81	ASTM D6084
Reduction in penetration after thin film oven test (%)	22	35	18	IS 1208

2.3 *Specimen fabrication*

Mixing temperature for each binder was chosen such that the viscosity of the binder at that temperature 0.17 ± 0.02 Pa.s. Aggregates were heated to 175 °C. Bitumen was mixed with the aggregates at the mixing temperature with the help of a heated mixer. The loose mixture was subjected to short term aging by maintaining the mixture at mixing temperature for 4 hours $\pm$ 30 minutes and then at the compaction temperature for 30 minutes, prior to casting as per AASH-

TO R30 specification (AASHTO R30). A PReSBOX shear compactor manufactured by IPC, Australia was used to cast beams of length 450 mm, width 150 mm and height 145 to 185 mm (ASTM D7981-15). The compacted beams were allowed to cool at room temperature for at least 12 hours to ensure enough stability before core cutting. Three cylindrical samples of diameter 93 ± 0.5 mm were first cored from each beam. From each cylindrical specimen, 10 mm was sawed off using a thin-saw arrangement so as to ensure that the end horizontality was within the tolerance limit of ≤ 0.5 mm and end perpendicularity was ≤ 1.0 mm. Each cylindrical sample was 93 ± 0.5 mm in diameter and 150 ± 0.5 mm high. Specimens were prepared with an air void content of $6 \pm 0.5\%$.

3 EXPERIMENTAL METHODOLOGY

Experiments were conducted using an Asphalt Mixture Performance Tester (AMPT) manufactured by IPC, Australia. The equipment is capable of conducting triaxial tests at isothermal conditions. It can apply confinement pressure up to 300 kPa, an axial load up to 15 kN. The equipment can maintain the temperature within the triaxial test chamber between 0 to $60\,^\circ$ C with an accuracy of $0.5\,^\circ$ C. Figure 2 shows the experimental set-up. Metal studs were glued on to the sample at three different locations that are 120° apart for fixing three linear variable differential transducers (LVDTs). The specimen was kept sandwiched between two steel plates and was covered by a tight polymer membrane for the purpose of applying confinement pressure. The membrane was fixed to the top and bottom plates with two O-rings. The three LVDTs were fixed on top of the membrane using the metal studs that were earlier glued to the sample. All the LVDTs were oriented along the axial direction as shown in Figure 2.

Figure 2. Experimental set up for pure confinement creep and recovery experiment

The tests were conducted at a temperature of $60\,^\circ$C. This temperature was so chosen so that there is significant volumetric strain observed during the test. Volumetric strain in creep recovery tests is expected to be higher at higher temperature and $60\,^\circ$C is the highest temperature that can be applied with this particular equipment. The specimens were conditioned at the test temperature for a minimum of 4 hours inside the triaxial testing chamber, prior to loading. The tests were so designed to observe the decrease in volumetric strain with time when a constant confinement pressure is applied and the increase in volumetric strain when the confinement pressure is removed. In each such creep-recovery test, the confinement pressure was ramped up to the desired magnitude in the first 40 seconds and was retained for 3000 seconds and then ramped down to 0 kPa in 40 seconds. The strain recovery in the specimen was observed over the next 3000 seconds. The loading history corresponding to this test is presented in Figure 3. The axial deformation of the three LVDTs and the applied confinement pressure were recorded every one-thousandth of a second by the data acquisition system. The axial deformation divided by the gauge length would give the axial strain in each location. The average of the axial strain values obtained at the three locations was taken as the axial strain of the specimen.

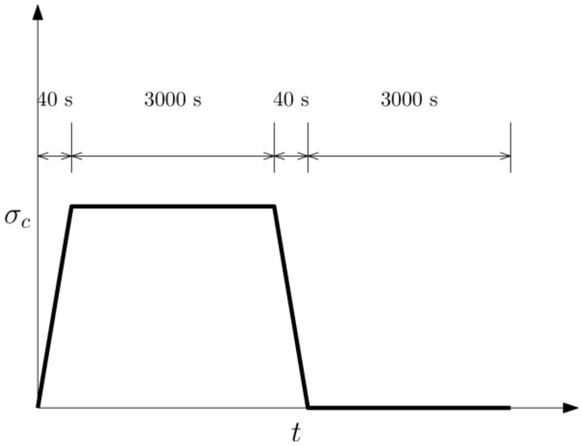


Figure 3. Schematic representation of the confinement pressure creep-recovery test

Creep-recovery tests in confinement were conducted at 100 kPa and 200 kPa confinement pressures for all binders. Test at each confinement level was conducted twice to ensure repeatability. As an example the axial strain history obtained when the bituminous concrete with plastomer modified binder was subjected to creep-recovery test at 100 kPa confinement pressure is shown in Figure 4. The repeatability of the creep-recovery tests were found to be satisfactory. The coefficient of variation between the three LVDT's is found to be less than 30% and this is acceptable since for such similar tests the acceptable range is 30% (AASHTO TP 79-10).

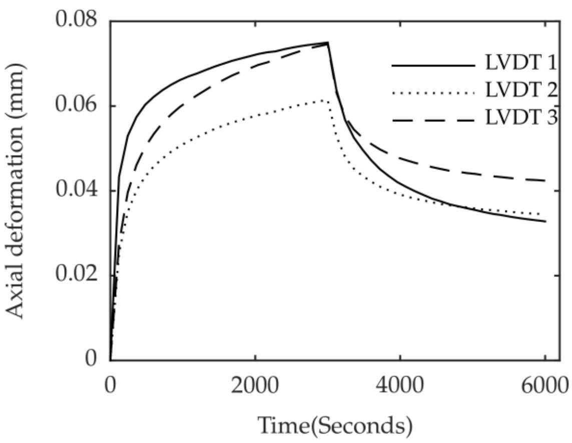


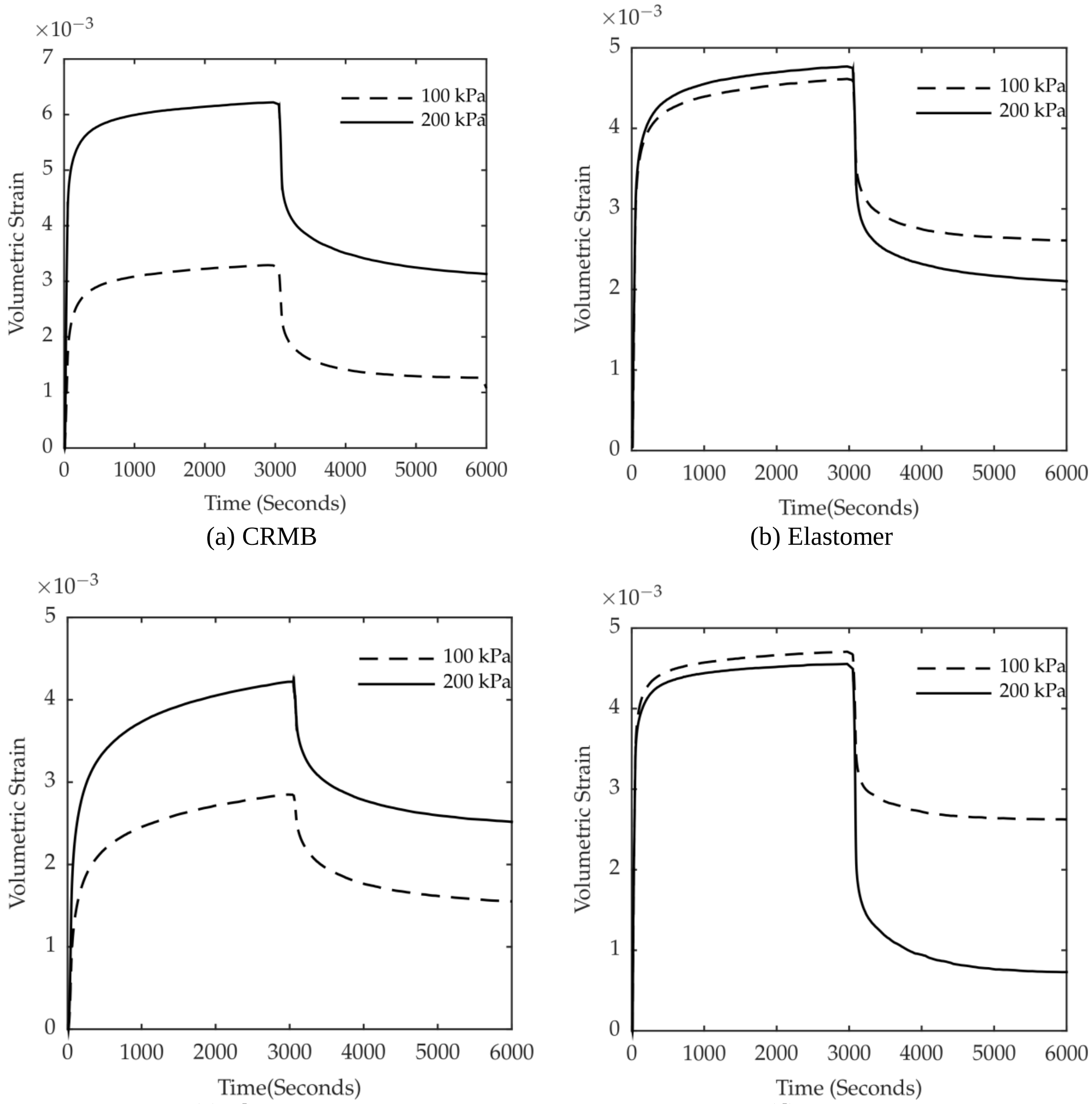
Figure 4. Axial strain history of bituminous mixture with plastomer at 100 kPa pressure

4 RESULT AND DISCUSSION

If bituminous concrete is assumed to be homogeneous and isotropic, as is usually done, for the pure confinement tests that are conducted in this study, the volumetric strain can be related to the measured axial strain in the following manner:

$$\epsilon_v = 3\epsilon_a$$

where ϵ_v is the volumetric strain and ϵ_a is the axial strain. The creep and recovery of the volumetric strain of each binder at different levels of confinement pressure are presented in Figure 5. At 200 kPa confinement pressure, the maximum creep volumetric strain ranged from about 4000 microstrain to 7000 microstrain which corresponds to a change in air-void content of about 0.4% to 0.6%. The permanent change in the air void content ranged between 0.1% and 0.4%. There have been observations in the literature that there is a limit to the permanent volume change above which all the permanent deformation is completely due to shear flow. Considering that the air void content is known to reduce by at least 2% in highways, and the permanent decrease in air void content is not more than 0.4% in these tests, it is reasonable to regard that the existence of a maximum limit on air void reduction would not cause a nonlinearity in the volumetric response observed in this study.



(a) CRMB (b) Elastomer

(c) Plastomer (d) VG-30

Figure 5. Comparison of volumetric strain of different binders at 100 kPa and 200 kPa pressure

A common trend found among all the bituminous concrete specimen is that during creep a significant portion of the increase in volumetric strain occurred during the 40 second ramping period. At 200 kPa confinement pressure, almost 68% of the total volumetric creep strain of the bituminous concrete with crumb rubber modified binder occurred during the ramping time. Similarly, almost 74% of the increase in volumetric strain of the bituminous concrete with the unmodified binder occurred during the ramping time. This can be regarded as the instantaneous elastic compressibility of the specimens. The decrease in volumetric strain in the 40 seconds of time when the confinement pressure is ramped down to zero is only between 32-60% of the increase in the volumetric strain during the ramping up of confinement pressure for all the bituminous concrete specimens. Had the mechanical behavior been viscoelastic, the entire instantaneous increase in strain at the start of the creep loading should be recovered instantaneously during unloading. This is because the accruement of permanent deformation in viscoelastic materials is a time dependent phenomenon. Thus, the difference between the instantaneous increase in strain and instantaneous recovery observed for these bituminous mixtures illustrates the existence of time-independent mechanisms of permanent deformation such as plastic behavior, in addition to the viscoelastic time-dependent mechanisms. The mechanical behavior of bituminous mixtures should therefore be not regarded as viscoelastic but possibly as visco-elastic-plastic. Results at 100 kPa and 200 kPa confinement pressures are as presented in Table 5 and Table 6 respectively.

Table 5. Creep and recovery results at 100 kPa confinement

Binder	CRMB	Elastomer	Plastomer	VG-30
Strain at 40th second (με)	1591	2839	778	3394
Percentage of maximum strain at 40th seconds	49	62	27	72
Maximum volumetric strain (με)	3216	4598	2847	4674
Strain recovered in 40 seconds during unloading (με)	846	905	291	1081
Percentage of creep in the first 40 seconds that is recovered during the 40 seconds of unloading	53	32	37	32
Residual strain (με)	1078	2609	1556	2624
Percentage residual strain	34	57	55	56
Slope of the creep response(με/s)	0.54	0.586	0.69	0.43

Table 6. Creep and recovery results at 200 kPa confinement

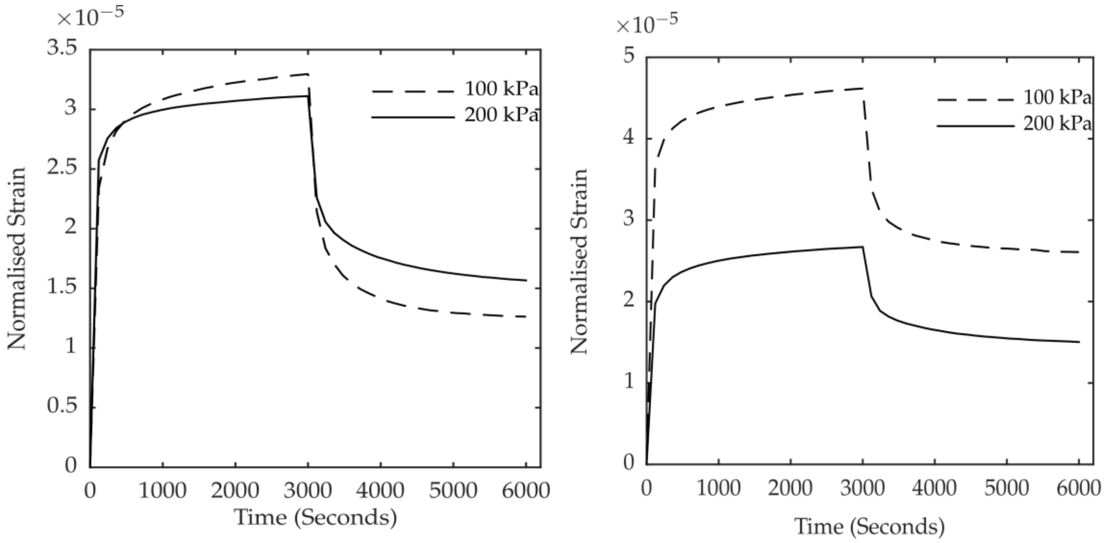
Binder	CRMB	Elastomer	Plastomer	VG-30
Strain at 40th second (με)	4213	2928	1428	3343
Percentage of maximum strain at 40th seconds	68	62	34	74
Maximum volumetric strain (με)	6184	4749	4220	4494
Strain recovered in 40 seconds during unloading (με)	1381	1221	453	1998
Percentage of creep in the first 40 seconds that is recovered during the 40 seconds of unloading	33	42	32	60
Residual strain (με)	3131	2102	2517	729
Percentage residual strain	50	44	60	16
Slope of the creep response (με/s)	0.66	0.61	0.93	0.38

For all the bituminous mixtures, the rate of increase in strain appears to reach a constant rate. This constant rate of increase of volumetric strain was measured at both confinement pressures and are shown in Table 5 and 6. At both the confinement conditions the bituminous concrete specimens with the plastomer modified binder was found to possess the highest rate of increase of strain. For the bituminous mixtures with binders modified by crumb rubber, elastomer and plastomer, the slope of the creep curve measured towards the end of the creep part of the test was found to increase with the increase in confinement pressure. But for the bituminous mixture with the VG-30 binder the slope was higher at the lower confinement pressure.

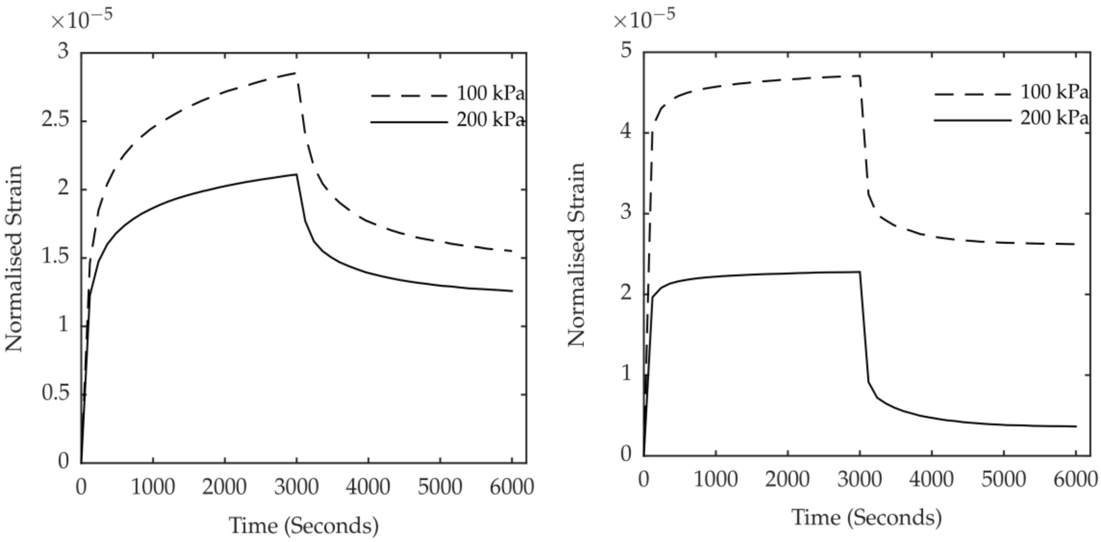
When the percentage recovery of strain at the end of the creep recovery test was analyzed, it was found to vary with the applied confinement pressure. At the lower confinement pressure, for the bituminous mixtures prepared with all the binders except that with CRMB, more than 50% of the maximum strain reached by the sample during loading remained as permanent strain at the end of the recovery period. Bituminous mixtures with CRMB had 34% of the maximum strain left unrecovered at the end of recovery. At higher confinement, for bituminous mixtures with CRMB and plastomer modified binder, at least 50% of maximum creep strain remained as permanent strain whereas for mixtures with unmodified binder and elastomer modified binder the permanent strain was between 15-45% of the maximum creep strain.

The bituminous concrete specimens were prepared with the same content of bitumen and compacted to the same air-voids content for all the four bitumens used. But the volumetric strain response in the creep-recovery tests was found to vary considerably from binder to binder. Linearity of the volumetric strain response was examined by normalizing the strain response of each binder at each confinement level by dividing it by the applied confinement pressure. These were plotted for each binder as shown in Figure 6. As is evident from the figures, only the bituminous concrete with the crumb rubber modified binder exhibited a response that is close to linearity. Bituminous concrete with all the other modified binders are seen to exhibit nonlinear response. Particularly, for both the bituminous concrete with the unmodified binder and that with the elastomer modified binder, the creep of volumetric strain appears to be nearly independent of the applied confinement pressure.

On closer inspection of the volumetric strain response of the bituminous concrete with unmodified binder and that with elastomer modified binder, it can be seen that there is a small but gradual increase in volumetric strain with time. Thus, the near independence of the volumetric strain response on the applied confinement pressure is not because of the volumetric strain reaching the maximum compressibility but due to some other reason.



(a) CRMB (b) Elastomer



(c) Plastomer (d) VG-30

Figure 6. Check for linearity of creep-recovery response

Since the binder content and the air void content of all the bituminous concrete specimen are the same, it is possible that the dependence of volumetric strain response on the confinement pressure has similar functional form for all the binders. In other words, although the volumetric strain response of the bituminous concrete with the crumb rubber modified binder is proportional to the confinement pressure in the tested range of confinement pressures, at higher confinement pressure the volumetric strain response may become nonlinearly dependent on the confinement and eventually become independent of the confinement pressure. Similarly, the response of the bituminous concrete with the unmodified binder could be nearly independent of applied confinement pressure over the 100 kPa to 200 kPa range but may linearly depend on the confinement pressure at lower confinement levels. The markedly different response shown by different binders may simply be due to each binder possessing a different threshold above which the response is nonlinear and another threshold above which the response is independent of stress.

5 CONCLUSIONS

In this study, pure constant hydrostatic pressure was applied on various bituminous concrete mixtures for a fixed period of time and then removed in order to observe the creep and recovery of volumetric strain in the specimen. Bituminous concrete with four different bitumen were studied with this test, and considerable variation was observed in the volumetric strain response from one bitumen to another. The bituminous concrete with the crumb rubber modified binder was found to exhibit nearly linear response, while the volumetric strain response of the bituminous concrete with the plastomer modified binder was found to nonlinearly depend on the applied confinement pressure, and the bituminous concrete made with the unmodified bitumen and the elastomer modified binder exhibited volumetric strain response that is nearly independent of confinement pressure. It was found that a major part of the permanent volume change during the test was due to a time-independent inelastic response such as a plastic response rather than a viscoelastic response. However, a part of the increase in volumetric strain during the creep period was also time-dependent.

The results illustrate that the three-dimensional mechanical behavior of bituminous concrete cannot be regarded as simply viscoelastic. At least a part of the three-dimensional response comprises of time-independent inelasticity similar to granular materials. Poisson's ratio or bulk modulus therefore may not be appropriate parameters for characterizing the compressible behavior of bituminous concrete.

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