FINITE ELEMENT MODELLING OF THERMAL STRESS RESTRAINED SPECIMEN TEST

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ABSTRACT

Low temperature cracks are developed when the temperature of pavement falls below zero degrees Celsius or when the variation in daily air temperatures becomes significant in the field. Various experimental techniques have been suggested to simulate low temperature cracking of asphalt concrete in the laboratory, out of which the thermal stress restrained specimen test (TSRST) is one of the well-known test methods. A research was carried out to model the TSRST using the finite element approach and to calculate the maximum stresses and corresponding strains near failure during testing. Test specimens were prepared with two different aggregate sources and gradations. Dynamic complex modulus tests were conducted to determine the relevant material properties necessary for the finite element analysis. A finite element model was then developed in Abaqus® for the specimens tested in TSRST setup to calculate the thermal stresses and strains near failure. The results of analysis showed that the test specimen can be successfully modelled using the finite element method to calculate maximum stress and corresponding strain in TSRST testing. The strains developed become smaller for limestone aggregate mixtures with higher fracture strength values. In terms of the effect of gradation, fine graded mixtures display smaller strains near failure. It is believed that smaller strains calculated indicate brittle behaviour of mixtures under thermal loading.

Keywords: TSRST: Low -Temperature, Fracture strength, Finite Element Model

1. INTRODUCTION

Low temperature cracks occur in the form of transverse cracks on pavement surface caused by large variations in daily temperature or by extreme minimum temperatures. Asphalt concrete, like other materials, contracts on cooling and because the pavement is restraint to contraction due to the friction at the bottom surface, large tensile stresses can develop causing eventual fracture of the surface layer. The thermal stress at this failure condition is known as fracture strength. Thermal failures in asphalt concrete can occur even after one cycle of temperature drop causing low temperature cracking or sometimes after repeated cycles of temperature changes creating thermal fatigue cracking. Thermal fatigue cracking is dependent upon the largest and the smallest strain rates developed during temperature variations. Vinson et al. [1] pointed out that the most of the thermal cracks occur between temperatures of 6.5 to 21°C while the low temperature cracks occur below 6.5°C. Visually the thermal fatigue cracks are in the form of block cracking as compared to low temperature cracking, which are one dimensional. This research, however, focuses on low temperature cracking behavior of asphalt concrete as the study of thermal fatigue cracking necessitates more involved research and time. Monismith et al. [2] introduced one of the first thermal stress restrains stress test (TSRST) devices that could maintain a constant length of a specimen during cooling, and thus causes an induced thermal stress to test specimen. However, in their initial setup they failed to control the deflection of the frame which resulted in stress relaxation or no fracture. Arand [3] modified the equipment by introducing a displacement feedback loop which took care of the stress relaxation and thus the length was corrected continuously during the test. Nam [4] further modified the instrument by placing LVDTs across an extension rod to measure deformation and controlled the deformation by a bolted nut that is fastened to a rigid frame. Their apparatus, however, did not help an accurate control of displacement during testing due to deformation of the testing frame. Raad et al. [5] concluded that the repeatability of TSRST machine is adequate to give a better representation of thermal stresses in the field. Kanerva et al. [6] also performed a field validation of TSRST results for low temperature cracking of asphalt concrete and found satisfactory results. Sebaaly et al. [7] concluded that TSRST test results are sufficiently accurate to represent thermal behavior of asphalt concrete in the field based on his investigation of mixtures used in Nevada. A detailed evaluation of the TSRST method was also presented by the National Transport Pool study 776 [8] indicating that the method can well represent the thermal behavior of asphalt mixtures.

There is, however, a limitation in testing low temperature cracking behavior of asphalt concrete using TSRST; the thermal strain evolved cannot be directly measured when the environment temperature is reduced as the total displacement due to shrinkage is continuously recovered by the displacement control system. The test method allows for measuring only the fracture strength and fracture temperature, both of which do not give insight into the stress-strain behavior of mixtures. In this study, the finite element analysis is used to estimate the strains developed during TSRST testing. The strains are calculated using a visco-elastic model based on properties measured from TSRST and dynamic modulus tests. The calculated strains are then evaluated in terms mix design parameters, i.e. aggregate type and gradation. The details of the study are presented in the following sections.

2. METHODOLOGY

The methodology adopted in this research includes three main steps: 1) preparation of test specimens and conducting TSRST tests to obtain stress versus temperature relations, and thermal properties of test mixtures; 2) conducting dynamic modulus tests to obtain necessary inputs for finite element analysis; 3) modeling TSRST specimen using finite elements procedure to determine maximum strains attained near fracture in TSRST. The specimens were modeled in Abaqus® [9] finite element analysis software, and strains corresponding to maximum stress levels were calculated by applying to the specimens the total temperature change necessary for the facture of specimens in TSRST. The strains calculated from the finite element analysis were then evaluated in conjunction with the mix design parameters, i.e., mix gradation and aggregate type. The objective of this evaluation is to observe if the strain levels reached near fracture are significant in terms of the mix design parameters.

2.1. Specimen preparation and testing

Tests including TSRST and dynamic modulus were carried out on specimens prepared in the laboratory. The specimens were prepared with two types of aggregate and gradation using an identical bitumen type. Gradations are selected based on the Turkish General Directorate of Highways specification guidelines [10]. The specimens were compacted to around 4% air voids satisfying the Superpave mix design guidelines according to AASHTO T312. Table 1 summarizes the details of the test specimens and the experimental program, and Table 2 is the volumetric data of the mixtures used in this study.

Table 1: Summary of test specimens

Description	**Explanations**	
Aggregate type	Limestone(L) and Basalt(B)	
Bitumen type	PG grade 58-22, Penetration grade 50-70	
Gradation	Coarse (C) and Fine (F)	
Air void content	4 %	
Test conducted	Dynamic Modulus	TSRST
Shape of specimen	Cylindrical	Prismatic
Specimen initial size (mm)	150 diameter; 170 height	500 x 180 x 200
Specimen size tested (mm)	100 diameter; 150 height	300 x 65 x 50
Number of replicates	2	2
Total number of specimens	8	8

TSRST tests were performed on prismatic beam specimens that were sawed cut from larger slab samples with dimensions of 500x180x200 mm. The glass transition tests were also performed to determine the coefficients of thermal contraction using the same setup as for the fracture strength. As shown Table 1, eight cylindrical samples were prepared for dynamic modulus tests having 150 mm diameter and 170 mm high. The samples were later cored and sawed to obtain 100 mm diameter and 150 mm height as required by the test protocol AASHTO TP62. The testing procedure required using sinusoidal loading at six frequencies and five test temperatures.

Table 2: Volumetric of asphalt concrete specimens

Aggregate Type	Gradation	Binder Content (%)	Air Voids (%)		VMA (%)		VFA (%)	
			TSRST	Dyn. Mod.	TSRST	Dyn. Mod.	TSRST	Dyn. Mod.
Limestone	Fine	5.3	3.8	4.0	14.1	14.9	72.3	73.0
Limestone	Fine	5.3	3.7	3.9	14.3	14.6	74.1	73.3
Limestone	Coarse	4.5	4.5	4.2	14.1	15.0	68.1	71.9
Limestone	Coarse	4.5	4.4	4.1	14.0	15.0	69.2	72.7
Basalt	Fine	5.0	3.8	4.2	14.3	16.9	74.0	75.1
Basalt	Fine	5.0	3.9	4.1	13.9	16.9	76.4	75.8
Basalt	Coarse	4.4	4.7	4.3	19.7	16.2	74.1	73.4
Basalt	Coarse	4.4	4.5	4.2	19.4	16.1	74.8	73.8

2.2. Data analysis

The finite element modeling in Abaqus® requires some basic input data for the analysis of the specimen model. These data include the elastic properties: Young's modulus and Poisson ratio; and viscoelastic data: relaxation modulus, shear modulus, instantaneous shear modulus and reduced time. The value of Young's modulus is taken as the relaxation modulus at infinite time. Poisson's ratio was assumed to be 0.35 for all the test mixtures. Because the relaxation modulus is not directly obtained from the dynamic modulus test, it was calculated based on Park and Schapery's method [11] using Prony series. Master curves need to be calculated for dynamic modulus or relaxation modulus from which to calculate the relevant visco-elastic properties. Master curves give a continuous function of modulus as a function of frequency and temperature, and the procedure to compute the master curves are described in AASHTO TP 60-03. For the selected mixtures, the calculated master curves for the relaxation modulus is illustrated in Figure 1. Once the relaxation modulus is known, the instantaneous modulus and the shear modulus can be calculated using trial and approach as described in the literature [12]. Table 3 summarizes the values of the infinite moduli and the thermal coefficients for the test specimens.

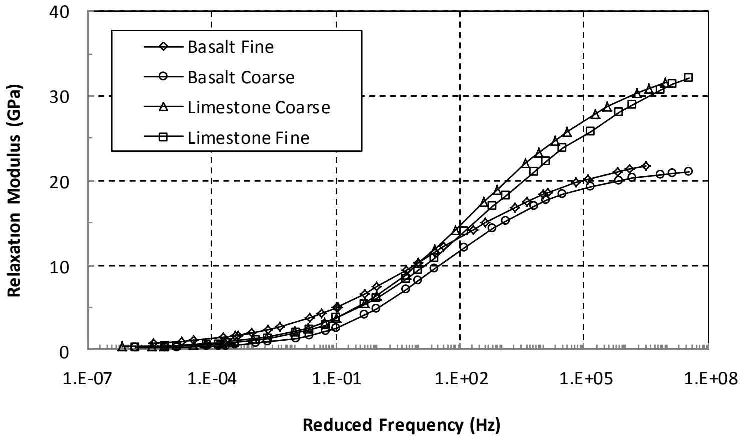


Figure 1: Master curves for relaxation modulus

Table 3: Summary of infinite and instantaneous modulus, and coefficients of thermal contraction

Specimen name	Infinite Elasticity Modulus, E∞	The Instantaneous Modulus, Ei (Young's Modulus)	Coefficient of thermal contraction
	MPa	MPa	/°C x 10^{-5}
Limestone Coarse	277	32190	3.689
Limestone Fine	365	31515	3.311
Basalt Coarse	247	21027	3.689
Basalt Fine	329	21773	2.763

To form the master curves, reduced time and shift factors need to be determined. Reduced time is the time at which the modulus measured at different temperatures is calculated at a single reference temperature. It is a function of both time and temperature and is calculated by taking reciprocal of the reduced frequency. Shift factors, which are used mainly for thermo rheologically simple materials, is the tool accommodating the effect of both time and temperature on the viscoelastic properties of asphalt mixtures. In this study, the classical formula as described by William-Lendl-Ferry [13] is used to calculate the shift factors as given in Equation 1.

$$\log a_T = \frac{-c_1(T-T_R)}{c_2+(T-T_R)} \qquad (1)$$

where c_1 and c_2 are material constants, T is the temperature to be converted and T_R is the reference temperature, taken as 21°C in this study. Since c_1 and c_2 are unknown they are estimated by trial and error method as can be found in the literature ([12], [14], [15]). The calculated values for constants c_1 and c_2 for each mixture type are summarized in Table 4.

Table 4: Shift factors used in the master curves

Sample Name	c_1	c_2	Log $a(T) = aT^2 + bT + c$		
			a	**b**	**c**
Limestone Coarse	93.7	589.2	0.0003	-0.1733	3.4421
Limestone Fine	81.8	472.7	0.0004	-0.1989	3.7846
Basalt Coarse	44.2	269.8	0.0007	-0.1939	3.7235
Basalt Fine	61.2	432.0	0.0004	-0.1585	3.1138

In terms of the thermal properties, the coefficient of thermal contraction is obtained from the glass transition temperature tests using the TSRST device. Once the longitudinal strain versus temperature relationships were obtained for each mixture, a bilinear equation as proposed by Nam et al. [16] was fitted to the test data to extract the coefficient of contraction.

2.3 Finite element modeling

Another task required for modeling in Abaqus® is to define the geometry and the appropriate boundary conditions of the TSRST specimen. The specimen tested in the TSRST machine is actually composed of three material types: the upper and lower steel platens, the epoxy used to glue the specimens to the platens, and the mixture specimen itself, as illustrated in Figure 2. In the finite element model, the geometry and the test conditions for the TSRST testing was defined in the following manner:

- Sample geometry of size 65 x 300 x 50 mm is assumed and fixed boundary conditions are applied at both ends
- Initial temperature of 5°C is used while a total of ΔT obtained from the TSRST is applied to bring the specimen close to the fracture level causing the maximum thermal stress developed right before fracture.

The next step is to define the intrinsic properties of materials involved in the analysis. These values include the elastic and thermal properties of steel and epoxy resin, and the elastic and visco-elastic properties of asphalt concrete mixtures as defined in the above section. Because steel is a common material, its properties are readily available in the literature while the properties of epoxy obtained from its specification catalogue provided by the manufacturer. For the sake of convenience, the epoxy is assumed as elastic material because of the lack of viscoelastic data. As given in Table 5, three sets of property are required in Abaqus® to perform the finite element analysis. The complete meshing of the specimen geometry is shown in Figure 2.

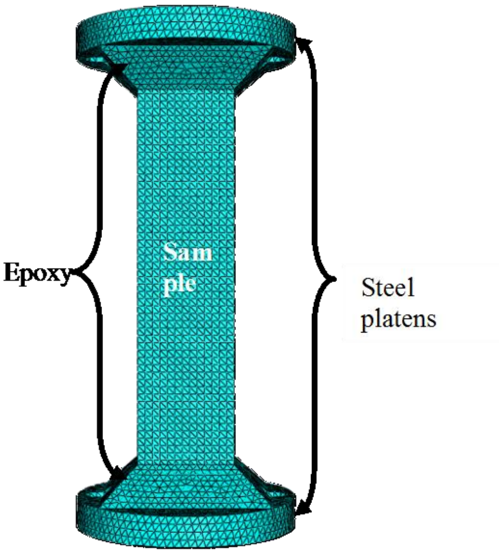


Figure 2: Sample geometry and element meshes used in the Abaqus® model

Table 5: Material parameters assumed in the model

Material	Properties required	Values taken
Steel Platens	Elasticity Modulus	200 GPa
	Coefficient of linear contraction	1.6 x 10^{-5}/°C
	Poisson's ratio	0.3
Epoxy	Elasticity Modulus	4,300 MPa
	Coefficient of linear contraction	9.1 x 10^{-6}/°C
	Poisson ratio	0.22
Specimen	Elasticity Modulus & Viscoelastic data	Refer to Table 3
	Coefficient of linear contraction	Refer to Table 3
	Poisson ratio	0.35

3. RESULTS AND DISCUSSION

The purpose of modeling the TSRST specimen in Abaqus® is to estimate the strains developed near fracture so that they can be evaluated in terms of mix design parameters. In order to observe that the strains are estimated at maximum stress levels near fracture, the calculated maximum stresses from the model were compared with the fracture strength data from TSRST. Once an agreement is established between the results of finite element model and the experimental data, the strains right before the fracture can easily be determined using the nodal displacements and the stresses. Therefore, the corresponding strains can be accordingly used to evaluate the behavior of each mixture in relation to the mix design parameters. A plot of these comparisons is shown in Figure 3 for each test specimen. It can be seen that the finite element model with the assumed viscoelastic properties successfully estimated the maximum stress levels attained in the specimens during TSRST. As can be seen the only significant deviation from the experimental data was obtained from one of the replicates of coarse graded mixture with basalt aggregate with more than 1 MPa difference in the calculated maximum stress level. The calculated strains before the specimen is reached to fracture are summarized in Table 6. It is seen that the maximum value of strains are obtained for mixtures of coarse gradation with basalt aggregate as compared to those with fine gradation.

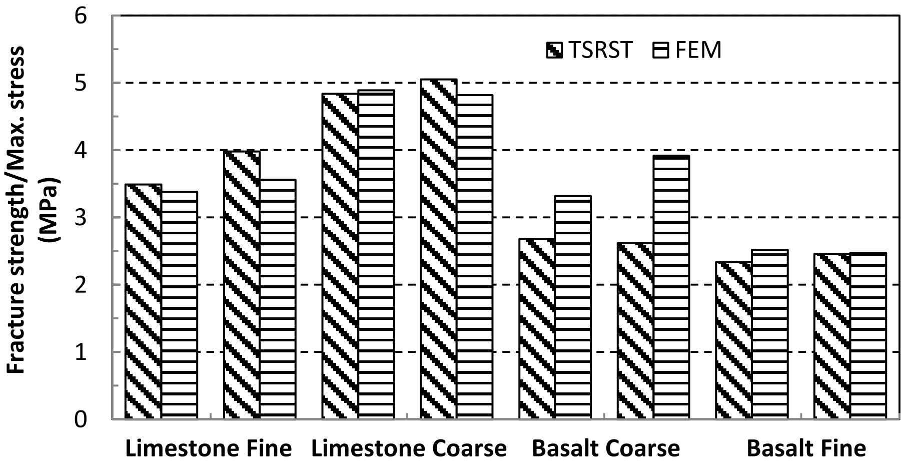


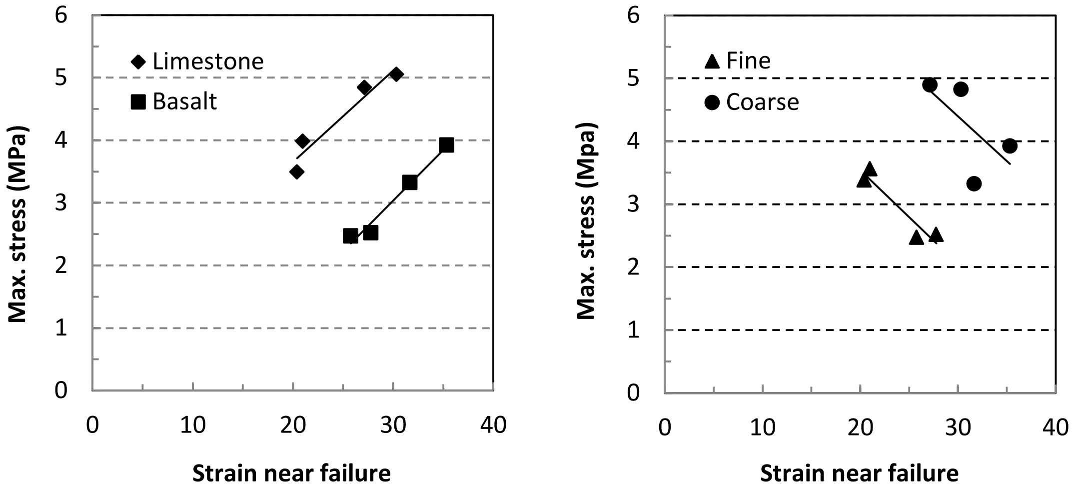
Figure 3: Comparison of stresses between TSRST results and finite element analysis

Table 6: Stress and strains computed from the finite element model

Specimen		**Fracture strength (MPa)**		**Strain (μ_s)**
	Replicate	**TSRST**	**ABAQUS**	**10^{-6}**
Limestone Fine	1	3.49	3.38	20.41
	2	3.98	3.56	20.99
Limestone Coarse	1	4.84	4.89	27.14
	2	5.05	4.82	30.33
Basalt Coarse	1	2.68	3.32	31.67
	2	2.62	3.92	35.33
Basalt Fine	1	2.34	2.52	27.79
	2	2.46	2.47	25.77

This is also consistent with the fact that mixtures with basalt aggregates generally fracture earlier than those with limestone during TSRST. An evaluation of strains near fracture level in relation to the mix design parameters, i.e., gradation and aggregate types, is shown in Figure 4 (a-b) for aggregate type and gradation, respectively. The first thing to observe from Figure 4(a) is that the strains near fracture show an increasing trend for those specimens with higher fracture strengths or when the maximum stresses that is developed become larger. However, a difference in the stress and strain trends can be clearly observed for mixtures prepared with limestone and basal aggregate. As emphasized in the above section, because the maximum stresses are calculated right before the fracture level, they can also be considered as fracture strength of the mixtures as demonstrated in Figure 3. Based on this assumption, it can be seen that although the maximum stresses are overall higher for limestone mixtures, the strains at a given stress level are always smaller for limestone mixtures than for basalt mixtures.

Although the experimental data presented in this work is limited, because of the fact that the time needed to obtain the thermal and visco-elastic properties together is quite long and it requires more efforts to extend the experimental program to mixtures of different properties, it still provides insight into the stress-strain behavior of test mixtures. The results in Figure 4 (a) indicate that limestone mixtures may display generally more brittle behavior or rapid fracture development under thermal shrinkage as compared to basalt mixtures. However, the basalt mixtures, in spite of having low fracture strengths, seem to allow larger strains near fracture because of extended stress relaxation during testing. Similar observations are made for aggregate gradations in Figure 4 (b). In terms of the magnitude of strains, it seems to be decreasing for increasing stress for both gradations indicating an opposite trend against what is found for aggregate type. For a given stress level, the strain near failure seems to be smaller for fine graded mixtures again indicating more brittle behavior as compared to coarse graded mixtures.



(a) **(b)**

Figure 4 (a-b): Maximum stress versus corresponding thermal strain for test mixtures calculated form the finite element model

4. CONCLUSIONS

In this study, stress-strain behavior of asphalt mixtures fabricated with limestone and basalt aggregates at two different gradations were investigated based on finite element model of TSRST specimen. TSRST tests were conducted on mixture specimens to measure the thermal properties, i.e., fracture strength, fracture temperature and coefficient of contraction while dynamic modulus test were performed to determine various elastic and visco-elastic properties. Finite element analyses were performed after applying the appropriate boundary conditions and a temperature differential up to the fracture of specimen as measured from TSRST. Strains were then computed corresponding to the maximum stresses attained within the specimen near fracture using nodal displacement and stress data, and evaluated in relation to aggregate type and mix gradations. Results indicated that strains become larger at higher stress levels near fracture and limestone mixtures seem to display more brittle behavior as compared to basalt mixtures. On the other hand, this trend becomes opposite when looking at aggregate gradation; strains take on smaller values at higher thermal stresses. Besides, fine graded mixtures display lower thermal strengths and more brittle behavior as compared to their counterparts.

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