Investigation of Fracture Behavior of Recycled Asphalt Mixtures Using a Discrete Element Computational Model

Meng Xu, Jia-Liang Le, Tianhao Yan, Mugurel Turos, Mihai Marasteanu, and Decheng Feng

Abstract A discrete element computational model is used to simulate the fracture behavior of asphalt mixtures, containing different RAP proportions, at low temperatures. In this model, coarse aggregates are explicitly represented by rigid spherical particles. The bonds that connect these particles represent the fine aggregate matrix (FAM), which is defined as the combination of asphalt binder and fine aggregates. The model is used to investigate the fracture behavior of four asphalt mixtures with different RAP contents. Semi-circular bend (SCB) fracture tests are performed on the asphalt mixtures and bending beam rheometer (BBR) strength tests are performed on FAM at low temperatures.

Keywords Fine aggregate matrix · Fracture energy · Discrete element method

1 Introduction

The use of recycled materials is common practice in the production of asphalt mixtures for pavement applications. In particular, the use of Reclaimed Asphalt Pavement (RAP) has significantly increased over the years due to considerable economic benefits and reduction in environmental impact. The use of recycled asphalt materials, however, can have a detrimental effect on the mechanical properties of asphalt mixtures at low temperature.

In this paper, a previously developed discrete element computational model is used to simulate the fracture behavior of asphalt mixtures, containing different RAP proportions, at low temperatures. In this model, coarse aggregates are explicitly represented by rigid spherical particles. The bonds that connect these particles represent the fine aggregate matrix (FAM), which is defined as the combination of asphalt binder and fine aggregates.

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Table 1 Asphalt mixture design parameters

Index	Parameter	Index	Parameter
AC%	5.35%	Mineral powder	1.5% of total weight of mixture
Design air voids	4%	Volume of FAM	64%
New binder grade	PG 58-34	RAP binder grade	PG 86.5-19.8

2 Materials and Testing Methods

Four asphalt mixtures that have RAP contents of 0%, 20%, 30% and 40%, respectively, are investigated. The four mixtures are named MIX-0%, MIX-20%, MIX-30% and MIX-40% respectively. All mixtures were designed at 4% air voids. The basic mixtures design parameters that will be used in the model are shown in Table 1.

The fracture properties of the asphalt mixtures were obtained using the SCB test [1]. All mixtures were tested in three replicates at −24 °C.

The tensile strength and the Young modulus of the fine aggregate matrix (FAM) were measured using the BBR testing protocol developed by Marasteanu et al. [2]. In this investigation, FAM was prepared with fine aggregates passing through No. 8 sieve (2.36 mm). The FAM mix design and sample preparation was done according to the procedure detailed elsewhere [3]. All BBR testing was performed at −24 °C using six replicates.

3 DEM Model

The discrete computational model was developed using the commercially available discrete element software PF3D. To reduce computational time, only the large aggregates were discretized using spherical particles of different sizes generated according to the gradation data of the mixture. For each sieve size, a linear distribution of the particle radius was adopted. The bond between the coarse aggregates was modeled based on FAM properties. The geometry of the model specimen is shown in Fig. 1.

In this research, the built-in Linear Parallel Bond Model of PFC3D software was modified to better represent asphalt component behavior. In the modified model, normal force (F_n), shear force (F_s) and moment (M), do not drop to zero, as shown in Fig. 2, when the bond reaches maximum value, they drop slowly. When the maximum force or moment exceeds the strength limits, the bond exhibits softening and the stress decreases linearly as the bond length increases, as shown in Fig. 3.

The modulus and tensile strength of the bond, T_n and $\bar{k}_n$, are calculated based on the FAM modulus E_{FAM} and tensile strength σ_{FAM}:

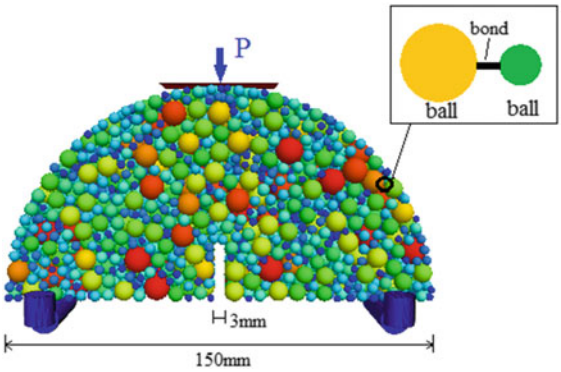

Fig. 1 Simulated SCB specimen

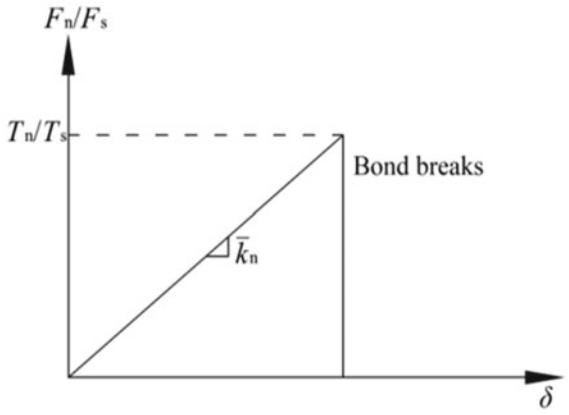

Fig. 2 Bond breaks in built-in contact model

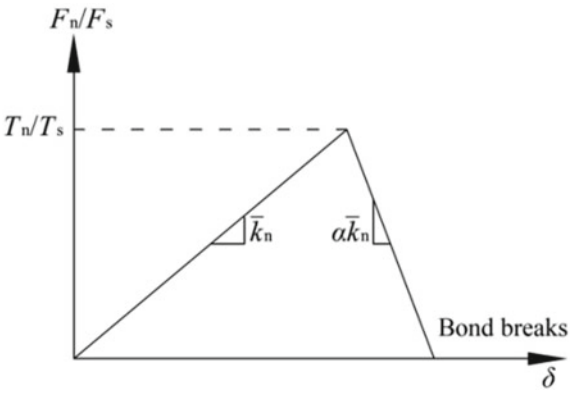

Fig. 3 Bond breaks in modified contact model

$$\bar{k}_n = E_{\text{FAM}} \pi R^2 / L \tag{1}$$

$$T_n = \bar{\sigma}_c A = \sigma_{\text{FAM}} \pi R^2 \tag{2}$$

R is the bond radius, equal to the minimum radius of two adjacent particles. L is the bond length, which is between 0 to 3 mm. In this model, α is set to 0.6. The modulus of coarse aggregates is assumed to be 50 GPa.

Since the probability of shear failure is very small in SCB test, the shear failure strength ($\bar{c}$) was set to a very large value of 200 MPa, and the friction angle ($\bar{\phi}$) was set to 40°. In this condition, bonds break mainly due to tensile force. The shear stiffness k_s and $\bar{k}_s$ were calculated according to classical elasticity theory:

$$k_n / k_s = 2(1+\nu) \tag{3}$$

The Poisson's ratio μ is assumed to be 0.3.

4 Simulation Results

The discrete element simulations and averaged experimental curves are shown in Fig. 4. The simulation results are in good agreement with the experimental results, and the crack mouth opening displacement (CMOD) values are very close to the experimental values at the end of the loading.

For peak force, the simulated values are almost the same (less than 5% difference) with the experimental values. For fracture energy, calculated using the area under the load and load-line displacement, the difference is smaller than 10% except for MIX-20%, for which is 16%. In addition, it can be seen that the more the RAP content, the lower the fracture energy is.

The results indicate that the proposed model can be used to estimate fracture behavior of mixtures based on FAM properties. However, it should be noted that the model is a semi-empirical model, and some of the parameters parameter, such as α and bond maximum length, were determined according to previous experience on asphalt mixtures with a maximum aggregate size of 19 mm. For mixture with smaller maximum aggregate size, the bond maximum length could be smaller. Also, changes in design air voids may results in less accurate estimations using current model parameters.

5 Parametric Study

To better understand the influence of FAM properties on mixture fracture behavior, a parametric study was performed. First, the bond strength is fixed at 12 MPa and

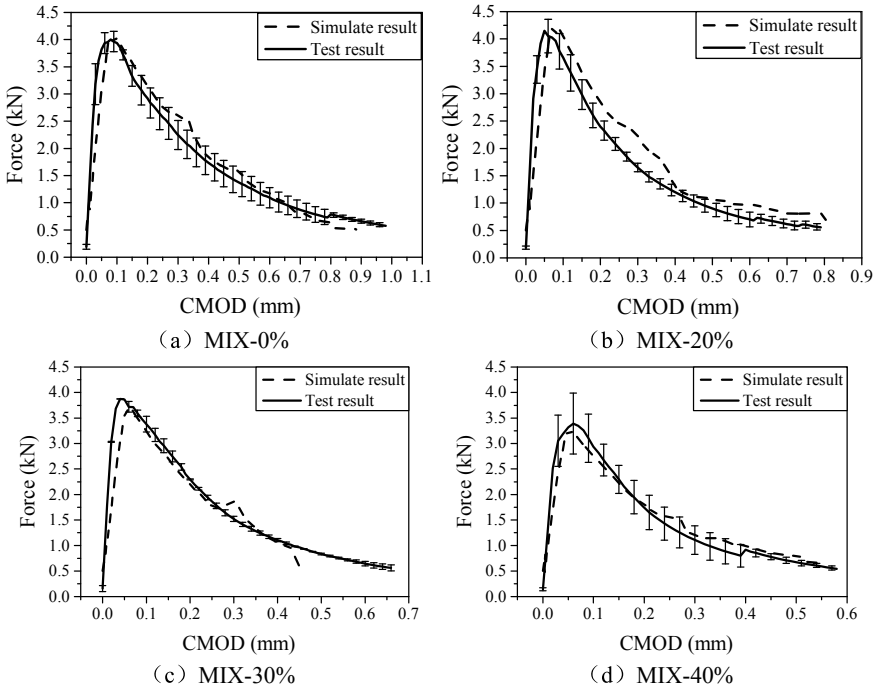

Fig. 4 Comparison of SCB test and simulation results

modulus is set to 9 GPa, 10 GPa, 11 GPa, 12 GPa and 13 GPa, respectively. The peak force and fracture energy values are shown in Table 2, and the simulated loading-CMOD are shown in Fig. 5. It can be observed that FAM modulus has no significant effect on the peak force, and fracture energy decreases significantly with increase in modulus.

Then, the modulus of the bond is fixed at 11GPa and the strength is set as 10 MPa, 11 MPa, 12 MPa, 13 MPa and 14 MPa, respectively. The simulated force-CMOD are shown in Fig. 6, and the peak force and fracture energy values are shown in Table 3. The results indicate that both the peak force and fracture energy increase with increase in tensile strength of FAM.

Using the data in Tables 2 and 3, linear relationships are found between FAM parameters and mixture fracture parameters, as shown in Figs. 7, 8, 9 and 10.

Table 2 Peak force and fracture energy of SCB test for different FAM moduli

Modulus	$E = 9$GPa	$E = 10$GPa	$E = 11$GPa	$E = 12$GPa	$E = 13$GPa
Peak force (kN)	3.76	3.75	3.68	3.63	3.61
Fracture energy (J/m^2)	884.12	619.39	648.63	489.62	420.90

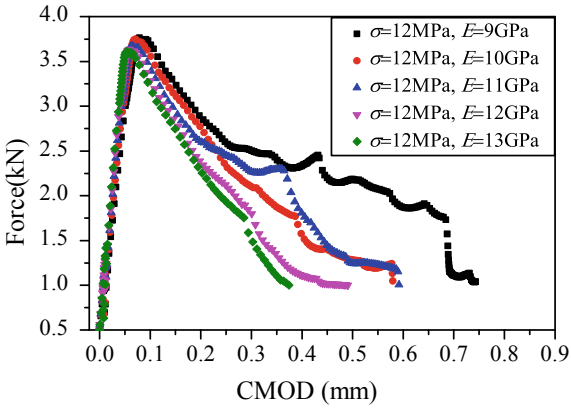

Fig. 5 Prediction curves of SCB test under different FAM modulus

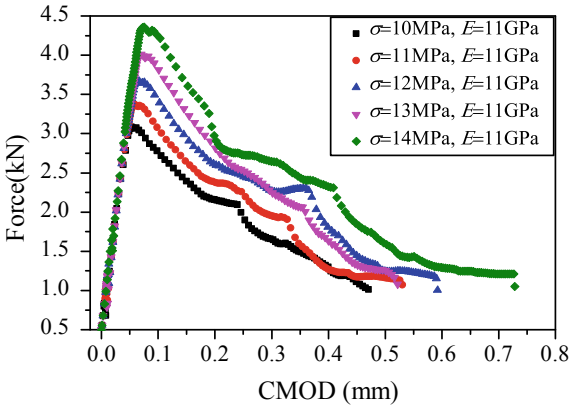

Fig. 6 Prediction curves of SCB test under different FAM tensile strength

Table 3 Peak force and fracture energy of SCB test for different FAM tensile strengths

Strength	$\sigma = 10$ MPa	$\sigma = 11$ MPa	$\sigma = 12$ MPa	$\sigma = 13$ MPa	$\sigma = 14$ MPa
Peak force (kN)	3.09	3.37	3.68	4.01	4.36
Fracture energy (J/m^2)	434.72	504.32	648.63	631.65	856.43

As seen in Figs. 7 and 8, simple linear expressions can be used to predict peak force and fracture energy of the mixture from the modulus and strength of FAM.

6 Conclusion

In this research, the influence of FAM properties on asphalt mixture fracture properties was investigated using a discrete element computational model. Only the coarse

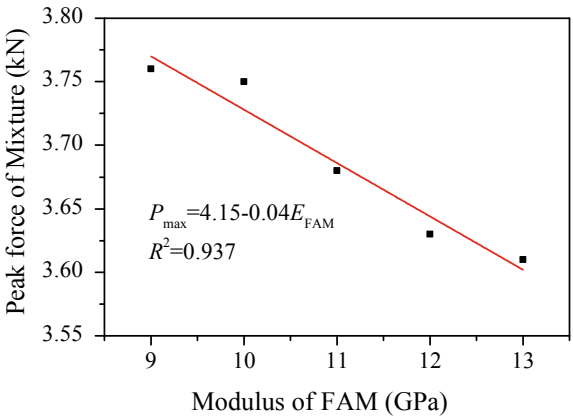

Fig. 7 Relation between FAM modulus and MIX peakforce

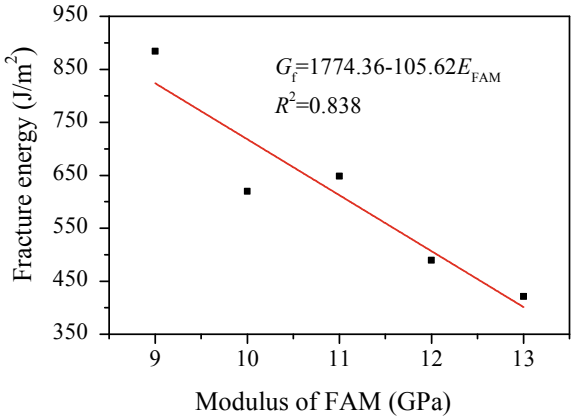

Fig. 8 Relation between FAM modulus and MIX fracture energy

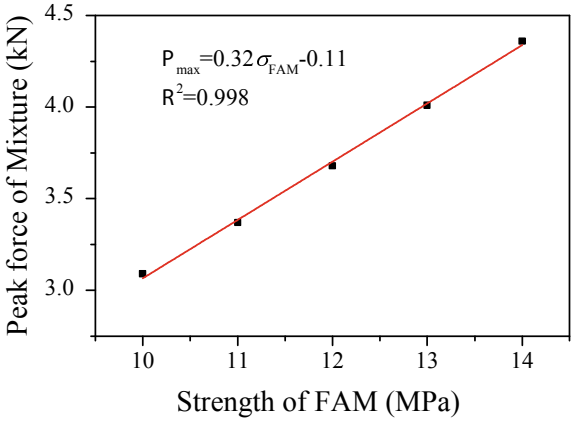

Fig. 9 Relation between FAM strength and MIX peak force

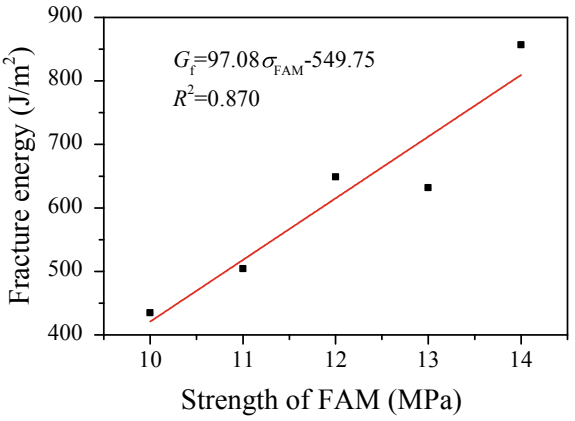

Fig. 10 Relation between FAM strength and MIX fracture energy

aggregates are discretized as rigid spheres matching the size and distribution of the original aggregates, while the contact model was derived from FAM properties.

The results show the model can predict reasonably well the load CMOD curves, and that the predicted peak force and fracture energy match the experimental results well. It is observed that the SCB peak load of asphalt mixture specimens is primarily governed by the tensile strength of the corresponding FAM and that a higher RAP content results in lower the fracture energy. In general, the fracture energy is negatively correlated with FAM modulus.

From simulations results, it is observed that FAM modulus has no significant effect on the peak force, while fracture energy decreases significantly with increase in modulus. The results also indicate that both the peak force and fracture energy increase with an increase in tensile strength of FAM.

References

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