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Investigation of Glass Transition Temperature of Asphalt Concrete

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ABSTRACT

The presented manuscript identifies the mix design parameters important for the glass transition temperature and thermo-volumetric properties of asphalt–concrete mixes. A number of compacted specimens were prepared at different air-void content, by mixing different composition of materials in terms of aggregate origins, asphalt types, and gradations. The compacted mixes were later sized to required dimensions and were subjected to a uniform rate of cooling in a specially designed testing machine. The contraction of the sample during the cooling was measured by linear vertical displacement transducers, and the recorded values obtained were converted into longitudinal strain. All variables investigated in the study were found statistically significant to impact the glass transition temperature of asphalt paving mixes. The methodology adopted in this study provides a new approach to predict glass transition temperatures in asphalt–concrete mixes and identifies the mix parameters that will be helpful in delaying the glass transition temperature of the mix for reliable performance of asphaltic pavements in cold regions.

Keywords

glass transition temperature, thermo-volumetric properties, ANOVA, statistical modeling

NOTE: This paper originally published online with a single author. This paper was updated on DATE with the current author listing. Please see the Corrigendum added to page 1690 for more information.

Nomenclature

A = aggregate
AC = asphalt cement
αg = thermal coefficients after glass transition temperature
αh = thermal coefficients before glass transition temperature
ANOVA = analysis of variance
B = basalt aggregate
C = coarse gradation
F = fine gradation
G = gradation
GTT = glass transition temperature
HMA = hot mix asphalt
L = limestone aggregate
LCPC = Laboratoire Central des Ponts et Chaussees
OAC = optimum AC content at 4 % air voids
OM = optimum minus (O % − 0.5 %)
OP = optimum plus (O % + 0.5 %)
P = percentage asphalt–cement content
Prob = probability value
R^2 = coefficient of determination
S = SBS modification
SBS = styrene butadiene styrene
SD = standard deviation
Z = neat or non-modified asphalt

Introduction

The glass transition temperature (GTT) of a binder can be stated as the temperature at which the binder flow and deformation property moves from a viscoelastic to an elastic medium. The mechanical behavior of asphalt binder during extreme service temperature is strongly influenced by GTT. It is generally believed that the binders having service temperatures below GTT perform admirably well under heavy traffic loading conditions [1]. It is also imminent from previous studies that that the GTT strongly influences the asphalt-mixture response during cooling and heating cycles and poses a serious threat to repel low-temperature cracking of asphalt paving mixtures. Low-temperature cracking is essentially a transverse crack occurring because of the shrinkage of pavement surface course by either the variance of daily air temperature or because of an extreme minimum temperature. Asphalt concrete exhibits behavior contracting upon cooling and expanding upon heating, like any other material. During a significant reduction in the air temperature, large tensile stresses are developed because the pavement is restrained to contraction caused by the friction at the bottom of the surface, thus resulting in an eventual fracture of the surface layer. At a given temperature, the higher the capability of the material to relax stress because of time-reliant behavior of viscoelastic materials, the lower the thermal stress buildup will be at a given temperature, and, consequently, the pavement can withstand lower temperatures before fracture [2,3]. Thus, the importance of stress relaxation cannot be ignored for predicting thermal cracking resistance of asphalt-mixture pavements [4]. Previous studies have indicated that the low-temperature cracking in asphalt concrete is influenced by factors [such as rate of cooling, coefficients of expansion (COE)/contraction, GTT, shape of the master curve at low temperatures, and tensile strength] that affect the critical cracking temperature [3]. A thermo-volumetric property of asphalt concrete includes COE and GTT. These properties are required to be measured to evaluate the mix performance under low service temperatures. The behavior of asphalt mixtures that are subjected to extreme low temperatures shows a bilinear curve for volume change versus temperature. At GTT, the slope changes abruptly and the value of COE is lower than the value measured earlier. The history of measuring the GTT is not very long, and, in the last decade, scientists found various successful laboratory methods to measure it. As there was, and still is, no universally agreed-upon method to measure GTT, studies in the 1960s used models to predict GTT empirically derived by testing a relatively small set of the mixtures and by using a typical COE value. This simplification is understandable because of the difficulty of measuring the COE together with the lack of ample knowledge about consequences of various mixture variables on these coefficients. Researchers [5] measured the thermal coefficients of nine asphalt binders, below GTT and above GTT, using a borosilicate glass dilatometer and found that the percentage of asphaltenes vary. They also found that the GTT ranged from 2°C to −37°C and the thermal coefficients below the glass transition were between 3.7×10^{-4}/°C to 3.4×10^{-4}/°C. They attributed the difference in the measurable properties to the existence of a varying percentage of asphaltenes in the binders (as shown in the last three columns of **Table 1**).

Some researchers [6,7] believed that the glass transition behavior of asphalt is a second orderly transition behind the melting point, and glass transition occurs when a change in volume rate with respect to temperature enters a discontinuous phase. The glass transition point of the asphalt binder was measured in the study [8], and it was found that a particular change of slope in the volume–temperature plot indicates an abrupt change in the thermal coefficients, once the GTT is reached. Most of the researchers [9] use formulation to estimate the cracking temperatures by the application of apposite coefficient of contraction (COC). But this estimation does not grasp the physical hardening and glass transition behavior observed in asphalt binders. In the last 25 years, many studies [9–21] noted that performance of asphalt concrete is strongly influenced by

TABLE 1 Values of GTT and thermal coefficients [4].

Sample	Asphaltenes (wt. %)	Density (20°C) g/cc	GTT (°C)	Thermal Expansion Coefficient (10^{-4}/°C)		
A	100.0	1.079	None	—	—	—
B	75.0	1.053	None	—	—	—
C	61.9	1.039	2.0	5.8	3.7	2.1
D	58.6	1.034	0.0	6.0	3.8	2.2
E	57.1	1.030	−2.0	6.3	4.0	2.3
F	52.5	1.027	−6.5	6.6	3.9	2.7
G	50.8	1.026	−7.5	6.8	3.9	2.9
H	28.6	1.014	−22.5	6.9	3.7	3.2
I	0.0	1.004	−37.5	7.6	3.4	4.2

temperatures near GTT, ultimately resulting in physical hardening of asphalt binders. The GTT of asphalt–concrete mixtures is influenced by the physical hardening of asphalt binders [14] that can change the position of the GTT in asphalt mixtures. Furthermore, change in relaxation properties has been noted in asphalt and many polymers during physical hardening [13–15]. Modern researchers [22–24] show that the physical hardening of mixtures can be predicted by measuring the hardness of the binder, and the GTT can be calculated by applying the Hirsch model. The binders have shown to have a higher BBR grade loss after 72 h of conditioning after relaxation stress [20]. A research project [25] studied the model for determining the effect of thermal cycles on the COE of asphalt mixtures. Their model accounted for the asphalt mixture glass transition and physical hardening, and it is claimed to predict the thermo-volumetric parameters that can significantly affect the asphalt-mixture response during cooling and heating cycles. **Table 2** shows values of GTT and the COE reported in the various literature available. Eminent researchers [26] proposed following empirical Eq 1 to estimate the mix thermal properties from the properties of the binder and aggregate:

$$\alpha_{mix} = \frac{VMA * \alpha_{AC} + V_{agg} * \alpha_{agg}}{3 * V_{total}} \quad (1)$$

where:

α_{mix} = the linear coefficient of thermal contraction of asphalt mixture (1/°C),

α_{AC} = the volumetric coefficient of thermal contraction of asphalt binder in the solid state (1/°C); an average value of 3.45×10^{-4} (1/°C) was used,

α_{agg} = the volumetric coefficient of thermal contraction of aggregate (1/°C),

VMA = the percent volume of voids in mineral aggregate (air voids + volume of effective asphalt),

V_{agg} = the % volume of aggregate in the mixture, and

V_{total} = is the total volume, 100 %.

Another study [1] used a simple dilatometer to measure the GTT of varying asphalt binders. The test setup measured the amount of contraction of asphalt-binder samples, and the volume change measurement was then converted into volumetric strain as a function of temperature. The obtained curve was fitted to Eq 2 by applying non-linear regression methods, to calculate the GTT and the COE. **Fig. 1** represents fitted data obtained from Eq 2. Results of these tests showed that the glass temperature is highly dependent upon the type of aggregate and the modification used. The author also pointed out that the GTT alone cannot be a good indicator to estimate the potential of a mix for low-temperature cracking:

$$v = C_v + \alpha_g(T - T_g) + R(\alpha_h - \alpha_g)\ln\left[1 + \exp\left(\frac{T - T_g}{R}\right)\right] \quad (2)$$

where:

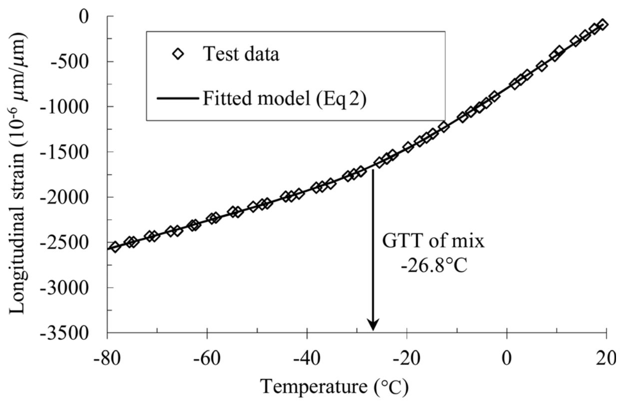
v = specific volume at temperature T,

C_v = volume at a given temperature,

TABLE 2 GTT and coefficients reported by different authors for asphalt concrete.

Researchers	Range of T_g (°C)	Range of α_h ($\times 10^{-4}$)	Range of α_g ($\times 10^{-4}$)
Wada and Hirose [5]	+2 to −37.5	5.8–7.6	3.4–4.0
Schmidt and Santucci [7]	+5.9 to −36.4	5.6–6.2	2.7–3.3
Jongepier and Kuilman [28]	NA	N.A.	2.7–3.6
Bahia and Anderson [4]	−4.1 to −28.2	5.9–6.8	3.3–3.6
Nam [1]	−17.2 to −54.7	5.2–7.3	2.3–4.9
Nam and Bahia [29]	−24.5 to −45.4	5.8–5.87	2.9–3.6
Marasteanu et al. [24]	−20 to −43.6	4.44–5.83	1.25–3.50

FIG. 1 A typical plot of a sample tested for GTT with data fitted by Eq 2.



T_g = glass transition temperature,
R = constant defining the curvature,
α_h = thermal expansion coefficient for $T > T_g$, and
α_g = thermal expansion coefficient for $T < T_g$.

Even though a number of researches have been conducted to study the effect of polymer modification and aggregate on GTT and COE, however, no well-developed test method and agreement among the outcomes of different researches has been agreed upon. This is because of the fact that the researchers used different configurations for testing thermal properties and because of the complexity of asphalt concrete behavior, which itself is dependent upon many variables. It is also pertinent from the literature that physical hardening of binders in asphalt mixture is one of the special causes of stress relaxation thus detrimental in low-temperature cracking of pavements. This would also mean that studying the properties of asphalt mixture is also important and very much related to investigation of GTT and COE of asphalt mixtures. Hence, it can be concluded that GTT in asphalt concrete may be affected by the material selection process, effect of mix properties, i.e., aggregate type and its gradation, polymer modification, and air-void content. This ultimately warrants the need to investigate these parameters in detail while arriving at the GTT of the mixtures. The motivation for this study is, thus, to research mix properties and test parameters using an improved testing procedure, verify the outcomes of previous findings, and investigate the thermal behavior of asphalt concrete fabricated using local materials.

Objective and Scope

The objectives of the proposed research can be summarized as follows:

1. To develop test setup for determining GTT of asphalt concrete test specimens, and
2. To present the empirical model for prediction of GTT of hot mix asphalt specimens.

The scope of the study includes development of a testing device, preparation of asphalt concrete specimens, performance of GTT tests, and modeling using statistical methods.

The outcomes of this study were aimed at determination of asphalt mix and testing parameters important for evaluation of GTT of asphalt concrete. It was also envisaged that the outcomes of this research would help practitioners in the selection of proper materials and mix design parameters, which, in turn, reduce the potential for low-temperature cracking of asphalt pavements.

Methodology

This section describes the methodology adopted in this study. The discussion includes design of the apparatus and preparation of samples for testing, along with the details of configuration of the samples tested under various testing conditions. In addition, the content presented in this section includes experimental design of samples, determination of the number of samples required, estimation of quantities of materials, sample mixing, compaction, and sizing.

THE TESTING MACHINE

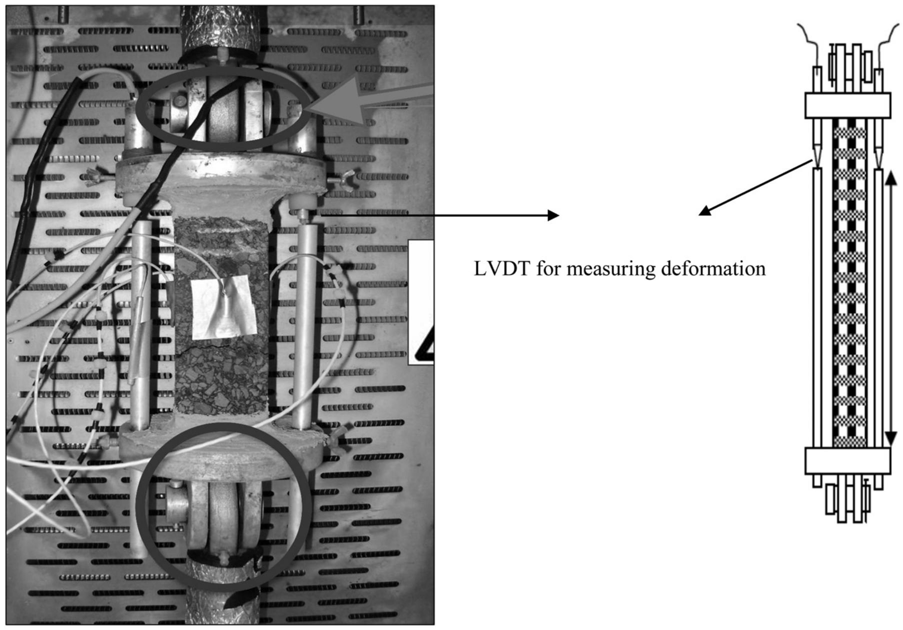
The first task in this study was to develop a machine that could measure contraction of AC beam specimens at each decreasing temperature under controlled loading and deformation state. The test setup included a special cooling chamber equipped with two linear variable displacement transducers to measure the amount of contraction of the AC beam sample. **Fig. 2** depicts the pictorial representation of test setup. The volume change measurement was then converted into volumetric strain as a function of temperature. The bilinear curve was fitted to Eq 2 by applying non-linear regression methods to calculate the GTT and the COE. Method of least squares was used in Microsoft Excel add-ins package solver functions to fit the curve. Thus, the values of the thermal coefficients and the GTT were estimated. The test setup is similar to the dilatometer as used by eminent researchers [1], with a difference that the rate of cooling and loading was accurately controlled in a machine at constant load.

SAMPLE PREPARATION

The task of the sample preparation involved a number of steps, including design of experiment, selection of mix design procedures, calculation of the optimum asphalt content, preparing mixtures for test specimens, and measuring mix volumetric for beam specimens.

Literature review showed that the previous researchers investigated different variables affecting the response of asphalt paving mixtures for GTT. In the light of this, it was considered necessary to study the effects of all parameters, i.e., polymer-modified asphalt, aggregate type, mix gradation, and optimum

FIG. 2 Sample mounted in the machine for measuring GTT with the line diagram.



asphalt content, on GTT of hot mix asphalt. Therefore, to accommodate these four variables, a complete experimental program was needed to determine the total number of samples required for the tests. The experimental program includes selecting two types of aggregates, basalt and limestone, and each of the aggregates were mixed with two asphalt types: neat-non-modified type and SBS-modified type and were sieved for three types of gradation: coarse, fine, and design. Each of the mixes were combined for three different asphalt content, namely, optimum (O), optimum +0.5 % (OP), and optimum −0.5 % (OM). The design variables used in the study are listed in **Table 3**.

The grading requirement of this study was selected from local specification books. The wearing course is specified in two types, namely, Type 1 and Type 2; therefore, coarse gradation was selected as the Type 1 and fine gradation was selected as Type 2, whereas the design gradation was taken from the average of both types. After selecting the mix gradations and estimating the number of samples, aggregate from the selected sources were subjected to sieve analysis for separation according to various size fractions. Some of the required sizes were unavailable; therefore, the oversize aggregates were crushed into a smaller size using a jaw crusher. The gradations selected for the study are shown in **Fig. 3**.

All of the test samples prepared in the study were prepared at the varying asphalt contents near optimum. Selection of the optimum asphalt content (OAC) was achieved based on the Superpave method of mix design. Although Superpave mix design can be used for the selection of asphalt binder grade, aggregate gradation, and asphalt content, the method was used here, only for the selection of OAC for the test mixes because of the graduation requirements of the study.

Three samples for each combination were prepared and tested for the OAC and three replicates were further prepared after finding the asphalt content required for 4 % air voids as per requirement of Superpave mix design procedures. A total of

TABLE 3 Details of variables used in the design.

Sample No.	Name of Variable	Level	Symbols	Coded
1	Aggregate type	2	L, B	+1, −1
2	Polymer modification	2	S, Z	+1, −1
3	Gradation	3	C, D, F	+1, 0, −1
4	AC content	3	OP, O, OM	+1, 0, −1

FIG. 3 Gradation used in experiments.

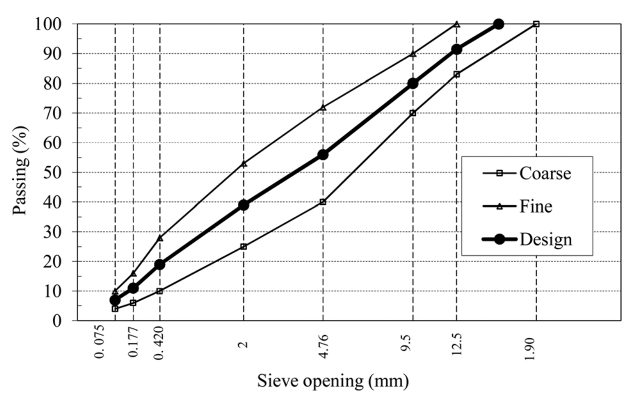


TABLE 4 Summary of specimens prepared for GTT.

Sample No.	Variables	Explanations	
1	Aggregate type	Limestone (L) and basalt (B)	
2	Gradation	Coarse (C), design (D), and fine (F)	
3	AC content	Optimum, optimum + 0.5, and optimum − 0.5	
4	Compaction machine	Superpave gyratory	LCPC
5	Specifications	AASHTO T 312	AASHTO TP 63
6	Shape of specimen	Cylindrical	Prismatic
7	Sample size	100-mm diameter; 115-mm height	$500 \times 180 \times 100$ mm^3

108 cylindrical specimens were prepared. The OAC for each mix configurations were then calculated from the relation of bulk-specific gravities and theoretical maximum specific gravities, which were measured by applying the standard methods (AASHTO T166) [31] and theoretical maximum density (AASHTO T209) [32]. Three samples were further fabricated to confirm the required optimum content. After the value of the OAC, voids filled with asphalt (VFA), voids in mineral aggregates (VMA), and the weight required for each combination of mixes were calculated. Some deviations (±0.5 %) from the target air voids, VFA and VMA were allowed to compensate for the variability in the design according to AASHTO standards. In this study, a total of 12 different mix design configurations were needed for OAC. The values of bulk specific gravity determined from the design samples were then used to calculate the total required amount of materials needed to prepare slab specimens of $500 \times 180 \times 100$ mm^3 dimension.

Because the test setup requires beam specimens, first slab specimens of size $500 \times 180 \times 100$ mm^3 were prepared and then beam specimens were obtained by sawing the slab specimens. Around 22–23 kg of asphalt and aggregate materials were mixed to prepare slab samples. The samples were compacted using the French (LCPC) slab compacter. Before compaction, the mix samples were subjected to short- term aging for 3 h in an oven.

After compaction, the slab specimens were cut into sections of $50 \times 65 \times 300$ mm^3 using a saw diamond machine. A uniform cross section of 65×50 mm^2 was chosen to keep the length to a width aspect ratio between 4 and 6. This value is selected to eliminate the effect of aspect ratio on the response variables of testing experimental design based on the findings of Jung and Vinson [2] who suggested that the effect of aspect ratio would not be statistically significant for test results if the aspect ratio is maintained constant. A uniform code numbers were assigned to each sample after cutting not only to recall material configuration of sample in terms of aggregate type, polymer status, and percentage asphalt added but also to identify its location of sections in a given specimen. The main idea behind this marking is to differentiate between specimens that were cut either from the sides or in the middle because of the fact that the middle of the slab sample is compacted usually more than the side sections. This may mean that the specimens taken from the sides have less air voids than those in the center. During the cutting operation, the cutting saw was cooled down with water to achieve a smooth cutting surface and prevent overheating of the beam specimen. To avoid the discontinuities on the surface of the beam specimens, the slab specimens were cut from both sides. The bulk specific gravity of each specimen was then measured after the required dimensions have been achieved. However, no significant variation of air voids was observed in the samples cut and identified from different positions of slab specimen. This may be because of the care adopted in calculating the exact amount of material needed to compact the mixes for target air voids of 4 %; hence, no implication was observed. **Table 4** summarizes the sample prepared in this study.

Result Analysis of Tests

This section presents a discussion on statistical analysis of GTT tests performed in a specially designed machine. The results were analyzed by adopting an analysis of variance (ANOVA) technique, and discriminant and regression analyses. The results of these analyses are presented in the following sections with relevant references for comparison with the current research outcomes.

ANALYSIS OF VARIANCE TESTS (ANOVA) FOR RESEARCH OUTCOMES

Table 5 presents the summary of GTT values and ANOVA results obtained from the GTT measurements. **Table 5** shows that the average GTT ranges between −25°C and −29°C. The minimum, median value was found for OP, whereas the most median value was found in specimens fabricated with design-graded mix. The effect of aggregate type was found to be significant on GTT results (**Table 5**). The results are not surprising because the aggregates are known to impart their own interaction in the mix. The average GTT for limestone mix was found to be −25.11°C as compared to that of basalt mixes −27.13°C. The median values presented in **Table 5** show that the difference in the average values of aggregate is 3.43°C, which means that the aggregate type is influencing the GTT. These results were also validated by performance of ANOVA analysis (**Table 5**),

TABLE 5 Statistics for GTT measurements.

Design Parameters	Levels	Symbol	ANOVA (*p*-Values)	Average (°C)	Standard Deviation (°C)	Median (°C)
Aggregate type	Limestone	L	0.036	−27.95	4.93	−22.06
	Basalt	B		−24.52	4.98	−27.21
Polymer modification	SBS	S	0.339	−25.51	5.14	−24.81
	Neat (zero)	Z		−26.72	5.28	−26.74
Gradation	Coarse	C	0.957	−28.84	4.59	−28.24
	Fine	F		−28.69	4.94	−26.34
	Design	D		−21.46	2.13	−21.08
AC content	Optimum	O	0.517	−29.07	5.82	−32.38
	Optimum − 0.5	OM		−24.17	4.76	−22.82
	Optimum + 0.5	OP		−25.63	4.37	25.66

showing values <0.05.The gradation of the mix was not found to be a significant factor influencing the GTT. The polymer-modified mixes when tested for GTT give no significant result. The average value of the mixes with polymer modified was −1.21°C higher than the mixes with neat binders (**Table 5**). These results do not conform to similar studies on modified mixes [23,27–29]. The variability of the asphalt content in GTT measurement was insignificant according to the ANOVA analysis. The median values acquired for mixes with less asphalt content are higher than those of mixes with more asphalt content. The difference in the average values for the two extreme asphalt content was found to be −2.84°C as shown in **Table 5**.

THERMAL COEFFICIENTS ABOVE GTT AND BELOW GTT

The thermal coefficients are important parameters in determining the glass transition behavior of asphalt concrete. ANOVA analysis of the results obtained for thermal coefficients shown in **Table 6**. Apparently, no significant effect of aggregate type was observed from the analysis. The coefficients of linear contraction for limestone mixes both above GTT and below GTT are lower than the corresponding coefficients for basalt aggregate mixes. The gradation affects appear to be also insignificant, which is in accordance with the findings in Ref 28. A comparison of the calculated values suggests that the fine gradation mixes show less contraction than do the coarse gradation mixes. This can be explained by the presence of low air-void spaces, which leads to reduced conductivity and hence less contraction of the specimens. Although varying asphalt content produce different values of GTT and the COE above GTT and below GTT, they fail to prove any statistically significant difference.

TABLE 6 Probability values calculated from ANOVA.

Source	Coefficient After Glass Transition, α_g	Coefficient Before Glass Transition, α_h
Aggregate type	0.200	0.218
Gradation	0.533	0.711
Polymer modification	0.455	0.830
AC content	0.745	0.660

DISCRIMINANT ANALYSIS

Discriminant analysis classifies observations into two or more groups called clusters. Cluster analysis or clustering is the task of grouping a set of objects in such a way that objects in the same group (called a cluster) are more similar (in some sense or another) to each other than to those in other groups (clusters). In this study, the discriminant analysis resulted in three clusters in the GTT data. The detailed ANOVA analysis of the GTT data is presented here.

ANOVA for GTT and COE of Clusters from Discriminant Analysis

ANOVA analysis was performed here in clusters from the discriminant analysis of the data obtained in this research. The ANOVA analyses provide the following inferences:

- Aggregate type does not seem to have an effect on the GTT of the mixes (**Table 7**). This finding is different from that of the original unclustered data, i.e., comparing 36 observations.
- Only the asphalt content seems to have an effect on the GTT of the mixes in only one cluster. This finding is also different from that of the original unclustered data for 36 observations.
- The gradation and polymer modification was found to

TABLE 7 Probability values for GTT response for clusters.

Variables	Original Data	Clusters for Discriminant Analysis		
No. of observations	36	10	12	14
Aggregate type	0.036	0.573	0.877	0.605
Gradation	0.957	0.409	0.973	0.363
Polymer modification	0.339	0.547	0.993	0.786
AC content	0.517	0.968	0.019	0.204

TABLE 8 Probability values for thermal coefficients.

Variables	Original Data	Clusters for Discriminant Analysis		
	Coefficients after glass transition temperature			
No. of samples	36	10	12	14
Aggregate type	0.200	0.899	0.358	0.186
Gradation	0.533	0.935	0.369	0.276
Polymer modification	0.455	0.569	0.711	0.683
AC content	0.745	0.757	0.333	0.473
Variables	Coefficients before glass transition temperature			
Aggregate type	0.218	0.373	0.430	0.653
Gradation	0.711	0.465	0.369	0.926
Polymer modification	0.830	0.979	0.761	0.215

have no influence on the GTT of the specimens as indicated by high probability values.

- The ANOVA analysis of COE data are presented in Table 8, which shows that none of the variables examined in the study is found to have an influence on the thermal coefficients.

REGRESSION ANALYSIS

All of the clusters identified and discussed above were then further analyzed for regression to find out the effective factors present either directly or indirectly in determining the response in respect to GTT. Minitab 14 was used to perform the stepwise regressions. In these analyses, multiplications and divisions of variables used in this study are also added as different independent variables to generate mathematical or statistical relationships. Because this procedure was found to be successful, other mathematical forms of the independent variables are not required to further study the interaction of factors between the variables.

The variables were coded in terms of (−1, 1) for two level factors and (−1, 10^{-6}, +1) for three level factors. It is to be noted here that for three level factors, the second level is defined by 10^{-6}, which can be assumed to be zero, but is mathematically not. This value is taken for the new variables that were derived by dividing the existing variables to form new variables and which could have remained statistically undefined otherwise.

In stepwise regression, all variables are studied at the same time either adding the most correlated to the least one by one or omitting the variables that are less significant. Alternatively, in each step, all the significant variables can be added or dropped based on the alpha values and a new regression equation is formed by calculating additional parameters of each case. The process is continued up to completion of this process. During this study, a default alpha value of 15 % was used to add or drop the variables. The generated statistical models are evaluated according to their adjusted coefficients of determination (R^2-adjusted) and standard deviations (SD) of the models. As an optimum, models with minimum number of variables were used considering greater R^2-adjusted values and smaller SD values of the model. The stepwise regression analysis of the given data was performed using different variables on different clusters obtained at various similarity levels. The clusters giving maximum R^2 values were selected as the final clusters for fitting the model. The coefficients present different impacts of various variables on the GTT in the following manner from Table 9:

TABLE 9 Comparison for GTT.

Cluster No.	1G	2G	3G
Variables	14	12	10
Constant	−20.70	−26.50	−33.40
A[a]		0.59	0.78
M[b]	0.466		
G[c]		−0.7	
AG			0.241
AP[d]	−1.19		−0.16
MG		−0.45	−0.45
MP	0.549		
A/P		−1e-07	
SD	0.86	0.07	0.25
R^2	77.4	99.9	98.9
R^2 (adjective)	67.4	99.7	97.5

[a] A = aggregate type.
[b] M = modification.
[c] G = gradation.
[d] P = percentage asphalt–cement content.

- Aggregate types are not influential in one of the cluster (1G). When combined with the other variables, it also has considerable impact upon the GTT of the mixes in two other clusters.
- Gradation has no influence in combination with the other variables in one cluster (3G), however, appears to be influential for the GTT of the mixes.
- Binder modification is independently influential in cluster 1G. In other clusters, i.e., clusters 2G and 3G, its influences on GTT results from a combination with the other variables.
- Asphalt content is not independently influential in any clusters; however, it also influences the GTT of the mixes in other clusters when combined with other variables.

Statistical Modeling

Statistical models were obtained by evaluating the clusters already discussed above. These models are in the form of separate regressed GTT. The selection criteria for finding these models is a two-step process: the presence of the highest number of clusters from the discriminant analysis for GTT data, and evaluation of the sensitivity of the performance of the standard regression parameters in terms of standard deviations, coefficient of determination (R^2) values, and R^2-adjusted values.

TABLE 10 Statistical parameters for GTT

Cluster	SD	R^2	R^2 (adjective)	Equation
1G	0. 860	77	67	3
2G	0.070	100	100	4
3G	0.250	99	98	5

Hence, for each category, three most acceptable equations were selected with their corresponding clusters (see Eqs 3–5). These models are presented in the following sections in terms of glass transition measurement. The criteria for the selection of the equations were the same as for the regression equations for fracture strength and fracture temperature. The regression equations are given as follows:

$$\mathrm{GTT} = -20.7 - 1.19\ \mathrm{AP} - 0.378\ M + 0.549\ \mathrm{MP} \tag{3}$$

$$\mathrm{GTT} = -26.5 + 0.585\ A - 0.7\ G - 0.45\ \mathrm{GM} - 0.0000001\ A/P \tag{4}$$

$$\mathrm{GTT} = -33.4 + 0.777\ A + 0.244\ \mathrm{AG} - 0.16\ \mathrm{AP} - 0.45\ \mathrm{GM} \tag{5}$$

where:

GTT = glass transition temperature,
A = aggregate type,
G = gradation,
M = modification, and
P = percentage asphalt–cement content.

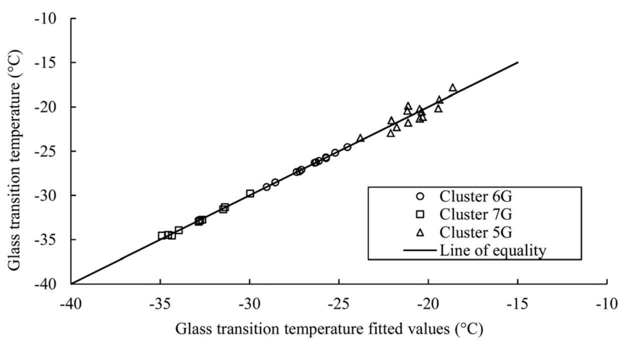
The regression equations for GTT show that the aggregate type and modification are important parameters to influence the GTT of mixes. The fitted data to the regression models and the statistical parameters for the regression equations are presented in **Table 10**. All clusters yield better models for the prediction of glass transition temperature as can be observed from the quality of fit to the line of equality in **Fig. 4** and from the corresponding R^2 values in **Table 10**.

Conclusions and Recommendations

This section summarizes the findings of this study and recommends steps to help the future researchers in pavement engineering for developing new research methodologies. It should be kept in mind that even though the technique adopted for testing statistical analysis was highly innovative and universal, the summarized results shown may vary depending on the experimental program used, materials selected for fabricating test specimens, and test procedures and conditions. The findings of the study can be summarized as follows:

- The testing machine was effectively used for measuring thermo-volumetric strain of asphalt concrete. The values obtained are consistent with the literature and, thus, it can be concluded that the test apparatus can be used for evaluating thermo-volumetric properties of asphalt concrete.
- The statistical modeling technique adopted in this research was effective in analyzing the data and deriving a statistical model. The model was successfully calibrated to the test results to estimate GTT. Based on the model results, one of the statistically insignificant factors, i.e., binder modification, was found to be significant and a contributing factor when subjected to cluster analysis. This highlights the importance of application of clustering technique to a large set of experimental data.
- The common factors identified in the derived models is aggregate type, polymer modification, gradation, and asphalt cement content, which act independently and in combination with other factors on the transition temperature of mixes. These findings support the results of multivariate ANOVA about the significance of these factors for different mix configurations.
- The GTT of mixtures ranged from −18.6°C to −34.7°C showing variations in type of aggregates, gradation, and asphalt content and type of modifier used. Based on these findings, it was assumed that mixtures with limestone aggregate could sustain lower pavement temperature without fracture, and the development of thermal stress will be within the $T < T_g$ range given with smaller thermal coefficient of 9.83×10^{-4}/°C. However, once the GTT is reached, a more brittle behavior was evidenced by a higher thermal coefficient of 6.63×10^{-4}/°C.
- The GTT value observed for SBS mixes are closer to that observed with neat mixes. This happens because the modified binder is behaving the same as neat binder, and it seems that the modification becomes redundant. This is because of the dependency of low-temperature parameters on base asphalt [30]. The present study used 40–50 as the base asphalt, which may not be adequate for low-temperature cracking.
- The presented results can be used to compare thermal properties of two mixtures prepared by limestone and basalt aggregates; however, a detailed investigation is still recommended using a larger data set to reach concluding results.
- Based on the limited scope of the study, it can be recommended that asphalt concrete made with limestone aggregates having a dense gradation with adequate binder

FIG. 4 Line of equality plot for GTT.



(polymer modified with suitable base) and at 4 % air-void content will perform well with regard to low-temperature cracking.

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