Chapter 4
Material characterization of asphalt concrete mixes

4.1 Introduction

In mechanistic design methods used for the analysis of layered pavement system, various layers in the asphalt pavement are considered as linear elastic, homogeneous, and isotropic under the application of static loading conditions [206]. These assumptions work reasonably if subgrade layer behaves as linear elastic layer [207].

However, in real field conditions, all the pavement layers are heterogeneous in nature and subjected to dynamic loading conditions. Materials in the various layers behave far from the ideal conditions as stated above. The asphalt concrete layer at the top exhibits more complex behaviour due to the presence of bitumen in it. The behaviour of asphalt layer is close to response of an elastic material at low temperature considering static loading; however, it behaves as viscoelastic material at an intermediate temperature and transient loading. So, it is important to understand the asphalt mix behaviour subjected to different environmental conditions.

4.2 Material characterization of asphalt concrete mix

The selection of suitable material parameters is crucial in both scientific research and engineering practices. This is important to identify reliable and representative material properties for subsequent pavement analysis. The correct material parameters and selection of appropriate model of a material facilitate the use of efficient numerical methods, and help to evaluate the pavement distresses using mechanical response (stress, strain, deformations) in the constitutive model. This is particularly important for asphalt mixtures, which are predominantly used as top layers in asphalt pavement and are most susceptible to many distresses due to direct contact with vehicular loading. These mixtures exhibit thermo-rheological behaviour, which properties varies with thermal conditions and load duration. Under a variety of circumstances, including static and dynamic loads, asphalt mixtures display their rheological behaviour.

The importance of these properties is considerable when describing the material at higher temperatures compared to lower ones. The response of asphalt mixture can be considered as elastic subjected to static loading at lower temperatures where linear-elastic models are adequate for modelling the material parameters. However, in reality, these mixes exhibit both elastic and viscous characteristics at intermediate and high temperatures subjected to static as well as dynamic loading conditions. The elastic properties, which are more prominent at lower temperatures, lead to permanent deformations in the asphalt surface, while the viscous characteristics are more common at higher temperatures.

4.2.1 Stress-strain relationship

The stress-strain relation in a viscoelastic material is time dependent. The time dependent relationship between stress and strain in a linear viscoelastic material is given by Boltzmann-Volterra law. To understand this law, consider the scenario of axial tension. As per Hooke's Law, the longitudinal strain of an elastic material, at any given time, is proportional to the tensile stress applied at that time, represented as $\varepsilon = \sigma/E$. In contrast, the increase in longitudinal strain $d\varepsilon(t)$ in a viscoelastic material at a specific time t, due to the applied load during the period $d\tau$, which lies between τ and $\tau + d\tau$ (where $\tau \leq t$), is proportional to the increase in the applied stress $d\sigma(\tau)$ within the preceding time period τ.

The proportionality factor D $(t - \tau)$ is dependent on the time interval $(t - \tau)$ between these points in time. The constitutive stress-strain relation is given as:

$$d\varepsilon(t) = D(t-\tau)d\sigma(\tau) \tag{4.1}$$

If we interpret the deformation of a viscoelastic material as a flow, then D(t) can be considered as a function that increases over time. The creep deformation in the material is proportional to the time of application of tensile stress. As duration of tensile stress increases, creep deformation also increases. Similarly, the increase in stress $d\sigma(t)$ at any time t is proportional to the increase in strain $d\varepsilon(\tau)$ applied just before time τ. The proportionality factor E $(t - \tau)$ is dependent on the time interval $(t - \tau)$. The constitutive relation is given as:

$$d\sigma(t) = E(t-\tau)d\varepsilon(\tau) \tag{4.2}$$

The stress and strain increment in a viscoelastic material as given by Eq. 4.1-4.2 under the application of tensile load during the incremental time τ can be combined and the time dependent relationship between stress and strain is expressed by Boltzmann given as:

$$\varepsilon(t) = \int_0^t D(t-\tau)\frac{\partial\sigma(\tau)}{\partial\tau}d\tau \tag{4.3}$$

$$\sigma(t) = \int_0^t E(t-\tau)\frac{\partial\varepsilon(\tau)}{\partial\tau}d\tau \tag{4.4}$$

As per the Boltzmann principle, the extent of deformation at any point in a material at a specific time t is affected by the state of stress in material during all preceding time τ. The influence further increases as time duration $(t - \tau)$ decreases, and this is represented by the function D(t). Similarly, the level of stress at any point in a viscoelastic material at a given time t is affected by the strains present during all preceding time τ. The influence is higher against the shorter time interval $(t - \tau)$, and this is represented by the function

E(t). The importance of Boltzmann's theory of viscoelasticity is similar as that of Hooke's law in the theory of elasticity. In this context, the functions E(t) and D(t) depict the stress-strain relationship and its time dependence, much like the relationship for elastic material (which is time-independent) is depicted by the elastic modulus E and elastic compliance 1/E. The function D(t) is empirically determined through tensile testing under constant stress and is referred to as the creep compliance. It is the ratio of the strain measured at a time t to the constant stress σ_c given as:

$$D(t) = \frac{\varepsilon(t)}{\sigma_c} \tag{4.5}$$

Modulus of relaxation, E(t) can be evaluated using tensile load testing under constant strain. It is defined as the ratio of stress measured at a point at time t to the constant strain, ε_c given as:

$$E(t) = \frac{\sigma(t)}{\varepsilon_c} \tag{4.6}$$

While designing a pavement structure considering the viscoelastic properties of asphalt mix, the role of relaxation modulus E(t) is similar to that of elastic modulus (E) considering the elastic behaviour of the material.

4.2.2 Mechanical modelling of asphalt mix behaviour

The time dependent response of a viscoelastic material can be explained by ordinary differential equations. Mechanical analogues, which include springs and dashpots, provide a practical method for formulating these relationships. To accurately depict a material's viscoelastic response, an assembly of multiple springs and dashpots is required. This necessity arises from the requirement of multiple relaxation times to accurately represent real materials. The employed combinations are typically either the generalized

Maxwell model (GMM) or the generalized Kelvin model (GKM). These mechanical models are discussed later in section 4.4.2.2.

4.2.3 Interconversion of stress relaxation and creep compliance data

It is widely recognized that all functions of linear viscoelastic materials are mathematically analogous, with each function encapsulating essentially identical information about the material's relaxation and creep characteristics. Consequently, one type of linear viscoelastic material function can be transformed into other types through suitable mathematical operations. The requirement for such interconversions emerges for various reasons. For example, conducting a constant-strain relaxation test on stiff materials can be challenging, whereas executing a constant-stress creep test is typically simpler. In such instances, the relaxation modulus can be derived from the creep compliance via an interconversion.

Numerous interconversion techniques, both precise and approximate, have been worked out and proposed by various researchers. The subject has been comprehensively addressed by scholars such as Ferry [41] and Tschoegl [42]. Approximate correlations between the relaxation modulus and creep compliance have been formulated by several authors [208–210].

4.2.3.1 Exact interconversion methods

The viscoelastic properties of asphalt mix are generally represented by creep compliance, D(t) and stress relaxation modulus, E(t). These two parameters are not reciprocal to each other however the relation between them can be represented by a convolution integral [41] given as:

$$\int_0^t E(t-\tau)D(\tau)d\tau = t \qquad for\ t > 0 \tag{4.7}$$

where, E(t) and D(t) are relaxation modulus and creep compliance parameters respectively. applying the Laplace transformation on Eq. 4.7, we get:

$$\overline{E(s)}\ \overline{D(s)} = \frac{1}{s^2} \tag{4.8}$$

where, $f(s) = \int_0^\infty f(t)e^{-st}dt$, represents the Laplace transformation of the function f(t) and s is a transform parameter. The numerical solution of the integral Eq. 4.7 can be found by employing a suitable numerical integration method. This strategy is particularly beneficial when the source function lacks an analytical form and is only represented by a dataset. The integration range is segmented into sufficiently small subintervals, allowing the integrand's variation within each subinterval to be approximated by a suitable average value. The target function can be established using a recursive formula. This method was further used by past researchers [211] to convert creep compliance data of asphalt mix evaluated experimentally to relaxation modulus data.

4.2.3.2 Approximate methods of interconversion (based on power law)

There are numerous approximate techniques for converting creep compliance data to stress relaxation data. These methods give a good approximation for weak linear viscoelastic material or elastic material. Here a Power law interconversion method has been discussed which has further been used in this study.

It is widely recognized that for various linear viscoelastic materials, creep compliance and relaxation modulus are typically depicted by basic power laws across their transition zones. Let's consider the subsequent forms of power laws for the relaxation modulus and creep compliance, respectively:

$$E(t) = E_1 t^{-n} \tag{4.9}$$

$$D(t) = D_1 t^{n} \tag{4.10}$$

where, E_1, D_1, and n are positive model constants. Using Eq. 4.9-4.10, the relationship between stress relaxation modulus and creep compliance can be established.

$$E(t)D(t) = \frac{sin\,(n\pi)}{n\pi} \tag{4.11}$$

Derivation of Eq. 4.11 can be found elsewhere [212]. It is important to note that power-law functions represented by Eq. 4.9-4.10 are graphically shown by straight lines on log-log scales, and the exponent n is evaluated as slope of these lines. For an elastic material (n approaches 0), sin(nπ)/nπ approaches to 1 and Eq. 4.11 is converted to Eq. 4.8. It has been well established that Eq. 4.11 serves as a reliable approximate correlation between E(t) and D(t) when both functions don't strictly adhere to Eq. 4.9 and Eq. 4.10, but exhibit smooth behaviour when plotted on log-log scales. In this scenario, n is the slope of local log-log scale of the source function and it is given as:

$$n = \left|\frac{dlogF(\tau)}{dlog\tau}\right| \qquad at\ \tau = t \tag{4.12}$$

where, $F(\tau)$ is one of the source functions, either $E(\tau)\ or\ D(\tau)$. It can be noted that, n is a time dependent function. The approximate interconversion method as represented by Eq. 4.11 is reliably accurate where relaxation modulus and creep compliance functions are represented as straight lines on log-log scale.

4.3 Material properties

Asphalt concrete (AC) pavements are considered as mechanistically complex systems due to their composition of different materials and regular interaction with surrounding conditions [213]. Hence, their performance is influenced by parameters such as material properties, loading conditions, and environmental factors. In emerging economies like India, the surface layer of AC pavement is recognized as bituminous concrete (BC) and stone mastic asphalt (SMA) as a popular choice for pavement construction compared to open-graded friction course (OGFC) [214]. The reason could be mainly because the road construction agencies are uncertain about the reliability of OGFC (a relatively new technology in the Indian market) [215]. The Ministry of Road Transport & Highways (MoRTH) specifications [216] categorize BC based on their aggregate sizes. The first category, BC-1, is classified with a nominal aggregate size of 19 mm, whereas the second category, BC-2, is classified with a nominal aggregate size of 13.2 mm. Similar to BC, MoRTH [216] categorizes SMA-1 with a nominal aggregate size of 13 mm and SMA-2 with a nominal aggregate size of 19 mm.

These different mixes are known to exhibit relatively different mechanical properties under varying surrounding conditions. Therefore, understanding the characteristics of these mixes under applied load and environmental factors is crucial for performance-based design. Both elastic and viscoelastic material properties of asphalt mixes have been determined in this study to evaluate structural response of the asphalt pavement using finite element modelling. The first phase of experimentation summarises the resilient modulus test (elastic properties) on four different asphalt mixes, BC-1, BC-2, SMA-1, and SMA-2 at three different test temperatures of 25, 35, and 45^{o} C. The second phase of experimentation summarises viscoelastic properties of BC-2 mix at three different test temperature of 5, 15, and 25^{o} C and three different air voids of 4, 5, and 6%.

This section deals with material properties of various constituents used in asphalt mix, the mix design, resilient modulus test results (elastic material properties based on recoverable strain) of four different asphalt mixes; BC-1, BC-2, SMA-1, and SMA-2 at three different test temperatures of 25, 35, and 45° C, and creep compliance test (linear viscoelastic response of BC-2 mixes). Resilient modulus test on asphalt mixes has been performed using Dynamic testing system (DTS-30) as per the guidelines of ASTM D4123 [217].

4.3.1 Physical properties of asphalt binders

In the present research, a viscosity graded binder, VG-40 was used with an absolute viscosity of 4480 Poise at 60° C which falls within the specified limit of 3200 to 4800 Poise [218]. It is relatively a stiff binder generally used in roads designed to service higher axle loads. It is a common choice for the construction of major roadways such as national highways and expressways in India expecting a load repetition of more than 30 million standard axle [219]. It is highlighted that the VG-40 binder is particularly effective in areas where the traffic load and maximum pavement temperature is high. The use of VG-40 binder is recommended when maximum pavement temperature falls between 58-76° C and traffic load is ≥ 20 msa (millions of standard axle). The use of VG-40 binder can be further extended subjected to a maximum of 50 msa traffic load with revised maximum pavement temperature of 64° C [216].

The binder properties were assessed before using it in the sample preparation and are shown in Table 4.1. As per Indian specifications [220], binders are classified based on viscosity, and there are no specific test protocols or specifications for performance grading and continuous grade at higher temperatures [221]. Therefore, ASTM guidelines [222] were followed to evaluate the rheological characteristics using a dynamic shear rheometer.

Table 4.1. Specification limit and physical properties of asphalt binder

Properties	Values obtained	Test method	Specification limit
Penetration at 25° C, 0.1 mm	41	IS 1203 [223]	35 (min)
Absolute viscosity at 60° C (Poises)	4480	IS 1206-Part 2 [218]	3200-4800
Softening point (°C)	54	IS 1205 [224]	50 (min)
High temperature continuous grade (°C)	77.2	ASTM D6373 [222]	NA
High temperature performance grade (°C)	76	ASTM D6373 [222]	NA

***NA –** Not applicable*

4.3.2 Physical properties of aggregates

In this study, Granite (a siliceous aggregate) was used for the preparation of bituminous mix samples. Granite is frequently used in the construction of flexible pavements in India. Prior to the preparation of the mix, the physical properties of the aggregates were examined, as shown in Table 4.2. As per the MoRTH [216] guidelines combined flakiness and elongation index, abrasion value, and impact value test of aggregates has been conducted to check the suitability of its usages in various layers of the AC pavement. Relevant IS codes as mentioned in the Table 4.2 has been used to conduct these physical tests on aggregate materials.

Table 4.2. Specification limits and physical properties of aggregates

Properties	Combined flakiness and elongation index	Abrasion value	Impact value
Specification limit	Max 35%	Max 40%	Max 30%
Test protocol	IS:2386-Part I [225]	IS:2386-Part IV [226]	IS:2386-Part IV [226]
Test results	19%	16.8%	14.6%

As granite aggregates are considered very tough and hard material in the construction of asphalt pavement, results of abrasion value and impact value tests confirms the same.

These materials were found very less susceptible to indentation and crushing subjected to wearing action and impact load. Test results shown in Table 4.2 mainly shows the hardness, toughness, and shape properties of aggregates.

4.3.3 Physical properties of asphalt concrete mix

Since, BC and SMA are common mixture types used in pavement construction, samples of BC-1, BC-2, SMA-1, and SMA-2 were prepared in the laboratory. Figure 4.1 shows the gradations of aggregates that were used for the preparation of the asphalt mixtures as per MoRTH [216] guidelines. The gradation curve is based on dry sieve analysis.

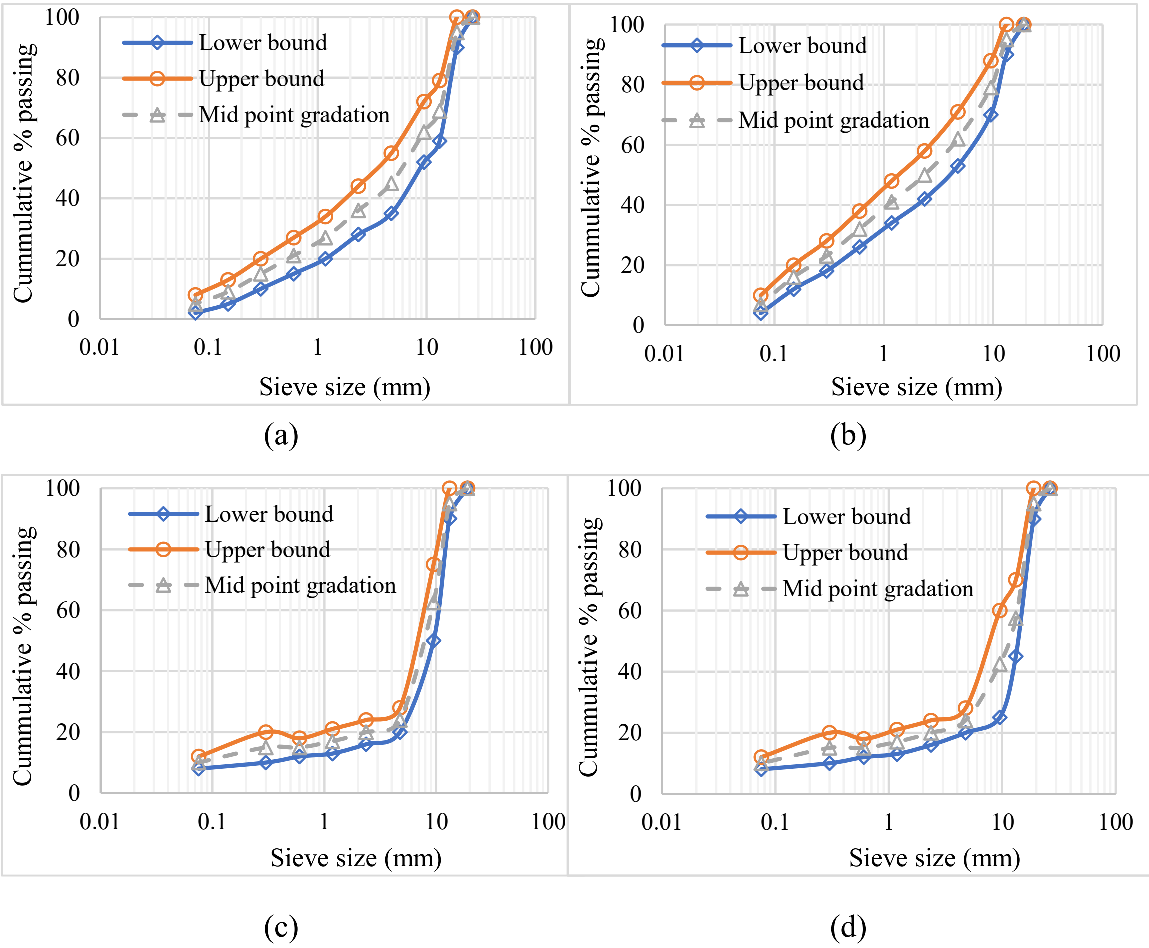

Figure 4.1. Specification limits and target (a) gradation of BC-1 (b) gradation of BC-2 (c) gradation of SMA-1 and (d) gradation of SMA-2.

During the study, wet sieve analysis was also performed to see the variation in retained weights on lower sieves (less than 4.75 mm IS sieve) by the two approaches. However, no significant difference in these weights were observed. It can be concluded that presence of clay content in the aggregate material was negligible and similar gradation curves were obtained in both cases. Mixture samples were prepared following the Marshall mix design procedure [33]. Similar to the practice adopted in field, SMA mixes were stabilized with 0.3% of pelletized cellulose fibres by weight of the total mix. These pelletised fibres are generally used to stabilize the mastic and also reduces the drain off of binder in the mix. SMA mixes are relatively thin (40-50 mm), gap-graded, densely compacted hot mix asphalt used as a surface course. These mixes are different from normal dense graded BC mixes as it contains higher percentage of coarse aggregates. It provides a rut resistant wearing course at higher temperatures. As compared to dense graded mix like BC-1 and BC-2, SMA has better shear resistance, abrasion resistance, cracking resistance, and skid resistance [228].

As can be seen from the figures, the target gradations selected for all the mixes fell within the maximum (upper bound) and minimum (lower bound) prescribed limits. The optimum binder content and other volumetric properties are given in Table 4.3.

For preparing all the asphalt mixes as shown in Figure 4.2, midpoint gradation has been selected in this study. Asphalt mixes were compacted at design optimum binder content with 75 blows from both the ends. Since the fine content in SMA mixes are lesser than BC mixes, penetration of water during bulk specific gravity (G_{mb}) determination is possible, so a thin coat of wax at its outer surface was applied before taking weight of sample in water. Wax was first heated to its liquefaction temperature and the sample was completely immersed in wax container. Once the asphalt mix sample was coated with a thin layer of wax at its surface, it was allowed to cool at room temperature so that wax is glued to the sample properly. After determining G_{mb} and theoretical maximum specific gravity (G_{mm}) of the mixture, bulk volume of sample is evaluated.

Table 4.3. Volumetric properties of various mixes obtained from Marshall mix samples

Mix type	Binder	OBC (%)	G_{mb}	G_{mm}	Air void (%)	VMA (%)	VFB (%)	Stability (kN)	Flow (mm)
BC-1	VG-40	5.47	2.447	2.550	4.039	17.170	76.480	15.684	3.240
BC-2	VG-40	5.70	2.432	2.534	4.025	17.616	77.150	14.216	3.196
SMA-1	VG-40	6.00	2.449	2.558	4.260	18.667	77.173	11.687	3.864
SMA-2	VG-40	5.92	2.425	2.526	3.998	18.073	77.870	12.712	3.752

The OBC of SMA-1 was found highest among all four mixes considered in this study as it is a gap graded mixture with stone-to-stone contact of coarser aggregates and relatively lesser fine contents (20%-30% passing 2.36 mm IS sieve). The high binder content mastics composed of fine aggregates, fillers, asphalt binder, and stabilizing additives fills the voids and provides durability to the mix.

Figure 4.2. Compacted asphalt mix samples.

The materials used (aggregates, binder, and fiber) for resilient modulus test (for evaluating elastic response of asphalt mixes) and creep compliance test (for evaluating linear viscoelastic response) were kept same. The aggregate gradation adopted in this study for BC-2 mix to study time-temperature dependency of asphalt mixes are shown in Figure 4.3.

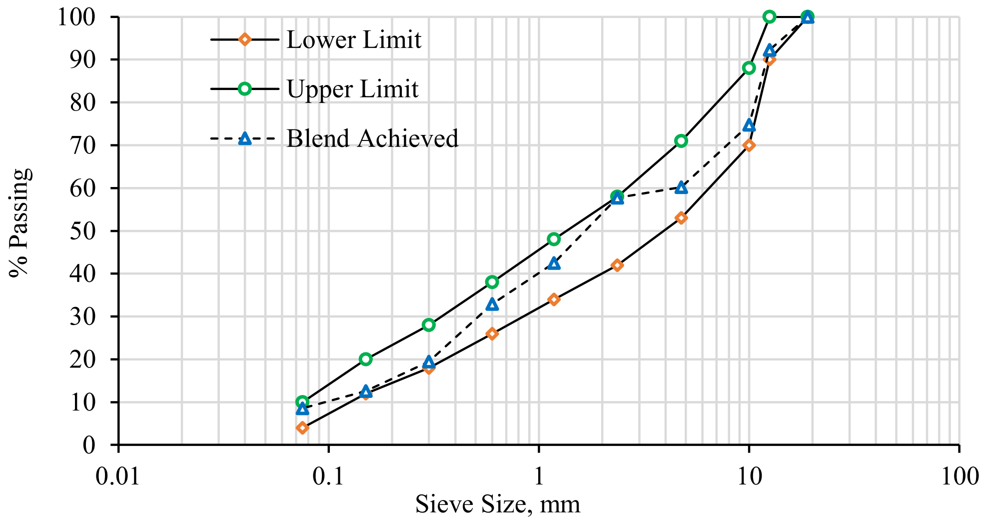

Figure 4.3. Aggregate gradation adopted for BC-2 mix.

The following section discusses methods (Indirect tensile strength test and resilient modulus test) and test results for evaluating elastic response of various asphalt mixes subjected to different environmental temperatures.

4.4 Test procedures

Material characterization of the asphalt mixes involves experimental testing subjected to static/dynamic loading and environmental conditions (temperature, moisture, etc.). In India, elastic material properties of asphalt mixes are evaluated using resilient modulus test discussed later in this section. These parameters can be used successively, where materials are subjected to static loading and low temperature conditions. However, materials subjected to dynamic loading and high temperature conditions, may not yield reliable results. Linear viscoelastic material characterization (time-temperature dependency) of asphalt mixes better represents material behaviour in this situation and requires determination of dynamic modulus or creep compliance data.

4.4.1 Linear elastic response of asphalt mixes

Linear elastic material characterization of asphalt mix is practiced in current pavement analysis and design guidelines in India. Relatively pavement engineers are more friendly with the testing procedures for evaluating elastic response of asphalt mixes as compared to time-temperature dependent material response (viscoelastic properties). Elastic material properties are considered as good representation of asphalt mix behaviour at low temperature and static loading conditions. Resilient modulus and Poisson's ratio are used as input parameters for the pavement analysis and design using linear elastic response of asphalt mixes.

Linear elastic response of the asphalt mixes was determined using resilient modulus test based on peak load obtained from indirect tensile strength (ITS) test discussed later in this section. Resilient modulus (M_r) test has been conducted on different types of asphalt mixes (BC-1, BC-2, SMA-1, and SMA-2) at three different test temperatures of 25, 35, and 45 ^oC.

4.4.1.1 Indirect tensile strength test

ITS test can be used to check the durability and resistance of compacted asphalt mixes before and after exposed to moisture. The ITS value can be further used to evaluate relative strength of asphalt mixes and its potential against rutting and cracking in the pavement. The ITS of asphalt mixture is determined by loading a cylindrical test sample across its vertical diametral plane at a fixed rate of deformation as per the specifications of ASTM D 6931 [229]. The peak load at failure is noted and used to find ITS of the sample. The asphalt mix sample is fixed between two loading stripes as shown in Figure 4.4 and it is loaded at a rate of 50 mm/min.

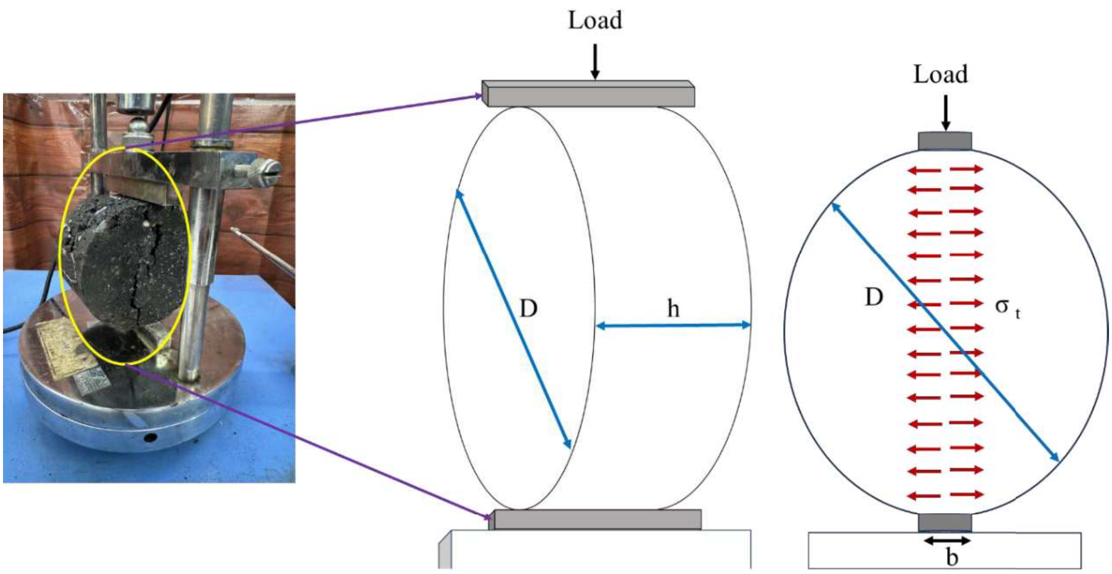

Figure 4.4. Indirect tensile strength test set up.

The diagrammatic representation of ITS test set up and test principles are shown in Figure 4.4. It is a destructive testing method in which load is increased to a value where cracks initiate and propagates axially (fracture point) also known as peak load. This load is further used in resilient modulus test of asphalt mixes.

Tensile strength test is first conducted and 10 to 50% of the peak load is considering for loading the sample in resilient modulus test. In this study, 10% of the ITS value has been considered for loading asphalt mix sample in resilient modulus test. The expression for tensile strength is given as:

$$S_T = 2P_{ult}/\pi hD \qquad (4.13)$$

where, P_{ult} is ultimate failure load, h and D are thickness and diameter of sample respectively. Test results of ITS are shown in Table 4.4.

Table 4.4. ITS-peak load (kN) values of AC mixes at different test temperatures

Mix type	**ITS peak load (kN)**		
	25° C	**35° C**	**45° C**
BC-1	8.42	7.12	5.88
BC-2	9.26	7.96	6.46
SMA-1	8.78	6.94	7.24
SMA-2	8.32	6.28	6.35

4.4.1.2 Resilient modulus test of asphalt mixture

In this research, stiffness of asphalt mix samples was measured using M_r tests based on ITS value using Dynamic Testing System [230,231]. M_r was used in this research because it is a widely accepted method for characterizing bituminous mixtures [232]. The M_r test was preferred because several measurements can be taken on the same specimen [233] reducing the specimen-to-specimen variability.

Resilient modulus of asphalt mixes was obtained using ASTM D4123 [217] guidelines. It is based on indirect tension test on asphalt mixes. The repeated load indirect tension test for determining resilient modulus of asphalt mixture is conducted by applying compressive loads with a haversine or another suitable waveform. The load is applied vertically in the diametral plane of a cylindrical sample. Test sample is firstly placed in a temperature-controlled chamber at specified test temperature for a duration of minimum 6 hrs. Then test sample is placed into the loading apparatus and loading strips are positioned parallel to vertical diametral plane of the sample as shown in Figure 4.5. Test sample is preconditioned by applying a repeated haversine load for a minimum period (100 load cycles) sufficient to obtain uniform deformation.

Axial deformation in the sample is monitored using LVDT's fixed in the axial direction of the test sample. Since Poisson's ratio was assumed in this study as per the guidelines of IRC:37 [20], so LVDT in vertical direction has not been used.

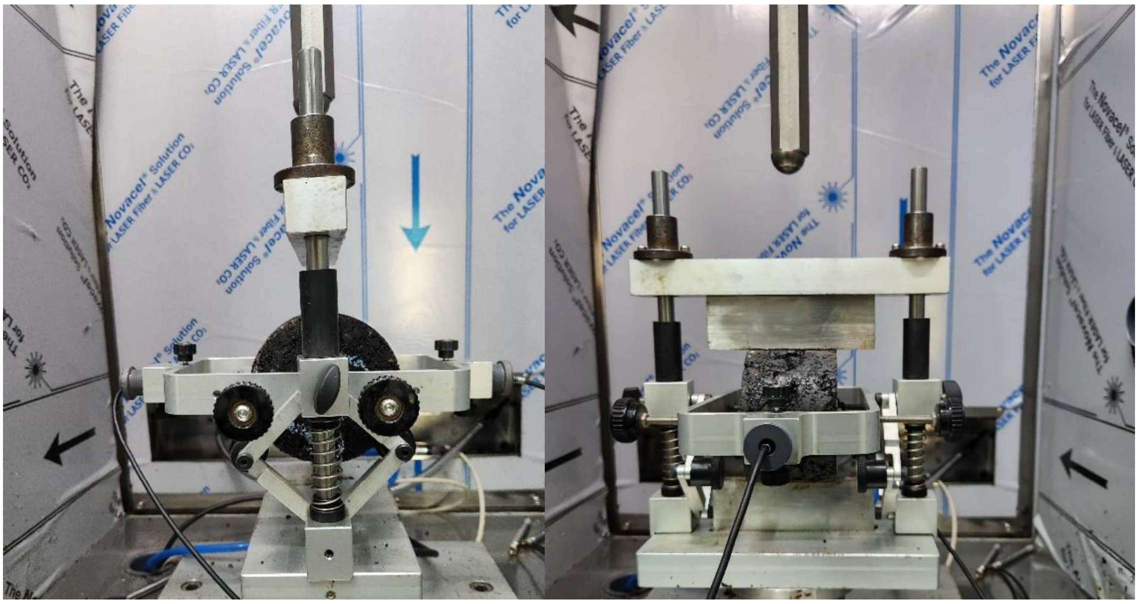

Figure 4.5. Resilient modulus test set up for asphalt mixes.

The Marshall mix samples were prepared with air voids of 7 ± 0.5%. The required voids were achieved by reducing the number of blows from 75. The tests were repeated at three different temperatures of 25, 35, and 45° C. A 10% of peak load (failure load) obtained from the ITS test [234] was used for M_r tests. The results of M_r values obtained for various asphalt mixes at different test temperatures are shown in Table 4.5.

Table 4.5. Resilient modulus (MPa) of AC mixes at different test temperatures

Mix type	Resilient modulus (MPa)		
	25° C	35° C	45° C
BC-1	2992	1826	618
BC-2	3373	2241	709
SMA-1	3134	1449	852
SMA-2	2809	1065	702

As shown in Table 4.5, it was found that at low and intermediate temperatures (25 and 35° C), resilient modulus of BC-2 mixes was higher than SMA mixes; however, at higher temperatures, resilient modulus of SMA mixes is higher than BC mixes. This could be explained by the fact that at lower temperatures, binder is stiff in the mix and BC offers more resistance to applied load due to relatively denser gradation. However, at the higher temperature, viscosity of binder reduces significantly, and load is mainly resisted by the aggregate skeleton. Since, SMA mixes are composed of a higher fraction of coarser particles, aggregate-to-aggregate contact is more effective. These findings support the usage of SMA mixes at extreme pavement temperatures where relatively higher deformations are expected. In the current design guidelines, it is recommended that grades suitable for temperatures nearest to the specified maximum should be adopted [20]. The maximum pavement temperature prevailing in different parts of India together with suggested M_r values are shown in Table 4.6.

Table 4.6. Maximum temperature [235] and M_r of mixes for different regions in India

City	State	Air temp (°C)	Pavement temp (°C)	Region	M_r (MPa)
Delhi	Delhi	45	66.87	Northern	339
Srinagar	J&K	28	50.74		727
Phalodi	Rajasthan	51	73.00		224
Surajpur	Chhattisgarh	46	68.30	Central	304
Munger	Bihar	47	69.11	Eastern	288
Jalpaiguri	West Bengal	34	56.60		582
Guwahati	Assam	45	67.13		328
Mumbai	Maharashtra	35	57.93	Western	542
Himmatnagar	Gujarat	42	64.46		388
Tirumangalam	Tamil Nadu	40	62.26	Southern	438
Udupi	Karnataka	37	59.68		495
Vizianagaram	A. P	48	70.34		264

Though these temperatures do not last long, they may play a vital role in the selection of suitable binder and deciding mix performance during their lifetime. As shown in Table 4.6, the pavement temperature has huge impact on mix stiffness and resilient modulus reduces significantly with the increase in temperature.

4.4.2 Viscoelastic material properties of asphalt mix

This section deals with creep compliance test and viscoelastic material characterization of BC-2 mix. Time and temperature dependence of the asphalt mix response is captured in creep compliance test. It is well known that depending upon loading and ambient (temperature) conditions, asphaltic materials such as BC can exhibit viscoelastic/visco-elasto-plastic behaviour [78]. Hence, many researchers in the past have studied the viscoelastic behaviour of binder [79][80] and bituminous mixes [81][82][83][84][85][86] for the analysis of flexible pavement. It is important to measure the properties of BC at a wide range of frequencies and temperatures to obtain viscoelastic behaviour. At high temperatures or under slow-moving loads, it may exhibit a purely viscous flow reflecting its propensity towards rutting. However, at relatively low temperatures and fast-moving loads, it becomes progressively harder and eventually brittle, which makes it vulnerable to non-load-associated distresses like low-temperature cracking. Moreover, it is susceptible to fatigue-related problems at normal temperatures as most of the vehicular load is applied at these temperatures [87].

The characterization of viscoelastic properties is often done by measuring creep behaviour [88]. The creep-related tests are popular because these tests make it possible to determine and separate the time-independent (elastic strain) and time-dependent (viscoelastic) components of the strain response [89] in a simplified way. In addition, parameters obtained from creep tests at low temperatures (m-value) are used to predict thermal cracking development and propagation, and those at high temperatures are used to predict rutting in the SD [90].

4.4.2.1 Creep compliance test

The test sample was prepared with all the volumetrics as discussed in section 4.3.3 (see Table 4.3). Creep compliance test procedures apply to samples having a maximum aggregate size of 38 mm or less. As per AASHTO T-322 [92], the sample should be 38 to 50 mm high and 150 ± 9 mm in diameter. Both ends of the sample were cut by 6 mm to provide smooth and parallel surfaces for better mounting of the deformation measurement transducer (LVDT). Four brass gauge points were attached to each flat face of the sample. The gauge distance was kept at 50 mm. Two 0.1 mm LVDTs were connected on each face, one in the axial direction of loading and the other in the lateral direction. The specimen was allowed to remain at test temperature for 3 hours prior to testing for conditioning of the sample.

A constant load of 2 kN for 100 sec was applied on the diametrical axis of the sample. Creep load was selected to keep the strain within the linear viscoelastic range i.e., produces a horizontal deformation of 0.00125 mm to 0.0190 mm. Based on horizontal and vertical deformations, normalised deformations and trimmed mean were calculated as per AASHTO T-322 for evaluating the creep compliance of the mix. The test setup for creep compliance is shown in Figure 4.6.

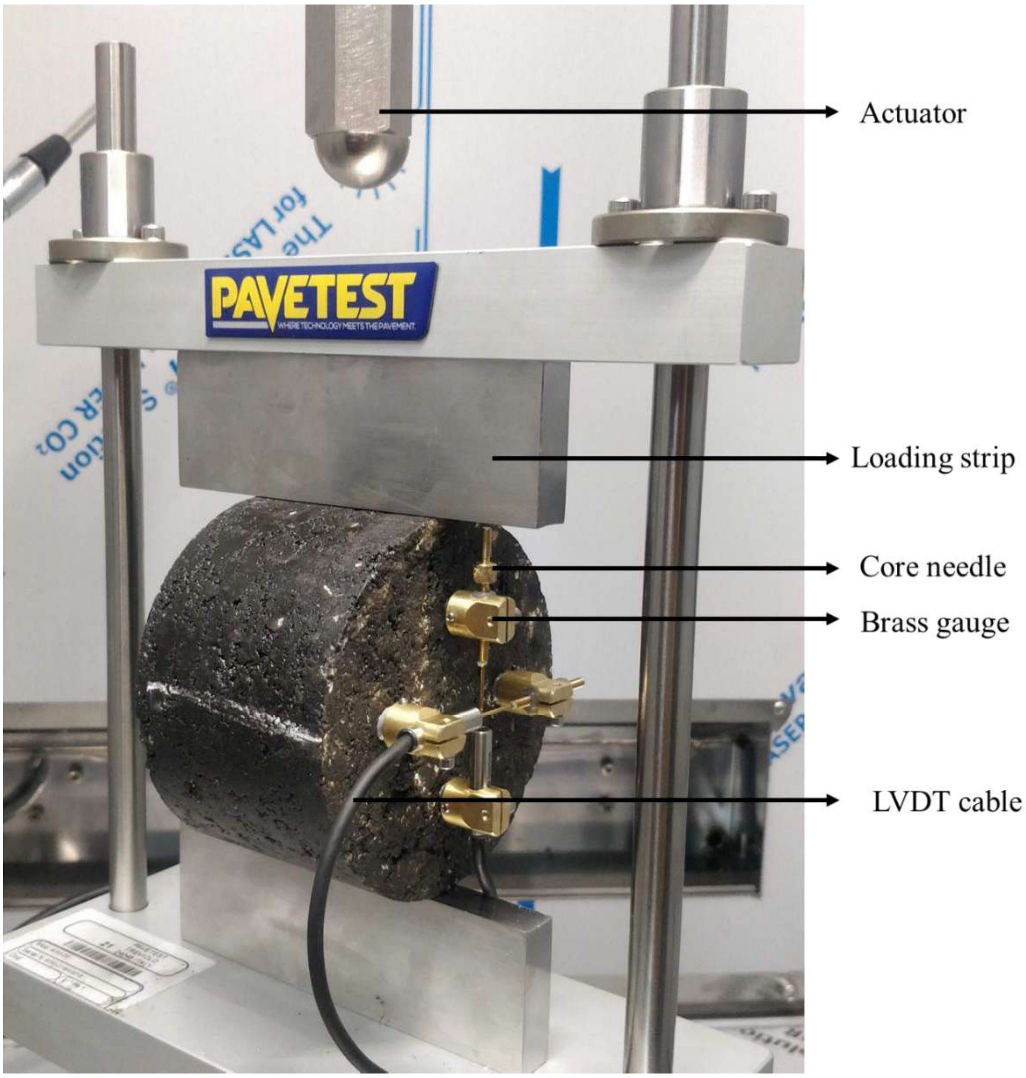

Figure 4.6. Specimen loading frame for creep compliance test.

Creep compliance test was conducted for the determination of the time-dependent response of BC-2 at three different air voids of 4, 5, and 6%. Samples have been tested at three different test temperatures of 5º, 15º, and 25º C against each air void. Horizontal and vertical deformations of the sample with temperature have been noted as shown in Figure 4.7.

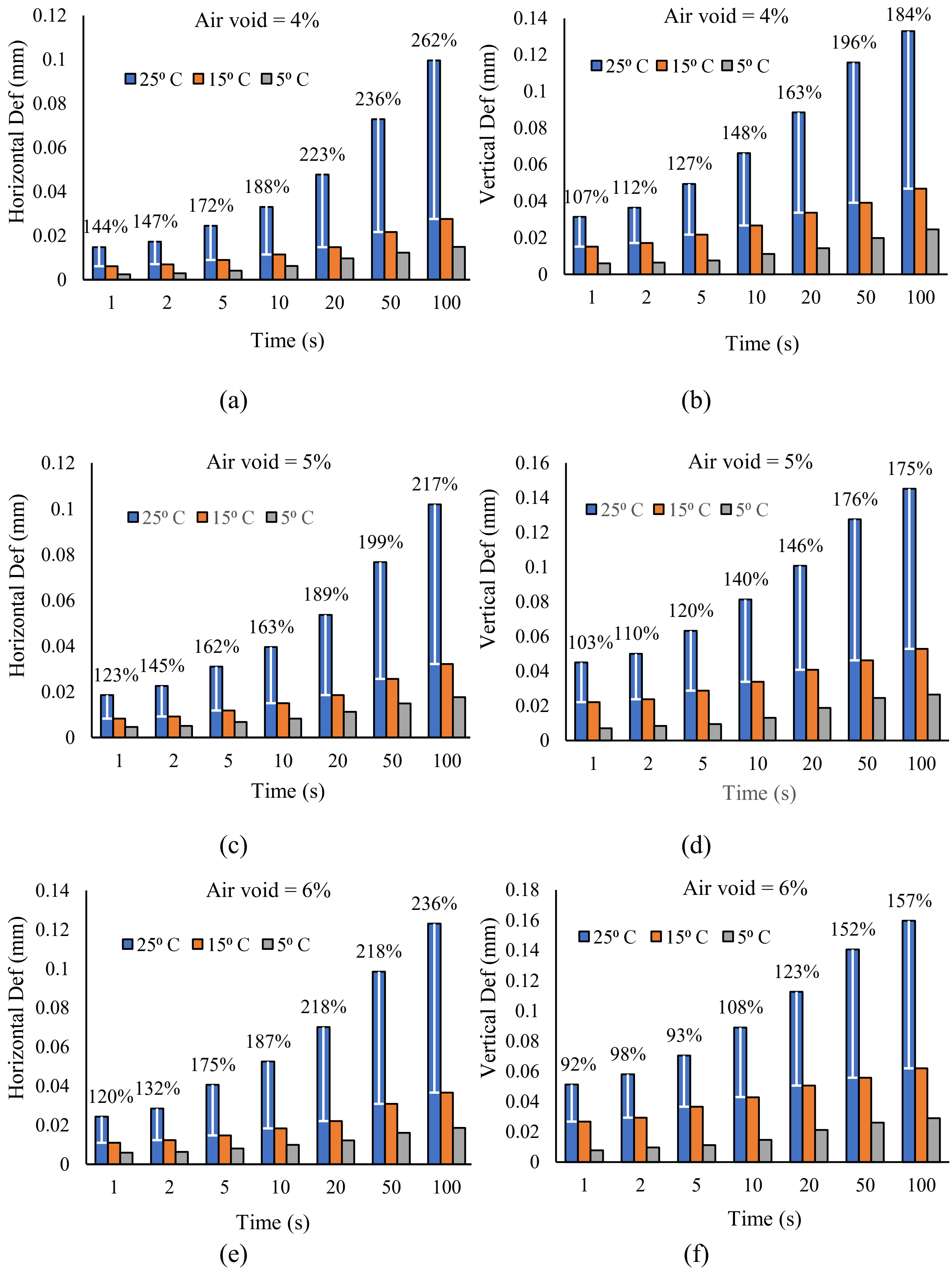

Figure 4.7. Variation of horizontal and vertical deformations with time.

It can be noted that as loading time increases, both horizontal and vertical deformation also increases. The gradient of the deformation-time graph is steeper at the beginning and gets flatter at the end. These deformations were also found to increase with air void and temperature. With the increase in temperature, the stiffness of the material decreases thus deformation is found to increase. Further, with the increase in air void in the mix, the density of the mix decreases which allows constituent particles to settle more easily into these voids, and deformations in the axial as well as lateral direction increases. Percentage change in deformation at each time step has been evaluated and shown for the temperature of 25° C compared to 15° C in Figure 4.7. It was found that, change in material deformation when temperature changes from 15° to 25° C is significantly higher as compared to same change in temperature from 5° to 15° C. It indicates the drastic decrease in material stiffness with increasing temperature.

The average annual temperature in India hovers around 25° C, so analysis is more focused on this temperature. Also, to maintain clarity in the figures, the percentage change in deformation at 15° C compared to 5° C has not been shown here. It can be seen from Figure 4.7 that, the percentage change in deformation is continuously increasing with time. It shows, higher material stiffness at lower temperatures, and consecutively, the deformation plot flattens more quickly than at higher temperatures. A similar trend was not observed for 15° C temperature compared to 5° C. Percentage changes in deformation were relatively stable and constant. This may be due to at lower temperatures, change in material stiffness is relatively constant, and elastic deformation is more dominant than plastic deformation. These deformation data were used to find creep compliance of the material as per AASHTO T:322-07 [92].

4.4.2.2 Material modelling

The generalized Kelvin model (GKM) and the generalized Maxwell model (GMM) are the two widely used models for characterizing linear viscoelastic properties of asphalt mix [101]. These models best fit the relaxation modulus and creep compliance as a series of decaying exponentials also called as Dirichlet or Prony series [101]. Viscoelastic functions represented using the Prony series can be mathematically converted from the time domain to the frequency domain [101]. The GMM for a viscoelastic solid consists of a spring and several Maxwell elements assembled in parallel. Maxwell elements are a combination of spring and dashpot representing elastic and viscous components of the mix. The GMM is convenient for analysing the relaxation behaviour of linear viscoelastic materials. The relaxation modulus of GMM has the form of the Prony series as shown below:

$$E(t) = E_{\infty} + \sum_{k=1}^{n} E_k \exp\left(-\frac{t}{\rho_k}\right) \tag{4.14}$$

Where E_{∞} is the equilibrium modulus, ρ_k and E_k are the relaxation time and the stiffness of the kth Maxwell element respectively. The complex modulus of GMM in the frequency domain is given by Eq. 4.15 [102].

$$E^*(\omega) = E_{\infty} + \sum_{k=1}^{n} \frac{i\omega\rho_k E_k}{1 + i\omega\rho_k} \tag{4.15}$$

where ω is the angular frequency. However, the GKM consisting of a spring and several Voigt elements connected in series is convenient for analysing the creep behaviour of viscoelastic material [101]. The creep compliance, D(t) of GKM is given by [102] as follows:

$$D(t) = D_o + \sum_{k=1}^{n} D_k \left(1 - \exp\left(-\frac{t}{\tau_k}\right)\right) \tag{4.16}$$

where D_o is instantaneous creep compliance, τ_k, and D_k are the retardation time and creep compliance of the kth Voigt element respectively. Model parameters, τ_k and D_k are determined by a series of constraint optimization processes using the least square approach [103].

In this study, the Prony series and power law series have been used to model linear viscoelastic material properties of BC-2. Power law series is a simple power function of time in which evaluation of only instantaneous creep compliance and time exponent is required [195]. A power law model if used with multiple power law terms can present a smooth and reliable viscoelastic response of bituminous mix with minimal impact from local variance in data. However, from the computational point of view, a Prony series representation is preferable to a power law model because of its efficiency and better exponential fitting of material response [196]. In the present study, the five-term Prony series and single-term Power series are used to model the viscoelastic properties of BC-2. It is noted that the Power Law series has been kept simple just for the pre-smoothing and comparison purposes (see Eq. 4.17). Pavement response analysis has been carried out based on outcomes of the Prony series model only.

$$D(t) = D_o + D_1(t)^n \tag{4.17}$$

where D_o is instantaneous creep compliance, D_1 is the model parameter and n is the time exponent.

4.5 Creep compliance test results

Creep compliance is a measure of material deformation with time. It measures the time and temperature dependency of viscoelastic material like asphalt mix. Variation of creep compliance as a function of time at an air voids of 4, 5, and 6% and a temperature of 5°, 15°, and 25° C is shown in Figure 4.8. The deformation data obtained (as shown in Figure 4.7) from the test was used to evaluate creep compliance using following expression:

$$D(t) = \frac{\Delta X_{tm,t} \times D_{avg} \times b_{avg}}{P_{avg} \times GL} \times C_{cmpl} \tag{4.18}$$

where, D(t) is creep compliance at time t, GL is gauge length (m), b_{avg} is average thickness of test sample, D_{avg} is average diameter, P_{avg} is average creep load, $\Delta X_{tm,t}$ is trimmed mean of horizontal deformations for face i at time t, and C_{cmpl} is a compliance factor given as:

$$C_{cmpl} = 0.6354 \times \left(\frac{X}{Y}\right)^{-1} - 0.332 \quad (4.19)$$

$$\frac{X}{Y} = \frac{\Delta X_t}{\Delta Y_t} \quad (4.20)$$

where, ΔX_t and ΔY_t are trimmed mean of horizontal and vertical deformations respectively.

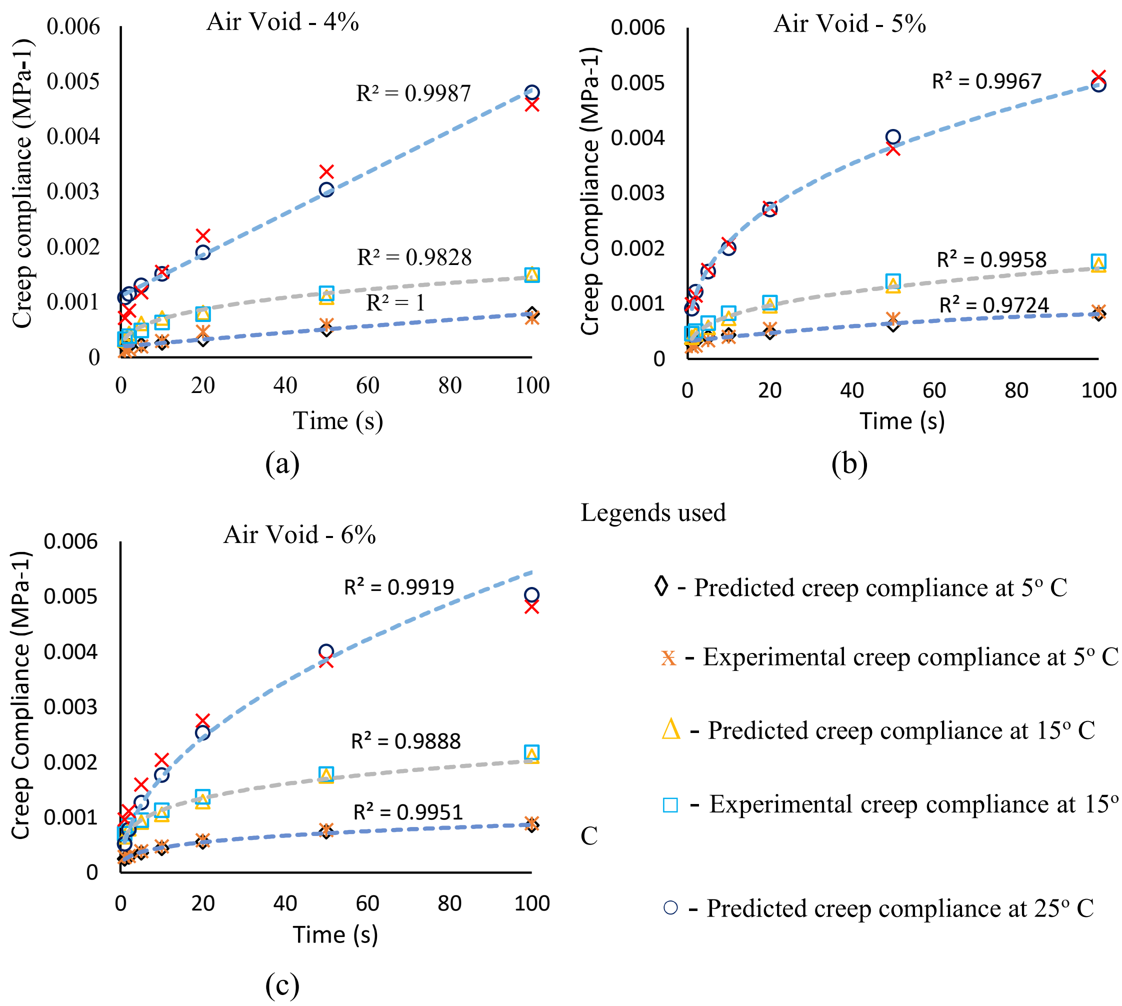

Figure 4.8. Variation of creep compliance (experimental and model fit) with time at (a) 4% air void (b) 5% air void (c) 6% air void.

It was observed that deformation in material at higher temperature (25° C) is significantly higher than at lower temperatures (5 and 15° C). It can be seen from Figure 4.7 and Figure 4.8 that trends of deformation and creep compliance plots are simillar as they hold a proportionality relationship among them. Creep compliance data as fitted in the Prony series model shows good agreement with lab-calculated data at lower temperatures and variation increases at higher temperatures. It can be noted that a model that fits compliance data with great accuracy at lower temperatures may not fit well at higher temperatures. In this study, the Prony series model was fitted to consider the elastic stiffness of the material and hence it is not that accurate to consider plastic flow behaviour at a higher temperature.

4.6 Conversion of creep compliance data to stress relaxation modulus

Creep test results were also used to study the material stiffness using relaxation modulus. This relaxation modulus was used to further study the shear and bulk modulus of BC-2 material. Power law and the Prony series model were used to fit the relaxation modulus variation with time. Then, the time-dependent variation of shear modulus G(t) and bulk modulus K(t) were estimated assuming constant Poisson's ratio given by the following relation:

$$G(t) = \frac{E(t)}{2(1+\upsilon)} \tag{4.21}$$

$$K(t) = \frac{E(t)}{3(1-2\upsilon)} \tag{4.22}$$

Creep compliance fitted by Power law and Prony series is presented in Figure 4.9 (a) and (b) respectively. Relaxation modulus, shear modulus, and bulk modulus as predicted from equations (4.11), (4.21), and (4.22) were plotted against reduced time and shown in Figure 4.9 (c) and (d). It is noted that as stress relaxation modulus hold inverse relation with creep compliance; so, relaxation modulus was found to decrease with reduced time. Creep compliance data fitted using Power law series was not found in agreement with laboratory test obtained data. The higher order series of Power law may predict better correlation however in present study it has been used as a pre-smoothing tool only.

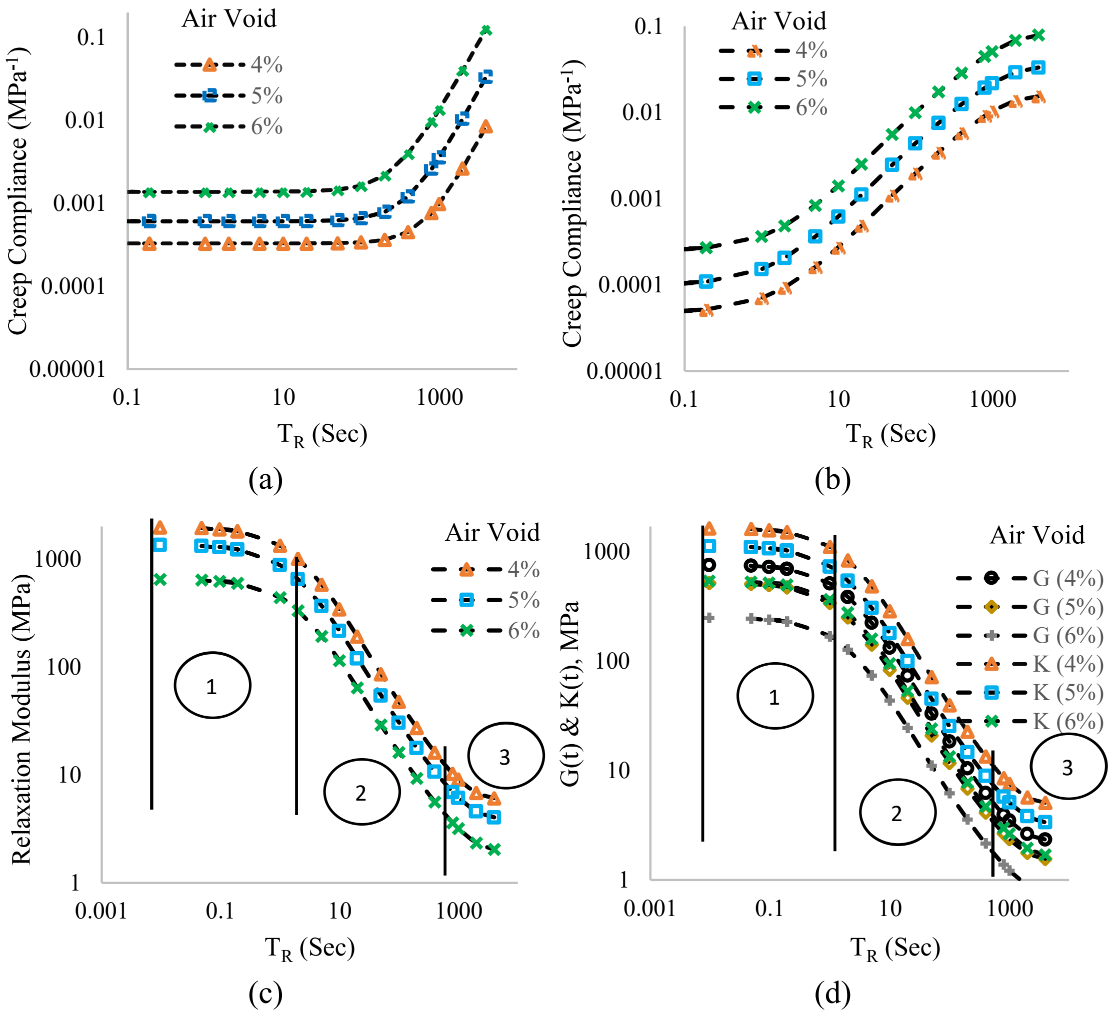

Figure 4.9. Variation of creep compliance with time fitting (a) Power law (b) Prony series (c) relaxation modulus with time and (d) shear modulus and bulk modulus with time.

The Power law model as shown in Figure 4.9 (a), is not a good fit of creep compliance data, as for a long period, there is almost no change in creep compliance and thereafter starts increasing with a steep gradient. It can be used to pre-smoothen the creep compliance data before fitting it to a Prony series model. Trends of creep compliance data as fitted in the Prony series model were found simillar as evaluated in the lab. So, the Prony series model was found to be a good fit for creep compliance data and can predict it well as a function of time as shown in Figure 4.9 (b).

Further, relaxation, shear, and bulk modulus data were also fitted. Relaxation modulus was found to follow the inverse trend compared to creep compliance variation with time as shown in Figure 4.9 (c). Since shear and bulk modulus hold a proportional relation with relaxation modulus, their plot also follows a simillar trend as that of relaxation modulus as shown in Figure 4.9 (d). Plots of relaxation modulus, shear modulus, and bulk modulus can be classified into three zones. Zone 1 and 3 are identical in nature and reflect very small variations in modulus values with reduced time. Plots are relatively flatter in these zones. In zone 1, the material offers the highest resistance to the applied load and modulus values mobilise to maximum as constituent particles are intact in the mix. As time passes, particles start slipping from their original position and the modulus keeps on reducing in zone 2. At the end of zone 2, when the resilience of the material is negligible against applied load, a relatively flat plot is obtained in zone 3.

4.7 Summary

Understanding the behaviour of material subjected to different loading and environmental conditions is important for reliable and economic pavement design in ME design method. Current design practices and guidelines in most of the emerging economies including India are based on linear elastic response of asphalt mixes. This assumption holds good, if asphalt mixes are subjected to static loading and low temperature conditions. However, at high temperature and transient loading conditions, theory of linear elasticity does not yield reliable behaviour of asphalt mixes and often underestimates pavement response. Past studies have shown that, these mixes exhibit viscoelastic behaviour at intermediate and high temperature conditions. Further, theory of linear viscoelasticity can be used reliably to explain asphalt mix response at intermediate temperature subjected to transient loading conditions.

However, complexities involved in the determination of viscoelastic properties is a major hurdle. In India, IITPAVE is used to analyse and design asphalt pavement based on linear elastic response of materials. AASHTO has developed AASHTOWare software which facilitates consideration of viscoelastic properties of asphalt mixes. Similar tools need to be developed/utilized for countries like India, which is capable of using viscoelastic properties of asphalt mixes. These advancements require huge scientific data under Indian environmental and loading conditions.

Present study includes both linear elastic and viscoelastic material characterization of asphalt mixes at different temperatures and air voids so that a comparative understanding of mix behaviour and its effect on the structural response of asphalt pavement can be presented. Elastic response of four different asphalt mixes (BC-1, BC-2, SMA-1, and SMA-2) commonly used in India were evaluated using resilient modulus test. Linear viscoelastic response of BC-2 mixes (dense graded) was determined using creep compliance test. Only BC-2 mixes were selected for viscoelastic material characterization of asphalt mixes in line with the set objectives and time constraint. Future studies may include other mixes also.

As mentioned earlier linear elastic material properties of four different mixes (BC-1, BC-2, SMA-1, and SMA-2) were evaluated at three different test temperatures of 25, 35, and 45 ^{o}C using resilient modulus test. It was found that, at low temperatures, BC mixes yield higher stiffness than SMA mixes. However, at high temperatures, stiffness of SMA mixes is higher than BC mixes. This could be explained by the fact that at lower temperatures, binder is stiff in the mix and BC offers more resistance to applied load due to relatively denser gradation. However, at the higher temperature, viscosity of binder reduces significantly, and load is mainly resisted by the aggregate skeleton. Since, SMA mixes are composed of a higher fraction of coarser particles, aggregate-to-aggregate contact is more effective. These findings support the usage of SMA mixes at extreme pavement temperatures where relatively higher deformations are expected.

Additionally, linear viscoelastic response of BC-2 mixes was evaluated at three different air voids of 4, 5, 6% and three different test temperatures of 5, 15, and 25 ºC. It was interesting to note that, stiffness of the asphalt mix decreases sharply as temperature in the mix rises. The change in deformation when temperature rises from 15 ºC to 25 ºC was found significantly higher (p value obtained from statistical analysis was 0.093) than same change in temperature from 5º to 15º C. It indicates the drastic decrease in material stiffness with increasing temperature.

The laboratory determination and material modelling of asphalt mixes has been presented in this chapter. The material characterization of UGMs in base, subbase, and subgrade layers based on linear elastic and stress dependent behaviour is discussed in next chapter (chapter 5). Finally, these material properties will be used in the FE model to evaluate structural response of the asphalt pavement.