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Analysis of Jointed Plain Concrete Pavement Containing RAP

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Abstract: The use of reclaimed asphalt pavement (RAP) material in concrete pavement as both fine and coarse aggregates has been shown to be a feasible way of utilizing this material. The results from previous studies indicated that RAP in concrete mix generates greatly improved toughness and energy absorbing capacity of Portland Cement Concrete (PCC) which can result in better performance in the concrete pavement application. However, most of the currently used finite element (FE) models consider the concrete slabs as a linear elastic material while the RAP concrete behavior shows a non-linear stress-strain behavior. In this study, a non-linear 3-D finite element model which incorporated the actual stress-strain behavior of the RAP concrete was developed to evaluate how the non-linear stress-strain behavior of these ductile concrete affects the prediction of the stresses in concrete. The results indicated that the FE model incorporating the actual stress-strain behavior of the RAP concrete, instead of the assumption of the concrete as a linear elastic material, tends to give lower computed stresses in the slab under critical temperature-load condition. This difference may cause the error in the predicted potential performance of the concrete pavement containing RAP. Therefore, the appropriate analytical model incorporating the actual stress-strain characteristics should be employed to accurately predict the structural responses of the RAP concrete pavement.

Keywords: Reclaimed Asphalt Pavement (RAP), Concrete Slab containing RAP, Rigid Pavements, Stress Analysis, and Non-linear Finite Element Analysis

I. INTRODUCTION

The use of reclaimed or recycled asphalt pavement (RAP) materials in Portland cement concrete pavement (PCCP) has become more and more popular in recent years. RAP materials have been used to replace coarse, and fine aggregates in PCCP. The concrete containing RAP shows that the compressive strength, modulus of elasticity, splitting tensile strength and flexural strength decrease as the percentage of RAP increases in the concrete mix [1-7]. Also, RAP in concrete mix generates greatly improved toughness and energy absorbing capacity of PCC, since the asphalt film in RAP at the interface of cement mortar and aggregate can dissipate more energy when cracks propagate [5].

More recently, concrete pavements containing RAP have been evaluated through a field demonstration project near Lewistown, Montana. The RAP concretes in these slabs were batched, placed, and finished using conventional equipment, and contractors were satisfied with its constructability. The performance of these slabs was monitored via site visual observation and internal vibrating wire gauges over a two-year period. The test slabs containing RAP did not experience visual damage (cracking and spalling) and excessive shrinkage or curling [8]. In another study, the structural behavior of RAP concrete has been evaluated using a Finite Element (FE) model [3]. The FE analysis results indicated that the stress-to-strength ratio under critical temperature-load conditions decreases as the RAP content of the mix increases. For pavement applications, a lower stress-to-strength ratio is desirable, since a lower stress-to-strength ratio indicates that the material can withstand more fatigue cycles and can perform better.

Although the previous research studies show the benefits of RAP in concrete mix through laboratory study, field demonstration, and FE analysis, it is still needed to study how the non-linear stress-strain characteristics of these ductile concrete may affect the structural behavior and performance characteristic of the RAP concrete pavements. Since, most of the currently used finite element programs, such as WESLIQID, FEACONS, and EverFE, consider the concrete slabs as a linear elastic material, there is a need to develop the FE model by incorporating actual stress-strain behavior of the RAP concrete to analyze the behavior of the concrete slab to better predict the behavior and performance of this type of pavement.

This paper presents the results of an analytical study to evaluate the effects of the non-linear stress-strain behavior of the RAP concrete on the response of the concrete pavement under critical temperature-load conditions.

II. MECHANICAL PROPERTIES OF HARDENED CONCRETE CONTAINING RAP

RAP is bituminous concrete material removed and reprocessed from pavements. The RAP material is a combination of both aged asphalt and aggregate. The properties of RAP dominantly depend on the condition of reclaimed pavement and can have significant variation due to the difference of the type of mix, aggregate quality and size, asphalt mix consistency, and asphalt content. Typically, the fine RAP is much coarser than the virgin fine aggregate, and the coarse RAP is much finer than the virgin coarse aggregate [9]. Toughness of the concrete could be improved by the addition of RAP due to the asphalt thin film in RAP.

2.1 Compressive, Flexural, and Splitting Tensile Strength

In concrete incorporating RAP, the compressive strength, flexural strength, and splitting tensile strength of concrete decrease as the percent of RAP increases [3, 6, 7, 9, 10]. Also, it was found that the use of fine RAP and coarse RAP cause more reduction in strength than the use of coarse RAP and sand [10]. According to a previous study [11], RAP can be used as aggregate in non-structural application but the percentage of RAP should be limited to achieve the required performance for the desired application. Fig. 1 shows the reduction of strength with increase in the percentage of RAP from a previous study [3].

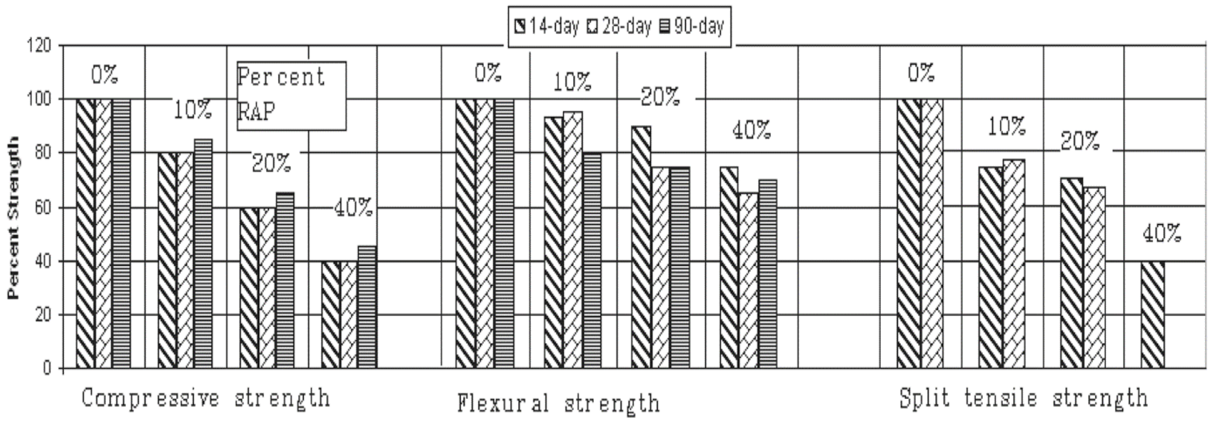


Fig. 1. Reduction in Compressive, Flexural and Splitting Tensile Strength [3]

2.2 Modulus of Elasticity

The elastic modulus of concrete containing RAP decreases with increasing percentage of RAP [2, 3, 6, 7]. It can be explained by the well-known fact that the elastic modulus of concrete is highly affected by the modulus of elasticity of the aggregate and the content of aggregate in the mix. RAP is softer than the natural aggregate, and has lower elasticity, which results in decrease of the elastic modulus of concrete. Thus, an increase in the percentage of RAP in the mix would further reduce the modulus of elasticity of the concrete.

2.3 Coefficient of Thermal Expansion

The coefficient of thermal expansion increases slightly with increasing percentage of RAP in the concrete mixture [6]. However, there is no clear trend observed in the difference between the RAP mix and the conventional concrete mix. This could be due to the variation in the RAP properties, since coefficient of thermal expansion of a concrete mix depends on the properties of the aggregate. Based on the fact that RAP contains asphalt, it can be expected that concrete containing RAP should have a higher coefficient of thermal expansion as compared with the concrete made with the virgin aggregate.

2.4Toughness

The modulus of toughness generally increases with increasing percentage of RAP in concrete mixture as shown in Fig. 2 [6]. These stress-strain plots were obtained from beam tests, and the toughness was defined as the area under the stress-strain curve. From these results, it can be observed that the failure stress decreases with increasing percentage of RAP, but the strain at failure increases as the percentage of RAP increases due to increased ductile behavior of the material. In the case of concrete without RAP, the failure stress is much higher, but the strain at failure is much lower due to the more brittle behavior of the concrete material.

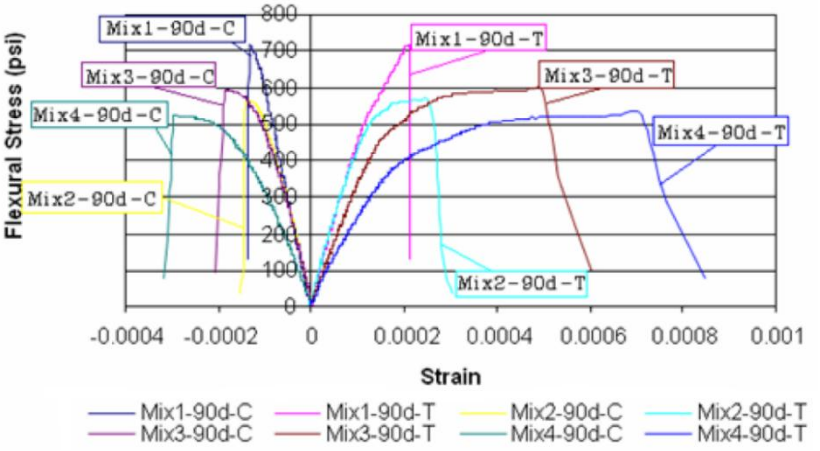


Fig. 2. Example of Stress-Strain Behavior [6]

III. CHARACTERIZATION OF RAP CONCRETE

The details of the RAP concrete testing result which are presented in this section were presented in a 2012 report by Tia et al. [7]. The RAP concrete mixtures were produced by replacing a part of both coarse and fine aggregate with a pre-wetted RAP and were mixed in the laboratory using a drum mixer. The mix designs of the concrete are presented in Table 1. For the hardened concrete samples at 28 days, compressive strength, flexural strength, splitting tensile, Poisson's ratio, and coefficient of thermal expansion (ASTM C39, C78, C496, C469 and AASHTO TP60) data are presented in Table 2.

Table 1. Mix designs of the RAP Concrete in the Study by Tia et al. [7]

Material	Mixture Design			
	RAP-0%	RAP-10%	RAP-20%	RAP-40%
Cement (kg/m^3)	301.4	301.4	301.4	301.4
Water (kg/m^3)	160.2	160.2	160.2	160.2
Virgin Coarse Aggregate (kg/m^3)	1,057.2	951.6	846.0	634.2
RAP Coarse Aggregate (kg/m^3)	0	99.1	198.7	397.5
Virgin Fine Aggregate (kg/m^3)	735.1	661.5	587.9	440.8
RAP Fine Aggregate (kg/m^3)	0	61.1	121.6	243.2
w/c	0.53	0.53	0.53	0.53

Table 2. The RAP Concrete Material Properties from the Study by Tia et al. [7]

Property	Mixture Type			
	RAP-0%	RAP-10%	RAP-20%	RAP-40%
Compressive Strength (MPa)	38.58	34.03	26.05	17.38
Flexural Strength (MPa)	4.82	3.90	4.11	3.66
Splitting Tensile Strength (MPa)	3.24	3.36	2.58	2.42
Coefficient of Thermal Expansion (×10-6/°C)	10.89	10.93	11.57	11.16
Poisson's ratio	0.24	0.24	0.25	0.25

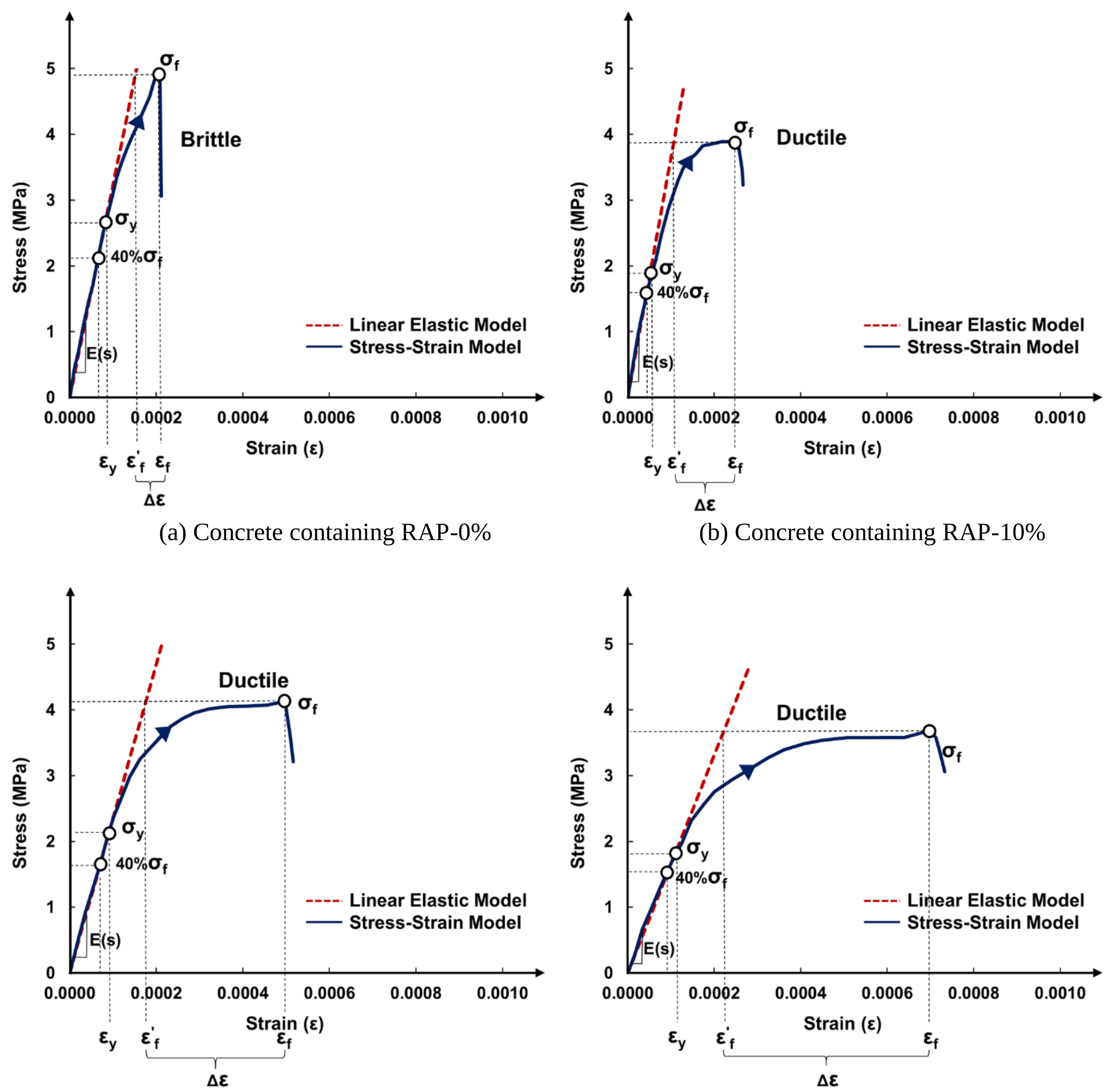
IV. FINITE ELEMENT MODELING

Most of the existing FE models for analysis of concrete pavements considered the concrete slab as a linear elastic material. According to the previous studies, the RAP concrete had a more non-linear stress-strain behavior and failed at a higher strain level. For more realistic and effective modeling of the RAP concrete behavior, the actual stress-strain characteristics of the concrete need to be incorporated in the model. To do this, a three-dimensional finite element model using the ADINA software for analysis of concrete pavement slabs, which was developed and validated for another research [12], was extended to analyze the structural behavior of these RAP concrete pavements under critical temperature-load conditions in Florida.

4.1 Modeling of RAP Concrete Material

Fig. 3 shows the difference between an assumed linear elastic behavior and an actual stress-strain behavior of the concrete. The elastic modulus is obtained by the standard method (slope of stress versus strain at stress range from 0 to 40% of ultimate concrete strength). As shown in Fig. 3, the concrete exhibits almost linear behavior up to the proportional limit at point σ_y and the actual stress-strain values start to deviate from the assumed linear elastic behavior. Therefore, it is expected that the actual behavior of concrete pavement containing RAP will exhibit some difference as compared with the assumed linear elastic behavior at a higher stress level.

There are several material options to be considered for modeling of the RAP concrete in ADINA software. These material options for concrete range from simple elastic material to a nonlinear-plastic materials. In this study, the actual stress-strain characteristics of the RAP concretes, which were determined in a previous research [7], were used to model the behavior of the RAP concrete. These stress-strain characteristics were determined from the Flexural Strength Test (ASTM C78) on the RAP concretes. For comparison purpose, a linear elastic model was also used in the analysis.



(a) Concrete containing RAP-0% (b) Concrete containing RAP-10%

(c) Concrete containing RAP-20% (d) Concrete containing RAP-40%

Fig. 3. Stress-Strain Curve for Concrete Containing RAP

Table 3 presents the actual stress-stain values obtained from the Flexural Strength Test on the concrete specimens containing different levels of RAP, and Table 4 shows the elastic material properties obtained by the standard method and used in the linear elastic FE model.

Table 3. Stress-strain values used in the non-linear models

RAP-0%		RAP-10%		RAP-20%		RAP-40%	
Strain (ε)	Stress (MPa)	Strain (ε)	Stress (MPa)	Strain (ε)	Stress (MPa)	Strain (ε)	Stress (MPa)
0.00E+00	0	0.00E+00	0	0.00E+00	0	0.00E+00	0
3.99E-05	1.37	4.57E-05	1.50	3.37E-05	0.83	4.65E-05	0.84
6.31E-05	2.08	6.59E-05	2.14	8.80E-05	2.12	7.97E-05	1.42
8.47E-05	2.72	7.93E-05	2.52	1.30E-04	2.85	1.20E-04	1.97
1.06E-04	3.27	1.03E-04	3.04	1.89E-04	3.45	1.50E-04	2.41
1.20E-04	3.57	1.26E-04	3.44	2.24E-04	3.72	1.81E-04	2.61
1.40E-04	3.87	1.43E-04	3.61	2.71E-04	3.90	2.28E-04	2.90
1.59E-04	4.18	1.67E-04	3.77	3.37E-04	4.03	2.97E-04	3.16
1.83E-04	4.50	1.95E-04	3.85	4.57E-04	4.07	4.22E-04	3.51
1.98E-04	4.82	2.28E-04	3.90	4.98E-04	4.11	7.03E-04	3.66

Table 4. Elastic modulus values used in the linear models

Layer	Modulus (GPa)	Poisson's ratio
RAP-0%	34.23	0.24
RAP-10%	32.94	0.24
RAP-20%	24.55	0.25
RAP-40%	18.10	0.25

4.2 Modeling of Pavement Structure

The FE model consisted of two layers; which include (1) 3.65 m (144 in.) wide, 22.86 cm (9 in.) thick concrete slab, and (2) 3.65 m (144 in.) wide and 254 cm (100 in.) thick subgrade layer. They were modeled by an assemblage of hexahedrons elements defined by eight nodes with three degrees of freedom (i.e. translations in the x-, y-, and z-directions). Mechanical and thermal parameters defined for the concrete slab were (1) modulus of elasticity (E), (2) Poisson's ratio, (3) coefficient of thermal expansion (CTE), and (4) mass density, which were obtained from a previous study [7]. For the subgrade layer to simulate the real boundary condition with sufficient accuracy but without excessive processing time, the subgrade was modeled as having a thickness of 254 cm (100 in.) and fixed in the z-direction. To reduce computer processing time, the double symmetry about x- and y-axes was used. Fig. 4 shows the 3-D FE model developed for the analysis of the RAP concrete pavements.

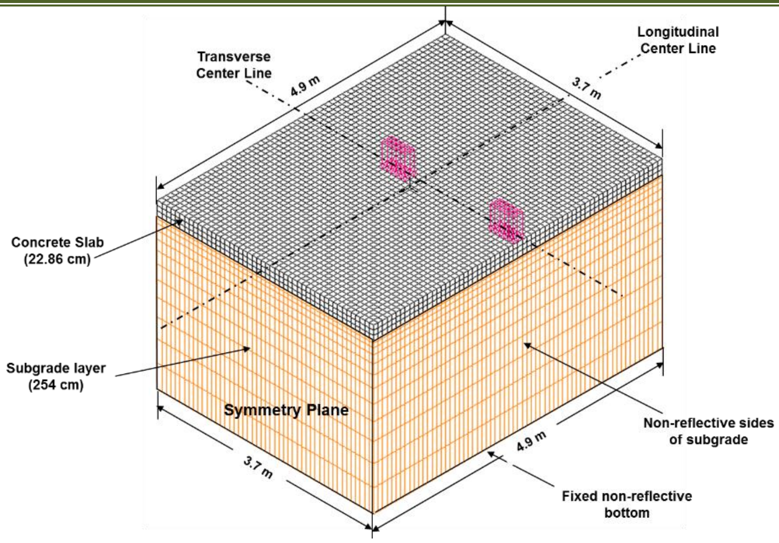


Fig. 4. 3-D finite element model developed

4.3Loading Configuration and Temperature Effects

Stress analysis was performed to determine the maximum stresses in the concrete slabs under a critical combined load-temperature conditions. According to a previous study on concrete pavements in Florida [13], the maximum tensile stresses in the concrete slab were induced if it were loaded by a 98 kN (22-kip) axle load which is the maximum legal single axle load in Florida at the middle edge with no load transfer across the joints as shown in Fig. 5. Various temperature gradients throughout concrete slab depth were also considered. The possible temperature differential in the concrete slab was varied from 0 °C to 16.7 °C (0 °F to 30 °F).

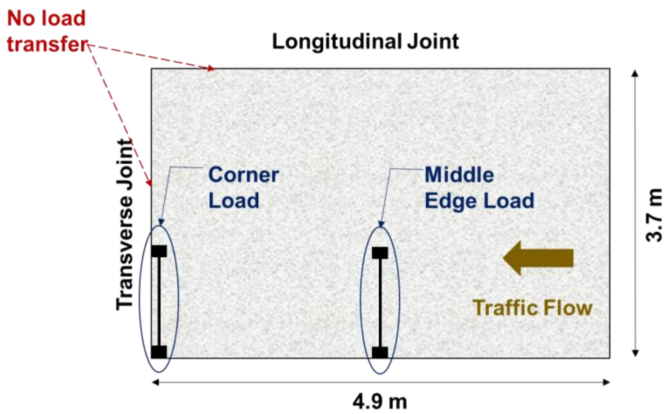
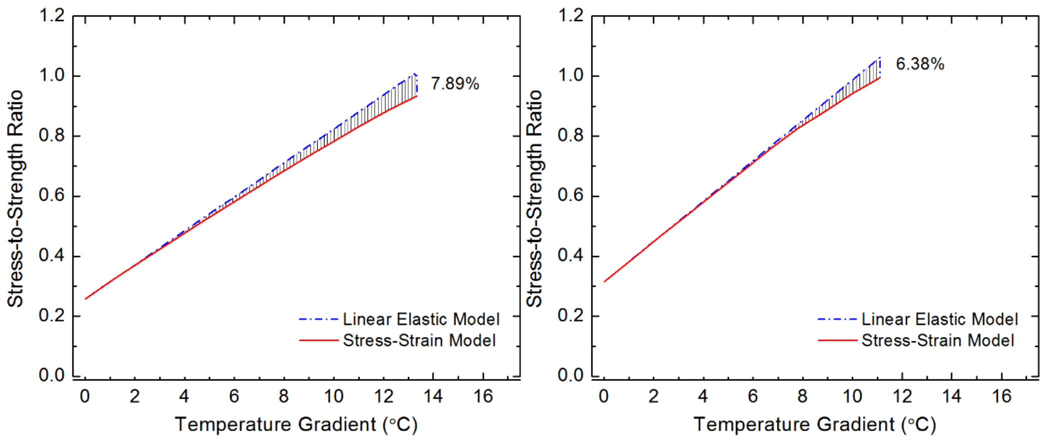


Fig. 5. Critical loading conditions

V. FE ANALYSIS RESULTS CONSIDERING ACTUAL STRESS-STRAIN CHARACTERISTICS

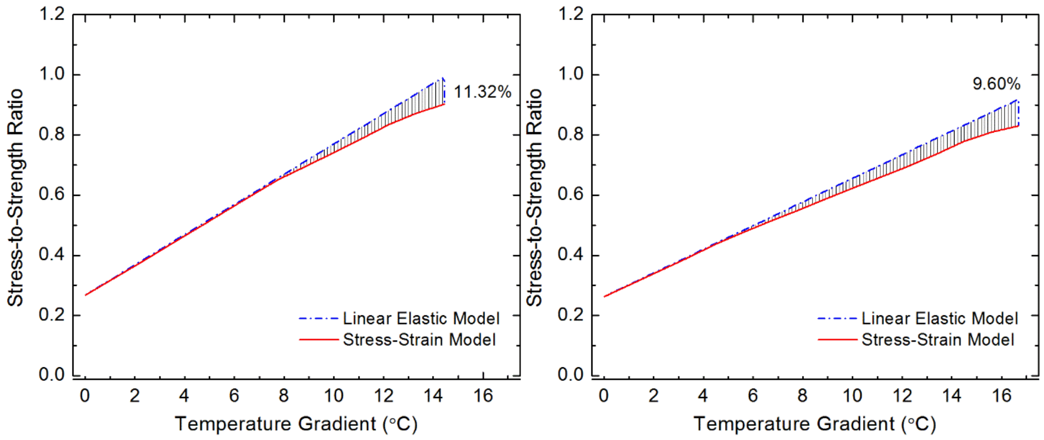
Using the developed 3-D FE models (i.e., linear elastic and stress-strain model), stress analysis was performed to determine the maximum tensile stresses in the concrete under the combined effect of a critical 98 kN (22-kip) axle load at mid-edge and various temperature differentials in the slab. The stress-to-strength ratio for each condition was calculated using the flexural strength of the concrete determined from laboratory test.

Fig. 6 shows the plot of calculated stress-to-strength ratio as a function of temperature gradient throughout the concrete slab depth using the two different FE model. From these analyses results, the difference between the linear elastic and actual stress-strain model increases as the temperature gradients increase. It can also be observed that both models are able to predict similar behavior up to stress-to-strength ratio of approximately 0.6, and thereafter the actual stress-strain model predicts consistently lower stresses in the concrete under the same temperature-load conditions. Since the maximum tensile stresses in the concrete are an important factor influencing the prediction of potential pavement performance, the effect of non-linear behavior of the RAP concrete must be considered when calculating the critical stresses in the concrete pavement. Therefore, it can be concluded that the modeling using actual stress-strain behavior of the RAP concrete, instead of the assumption of a linear elastic material, can be used to more accurately analyze the concrete pavement containing the RAP under critical temperature-load condition. Tables 5 through 8 present the maximum stresses and stress-to-strength ratio predicted by the two different FE models.



(a) Concrete containing RAP-0% (b) Concrete containing RAP-10%

Fig. 6. Computed stress-strength ratios for concrete slabs containing RAP



(c) Concrete containing RAP-20% (d) Concrete containing RAP-40%

Fig. 6. Continued

Table 5. Comparison of maximum stresses computed by the linear elastic and actual stress-strain models for the concrete mix with 0% RAP

Temperature Gradient (°C)	Linear Elastic Model		Stress-Strain Model		Difference (%)
	Stress (MPa)	Stress Ratio	Stress (MPa)	Stress Ratio	
0	1.246	0.26	1.246	0.26	0.00
1.1	1.549	0.32	1.553	0.32	-0.20
2.2	1.853	0.38	1.844	0.38	0.43
3.3	2.156	0.45	2.130	0.44	1.19
4.4	2.459	0.51	2.416	0.50	1.76
5.6	2.762	0.57	2.697	0.56	2.34
6.7	3.065	0.64	2.972	0.62	3.03
7.8	3.369	0.70	3.251	0.67	3.49
8.9	3.671	0.76	3.518	0.73	4.19
10.0	3.975	0.82	3.776	0.78	5.02
11.1	4.278	0.89	4.036	0.84	5.66
12.2	4.582	0.95	4.280	0.89	6.57

13.3	4.884	1.01	4.500	0.93	7.89

Table 6. Comparison of maximum stresses computed by the linear elastic and actual stress-strain models for the concrete mix with 10% RAP

Temperature Gradient (°C)	Linear Elastic Model		Stress-Strain Model		Difference (%)
	Stress (MPa)	Stress Ratio	Stress (MPa)	Stress Ratio	
0	1.229	0.31	1.229	0.31	0.00
1.1	1.521	0.39	1.521	0.39	0.00
2.2	1.813	0.46	1.816	0.47	-0.16
3.3	2.105	0.54	2.099	0.54	0.30
4.4	2.397	0.61	2.381	0.61	0.66
5.6	2.689	0.69	2.666	0.68	0.87
6.7	2.981	0.76	2.949	0.76	1.10
7.8	3.274	0.84	3.221	0.83	1.59
8.9	3.565	0.91	3.445	0.88	3.38
10.0	3.858	0.99	3.674	0.94	4.74
11.1	4.149	1.06	3.885	1.00	6.38

Table 7. Comparison of maximum stresses computed by the linear elastic and actual stress-strain models for the concrete mix with 20% RAP

Temperature Gradient (°C)	Linear Elastic Model		Stress-Strain Model		Difference (%)
	Stress (MPa)	Stress Ratio	Stress (MPa)	Stress Ratio	
0	1.102	0.27	1.100	0.27	0.26
1.1	1.332	0.32	1.325	0.32	0.51
2.2	1.561	0.38	1.550	0.38	0.71
3.3	1.791	0.44	1.775	0.43	0.84
4.4	2.019	0.49	2.001	0.49	0.95
5.6	2.249	0.55	2.226	0.54	1.00
6.7	2.478	0.60	2.461	0.60	0.70
7.8	2.708	0.66	2.682	0.65	0.95
8.9	2.937	0.71	2.866	0.70	2.42
10.0	3.166	0.77	3.050	0.74	3.68
11.1	3.396	0.83	3.233	0.79	4.79
12.2	3.625	0.88	3.429	0.83	5.40
13.3	3.854	0.94	3.588	0.87	6.90
14.4	4.083	0.99	3.709	0.90	9.15
15.6	4.313	1.05	3.825	0.93	11.32

Table 8. Comparison of maximum stresses computed by the linear elastic and actual stress-strain models for the concrete mix with 40% RAP

Temperature Gradient (°C)	Linear Elastic Model		Stress-Strain Model		Difference (%)
	Stress (MPa)	Stress Ratio	Stress (MPa)	Stress Ratio	
0	0.965	0.26	0.964	0.26	0.08
1.1	1.125	0.31	1.120	0.31	0.40
2.2	1.284	0.35	1.276	0.35	0.65
3.3	1.444	0.39	1.431	0.39	0.88
4.4	1.604	0.44	1.593	0.44	0.68
5.6	1.764	0.48	1.742	0.48	1.21

6.7	1.924	0.53	1.877	0.51	2.41
7.8	2.084	0.57	2.013	0.55	3.39
8.9	2.244	0.61	2.147	0.59	4.30
10.0	2.403	0.66	2.279	0.62	5.17
11.1	2.563	0.70	2.411	0.66	5.92
12.2	2.723	0.74	2.548	0.70	6.40
13.3	2.883	0.79	2.694	0.74	6.54
14.4	3.042	0.83	2.845	0.78	6.49
15.6	3.202	0.87	2.963	0.81	7.45
16.7	3.362	0.92	3.039	0.83	9.60

VI. SUMMARY OF FINDINGS

In this study, a non-linear FE model by incorporating the actual stress-strain behavior of the RAP concrete obtained from the flexural strength test was developed to evaluate the effects of the non-linear stress-strain behavior of the RAP concrete in a critical stress analysis. The analytical results from the FE model incorporating the actual stress-strain behavior of the RAP concrete were compared with the corresponding results from the linear elastic FE model. From the results, it was observed that the FE model using actual stress-strain behavior of RAP concrete tends to give lower predicted stresses at high stress level. Therefore, it can be concluded that in the analysis of the concrete pavement containing the RAP, an appropriate analytical model using the actual stress-strain characteristics, instead of the assumption of the concrete as a linear elastic material, should be employed to accurately predict the maximum stresses in the concrete. The model incorporating the actual stress-strain behavior of the RAP concrete can simulate the structural responses more accurately and can better predict the potential performance of the pavement.

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REFERENCES

[1]. Berry M, Stephens J, Bermel B, Hagel A, Schroeder D., Feasibility of Reclaimed Asphalt Pavement as Aggregate in Portland Cement Concrete, Research Report, Montana Department of Transportation, MT, 2013.

[2]. Delwar M, Fahmy M, Taha R., "Use of reclaimed asphalt pavement as an aggregate in Portland cement concrete", ACI Materials Journal. 1997; 94(3).

[3]. Hossiney N, Tia M, Bergin MJ., "Concrete containing RAP for use in concrete pavement", International Journal of Pavement Research and Technology, 2010;3(5):251-8.

[4]. Hossiney N, Wang G, Tia M, Bergin M., "Evaluation of Concrete Containing Recycled Asphalt Pavement for Use in Concrete Pavement", Transportation Research Board 87th Annual Meeting 2008.

[5]. Huang B, Shu X, Li G., "Laboratory investigation of portland cement concrete containing recycled asphalt pavements", Cement and Concrete Research. 2005;35(10):2008-13.

[6]. Tia M, Hossiney N, Su Y-M, Chen Y, Do TA., Use of Reclaimed Asphalt Pavement in Concrete Pavement Slabs. Research Report. University of Florida, Gainesville, FL, 2012.

[7]. Tia M, Liu Y, Haranki B, Su Y-M. Modulus of Elasticity, Creep and Shrinkage of Concrete–PHASE II: Part 1–Creep Study. Research Report. University of Florida, Gainesville, FL, 2009.

[8]. Berry M, Dalton K, Murray F. Feasibility of Reclaimed Asphalt Pavement as Aggregate in Portland Cement Concrete Pavements Phase II: Field Demonstration. Montana Department of Transportation, MT, 2015.

[9]. Huang B, Shu X, Burdette E., "Mechanical properties of concrete containing recycled asphalt pavements", Magazine of Concrete Research. 2006;58(5):313-20.

[10]. Hassan K, Brooks J, Erdman M., "The use of reclaimed asphalt pavement (RAP) aggregates in concrete", Waste Management Series. 2000;1:121-8.

[11]. Al-Oraimi S, Hassan HF, Hago A., "Recycling of Reclaimed Asphalt Pavement in Portland Cement

Concrete", The Journal of Engineering Research. 2009;6(1):37-45.

[12]. Kim K, Subgranon T, Tia M, Bergin M. "Internally Cured Concrete for Use in Concrete Pavement Using Accelerated Pavement Testing and Finite-Element Analysis", Journal of Materials in Civil Engineering. 2016:04016011.

[13]. Wu C, Tia M, Larsen T. Analysis of structural response of concrete pavements under critical thermal-loading conditions. Fifth International Conference on Concrete Pavement Design and Rehabilitation, 1993.

