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Laboratory Investigation on Residual Strength of Reclaimed Asphalt Mixture for Cold Mix Recycling

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Abstract: The purpose of this study is to evaluate the residual strength of reclaimed asphalt pavement (RAP) to understand the strength forming mechanism of RAP in cold recycled asphalt mixture. The mechanical properties of the RAP were investigated as compared to the properties of pure aggregates. Triaxial shear tests were conducted to analyze the residual cohesion of asphalt binder in the RAP. The gradation and specific surface area of RAP were analyzed to understand the agglomeration structure of coarse RAP particles. Splitting strength of cement-RAP mixtures was tested as compared to cement-aggregate mixtures. It can be concluded that the RAP in the cold recycled asphalt mixture does not act exactly like “black color” aggregates. The aged asphalt in the RAP has active cohesion although its cohesion strength is much lower than the binder in the hot-mix asphalt mixture. The coarse RAP particles formed by agglomeration of fine particles and the aged binder have important influences on the strength of cold recycled asphalt mixtures. The cement-RAP mixture has much lower splitting strength than the cement-aggregate mixture with the same gradation and cement content. It is important to add new aggregate into the recycled mixture to increase the effective aggregate surface area that can be coated with the new binder.

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Introduction

It has been shown that cold recycling technologies, including central plant cold recycling and cold in-place recycling, are cost effective, environmentally friendly rehabilitation methods for deteriorated asphalt pavements [1-3]. In the cold recycling, the reclaimed asphalt pavement (RAP) is first milled and subsequently mixed with emulsified or foamed asphalt, additional water and aggregate, and sometimes, additives. The cold recycled asphalt mixture is then spread and compacted. The whole process is completed at normal atmospheric temperature. Compared to other maintenance and rehabilitation technologies for asphalt pavement, the cold recycling technology has a lot of benefits including elimination of pavement surface distress, strengthening of pavement structure, improvement of ride quality, high effectiveness of RAP usage, low engineering cost, and minimal environmental impact [4-5].

To successfully conduct cold recycling for asphalt pavement, much research has studied the mechanical properties of cold recycling asphalt mixture and its mix design method [6-8]. However, the performance of cold recycled asphalt mixture is not as good as hot mix asphalt mixture or hot recycled asphalt mixture. Thus, cold recycling of asphalt mixture is mainly used as base layers. More importantly, there are still many disagreements about the practical performances of the cold recycled asphalt mixture, and there is no universal mix design method available [9]. For instance, almost every state in the U.S. has its own mix design method for cold recycling of asphalt mixture [10].

The “black rock” theory is widely used for the design of cold recycled asphalt mixtures [11]. During cold recycling, RAP was fully considered as aggregates. Some research proved that the cold recycled asphalt mixture that is composed of the RAP and foamed or emulsified asphalt does not have strength sufficient to meet load carrying requirement [12]. Thus, cement is commonly used as modifying additive to improve the strength of cold recycled asphalt mixtures. Based on previous studies, the content of cement is usually no more than 3% by the weight of aggregate in cold recycling of asphalt mixture [13-14]. The splitting strength of hot-mix asphalt mixtures or hot recycled asphalt mixtures is usually between 0.8 and 1.6 MPa while the splitting strength of cold recycled mixtures is usually between 0.4 and 0.6 MPa, even with the addition of new binder and cement [15-17]. Studies tried to explain this from the angle of interaction between new cements [18-19]. However, there are no common agreed conclusions. The relative weak strength is one of the most important reasons preventing wide usage of cold recycled asphalt mixtures.

Actually, due to the existence of the aged asphalt in the RAP, the strength of RAP may not be the same with the real aggregates. If RAP does not play the same role as aggregate in the cold recycled asphalt mixtures and new aggregates are not added, it may lead to improper mixture design and poor mixture performance.

Thus, understanding the real role of RAP in the cold recycled asphalt mixture and its influences on the strength mechanism of cold recycled asphalt mixtures is the basis for proper design of cold recycled asphalt mixtures to achieve the desired long-term pavement performance. This study tries to evaluate the residual properties of RAP and understand the strength mechanism of RAP in the cold recycled asphalt mixture.

Materials and Methods

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The RAP was obtained from milling materials of the asphalt layer of an expressway that has been in service for 10 years in Jiangsu province, China. The gradations of the RAP material and the aggregates extracted from RAP are shown in Fig.1. The properties of the recovered asphalt from the RAP were tested, as shown in Table 1. It can be seen that, after 10 years of service, the gradation of RAP became finer and the asphalt was aged.

Triaxial shear test was used to evaluate cohesion strength and internal friction of the RAP. The testing samples were prepared by gyratory compaction and then tested to analyze the shear strength of recycled asphalt mixtures. During the triaxial shear test, the loading rate was selected as 1.27 mm/min, and three different confining pressure levels (0, 138 kPa, and 276 kPa) were used. All the testing specimens were prepared at the same size with a height of 150 mm and a diameter of 100 mm. Five different conditions were used to prepare the testing samples: 1) aggregates extracted from recycled asphalt mixture (named as only-aggregate); 2) the recycled asphalt mixture without heating (named as no-heating); 3) the recycled asphalt mixture heated at 60℃ for 16h (named as 60℃-16h); 4) the recycled asphalt mixture heated at 60℃ for 24h and (named as 60℃-24h); 5) the recycled asphalt mixture heated at 120℃ for 24h (named as 120℃-24h). Three samples were prepared and tested for each type of mixture.

The RAP is usually used at ambient temperatures such as 25℃ in the clod recycled mixture. The highest pavement temperature in summer is about 60℃. The usual temperature used for RAP in the hot recycled mixture is as high as 120℃. These three heating temperatures were used in the test to analyze the strength properties of RAP at different temperatures. It can help understand the contribution of RAP to the mechanical strength in the cold and hot recycled mixture, respectively. Different curing periods were selected to analyze the influences of heating time on the RAP properties and the relatively longer heating time was used to assure the RAP was fully heated.

Extraction and sieving tests were used to analyze the gradation of the RAP. First, the RAP was sieved directly to get its gradation. Then aggregates were extracted and recovered from the RAP for sieving tests to get the real aggregate gradation for the RAP. Based on the gradation analysis, the specific surface area was calculated for RAP and its extracted aggregates, respectively.

Currently there is no standard test method to measure the residual strength of the RAP. In this study, splitting strength tests were used. Testing samples were prepared by mixing the RAP with cement mortar. The purpose of adding cement mortar is to cause the tensile failure happening inside the coarse RAP particles because the strength of cement mortar is much greater. The cement mortar was prepared with water, cement, and sand according to a mass ratio of 1: 2: 3. Marshall testing samples were prepared by mixing cement mortar and RAP at different RAP contents (0, 10, 20, 30, 40, and 50%).

The test samples were prepared by vibration in the Marshall mold, which has the proper size for the splitting strength test. Before demolding, all the samples remained in the Marshall molds for curing at room temperature for two days. After demolding, all the samples were cured at room temperature for another five days. Then splitting tests were conducted for all the samples to obtain the splitting strength. In addition, splitting tests were conducted for the cement-aggregate mixture, which is composed of cement mortar and virgin aggregates, for comparison of the mix strength with different components.

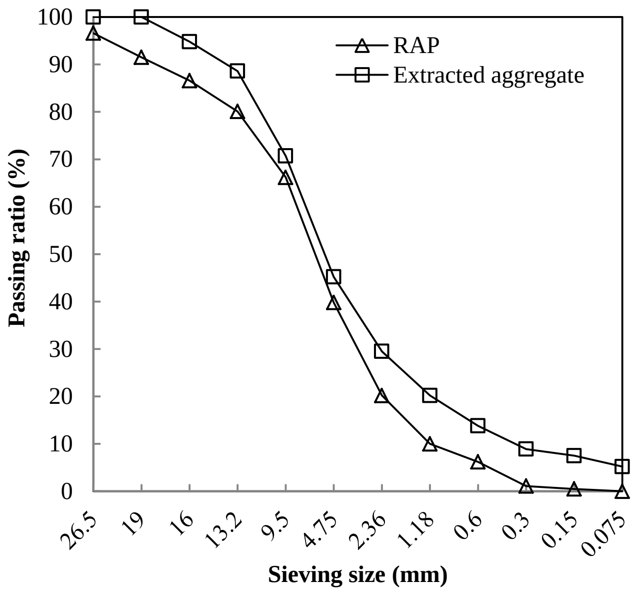

Fig. 1. Gradations of RAP and its Extracted Aggregates.

Table 1. Properties of Aged Asphalt in RAP.

Properties	Penetration (25℃)/0.1mm	Soften Point /℃	Ductility (15℃)/cm
Testing Results	35	60	10

Results and Discussion

Triaxial Shear Strength of RAP

During the triaxial shear test, five types of recycled asphalt mixtures were prepared at different heating and curing conditions, as shown in Fig. 2. It can be seen that the color of the specimens gets darker with a higher heating temperature and a longer heating time. When the specimen was heated at 120℃ for 24h, it looked like the hot-mix asphalt mixture. This indicates that heating can make the asphalt binder in the RAP flow and redistribute around the aggregates.

The triaxial shear testing results, including cohesion strength (c) and internal friction angle (φ), are shown in the Table 2. The data show that for the only-aggregate sample, the cohesion strength is zero and the internal friction angle is greater compared to the other samples. It is because the shear strength is only provided by the internal friction of aggregates due to lack of binding agent. Compared to the only-aggregate sample, the no-heating sample has the smaller internal friction angel but the greater cohesion strength due to the existence of binder. Although the RAP was not heated, the aged asphalt still has active cohesion binding the aggregates.

It is clearly shown that the cohesion strength increases but the internal friction angle decreases as the heating temperature is higher and the heating time is longer. When the recycled asphalt mixture

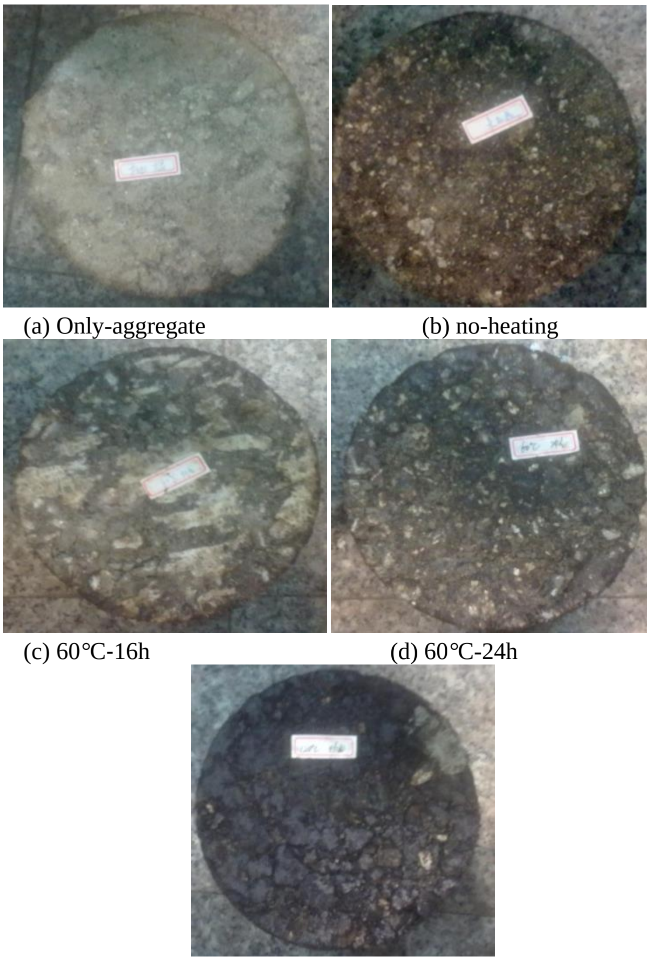

Fig. 2. Samples for Triaxial Shear Test (a) Only-aggregates, (b) no-heating, (c) 60℃-16h, (d) 60℃-24h, and (e) 120℃-24h.

Table 2. Testing Results for Triaxial Shear Test.

No.	Samples	c/kPa	φ/°
1	Only-aggregate	0	57
2	No-heating	126	49
3	60℃−16h	134	46
4	60℃−24h	199	44
5	120℃-24h	308	21

was heated at 60℃ for 16h, the cohesion strength and the internal friction angle are similar to the ones for the no-heating sample. It is noted that the 60℃-16h sample has similar strength with the no-heating samples. When the temperature increases to 120℃, the cohesion strength and the internal friction angle change significantly.

For the cold recycling, the RAP is used without heating and treated as “black rock” aggregates. However, the test results show that the RAP has certain cohesive strength and does not act just like “black color” covering aggregates. Meanwhile, it can be seen that, the non-heated RAP acts much different with the heated RAP. Thus, the RAP in the cold recycled mixture is not exactly like virgin aggregates and is also different from the RAP used in the hot recycled mixture. The RAP has certain residual strength due to its agglomeration structure that will significantly influence the mechanical behavior of the cold recycled asphalt mixture.

Specific Surface Area of RAP

Based on Fig. 1, it is clear that the gradation of extracted aggregates from the RAP is much finer than the gradation of the original RAP. This is because many fine aggregate particles adhere together to form coarser particles due to the binding of asphalt. The maximum particle size of extracted aggregates is 19 mm while the maximum particle size of the RAP is 26.5 mm. The gradation curve of the RAP shows that there are many fewer RAP particles passing through the sieve of 0.3 mm. This confirms that RAP particles are much different from real aggregates. Although the coarse RAP particles may have the same sizes with real aggregates; they are composed of fine particles bonded by asphalt.

During the cold recycling process, the emulsified or foamed asphalt are added into the RAP as a new binder. Therefore, the specific surface area of RAP particles is very important for the coating of binder on aggregates. The specific surface area affects the optimum binder content of recycled mixtures and the adhesive strength between the binder and RAP particles. Based on previous gradation results, the specific surface area of RAP and its extracted aggregates were calculated according to Eq. (1) [20]. The specific area is calculated by the summation of the specific area coefficient for each sieving sizes multiplied by its corresponding passing ratio in the gradation. The calculated results are shown in Table 3.

$$SA = \sum P_i \times FA_i \tag{1}$$

where,
SA is specific surface area of total sieving sizes, m^2/kg;
P_i is passing ratio of different sieving sizes, %; and
FA_i is coefficient of specific surface area for different sieving sizes.

It can be seen that the specific surface area of the extracted aggregates is more than three times of the surface area of the RAP. Therefore, when the new binder is added into the RAP, only less than one-third of the total surface of the aggregate in the RAP can be covered by the new binder. The remaining surface of the aggregates in the RAP is covered by aged binder and exists inside the RAP particles.

According to experiences of cold-recycling field projects, new aggregates can be used to improve the gradation of the RAP. Therefore, in this study, 78% RAP and 22% new aggregates (including 2% new mineral filler) were used as mixed aggregates to produce the cold recycled asphalt mixture. The gradations of two different mixed aggregates—one composed of the RAP and new aggregates and another one composed of extracted aggregates from the RAP and new aggregates—are shown in Table 3, respectively. The specific surface areas for these two different mixed aggregates were calculated based on Eq. (1).

It can be seen that the specific surface area of the mixed aggregates with extracted aggregates is more than 1.5 times of the specific surface area of the mixed aggregates with the RAP particles.

This again indicates that less aggregate surface can be used for binder coating if the RAP particles are directly used. It explains why

Table 3. Specific Surface Area for Different Materials.

Sieving Size (mm)		19	4.75	2.36	1.18	0.6	0.3	0.15	0.075	Total Surface Area (m^2/kg)
Factor of Specific Surface Area (FA_i) (10^{-2})		0.4	0.4	0.8	1.64	2.87	6.14	12.3	32.77	
RAP	Passing Ratio P_i (%)	100	39.4	20.1	10.7	5.8	1.7	0.7	0.1	1.30
	Specific Surface Area (m^2/kg)	0.41	0.16	0.16	0.18	0.17	0.10	0.09	0.03	
Extracted Aggregates from RAP	Passing Ratio P_i (%)	100	45.1	28.6	20.2	12.7	8.6	7.1	4	4.24
	Specific Surface Area (m^2/kg)	0.41	0.18	0.23	0.33	0.36	0.53	0.87	1.31	
RAP and New Aggregates	Passing Ratio P_i (%)	100	41.7	22.5	14.4	10.5	5.1	5.1	3.9	3.53
	Specific Surface Area (m^2/kg)	0.41	0.17	0.18	0.24	0.30	0.32	0.62	1.29	
Aggregates Extracted from RAP and New Aggregates	Passing Ratio P_i (%)	100	46.2	29.1	21.8	15.9	10.5	10.1	6.98	5.82
	Specific Surface Area (m^2/kg)	0.41	0.19	0.24	0.36	0.46	0.65	1.24	2.29	

the asphalt content of cold recycled mixture is usually much lower than the one required in the hot mix asphalt mixture. On the other hand, the internal surfaces inside the coarse RAP particles can be the weak points in the cold recycled asphalt mixture subject to mechanical and environmental loading. This also emphasizes the importance of adding new aggregates into the cold recycled asphalt mixture to achieve the desired gradation and mechanical properties.

Splitting Strength of Cold Recycled Mixture

Based on the previous analysis, in the cold recycled mixture, the coarse RAP particles form “fake” coarse aggregates, and the added new binder cannot penetrate into the aggregate surface of the coarse RAP particles very well. Thus, it is expected that the residual strength of RAP particles have significant influences on the strength of the cold recycled asphalt mixture.

Splitting tests were conducted for cement mortar-RAP samples containing different percentages of RAP. Fig. 3(a) shows the testing sample with 70% cement mortar and 30% RAP and Fig. 3(b) shows the testing sample with 50% cement mortar and 50% RAP.

Fig. 4 shows the splitting strength testing results at different RAP percentages. It shows that the splitting strength decreases as the percentage of RAP increases. A linear relationship was obtained with a high R^2 value. According to the linear equation, the splitting strength of the pure RAP mixture is estimated to be 0.51 MPa when the percentage of RAP is 100%. The value is within the range of 0.4 and 0.6 MPa of cold recycled asphalt mixtures observed from field projects [18]. Combined with the previous analysis of triaxial test and the specific surface area, it can be concluded that the strength of the cold recycled asphalt mixture is significantly affected by the strength of RAP and its percentage.

To further confirm the analysis results, new aggregates and cement were used to obtain the cement-aggregate mixture as compared to the cement-RAP mixture. In the two mixtures, new aggregates and the RAP having the same gradation were used. For both mixtures, cement content changed from 1% to 3% by the weight of aggregates. The small amount of cement was added, considering the asphalt (foamed or emulsified asphalt) is the major component binding the mixture in the cold recycled mixture. Splitting tests were conducted for the cement-aggregate mixture and the cement-RAP mixture.

Fig. 5 shows the strength test results. The data show that, although the RAP and new aggregates have the same gradation, the relationships between splitting strength and cement percent are much different between the cement-aggregate mixture and the cement-RAP mixture. It is clearly shown that the splitting strength of the cement-aggregate mixture grows linearly as the cement percent increases. When the cement percent is smaller than 2%, the splitting strength of the cement-RAP mixture grows with the increasing of cement percent. When the cement percent exceeds 2%,

(a) (b)

Fig. 3. Samples after Splitting Tests for (a) 70% Cement Mortar + 30% RAP and (b) 50% Cement Mortar + 50% RAP.

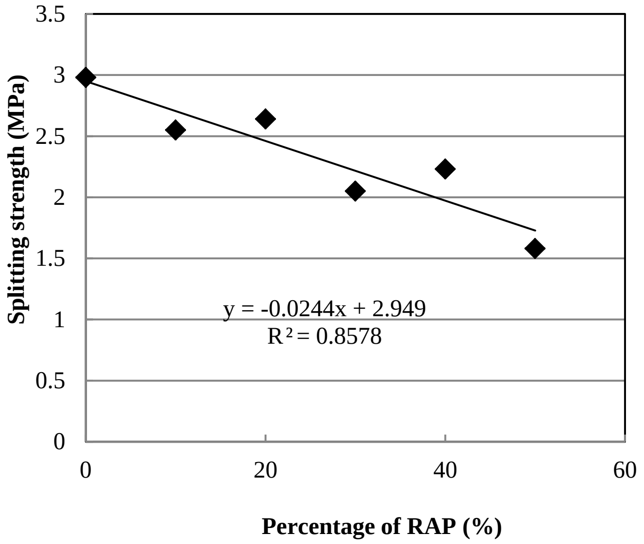

Fig. 4. Splitting Strength vs. RAP Percentages.

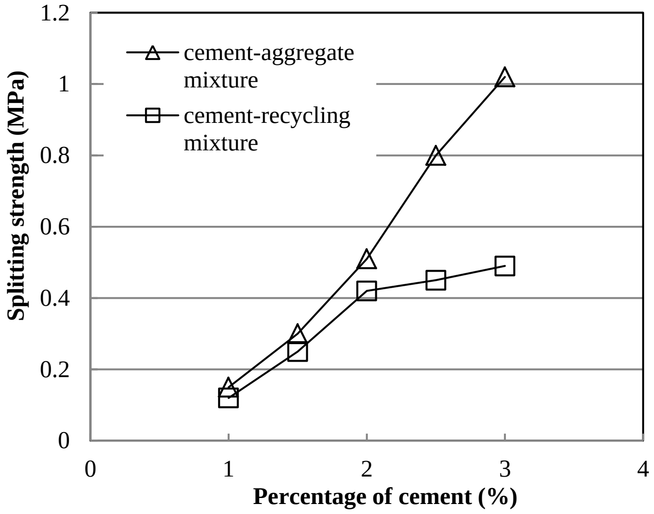

Fig. 5. Splitting Strength for Cement-aggregate and Cement-RAP Mixtures.

the splitting strength of the cement-RAP mixture barely grows with the increasing of cement percent. It is shown that the cement-RAP mixture has lower splitting strength than the cement-aggregate mixture with the same gradation and cement content.

The splitting strength of the cement-RAP mixture with 3% of cement is about 0.5 MPa, while the splitting strength of the cement-aggregate mixture at the cement content is about 1 MPa. It proves again that the RAP cannot be simply treated as “black rock” in the cold recycled asphalt mixture. Even with the same gradation, the strength of RAP is much lower than the new aggregates, and it will affect the splitting strength of cold recycled asphalt mixtures. This indicates that the strength of cold recycled asphalt mixture is usually lower than common semi-rigid materials such as cement treated aggregate.

Conclusions

This study investigated the residual strength of RAP in the cold recycled asphalt mixture. Based on laboratory testing results, the main findings are as follows:

1. Triaxial test results show that RAP samples have higher cohesion strength and lower internal friction angle than pure aggregate samples, while it has lower cohesion strength and higher internal friction angle than the heated RAP samples. It means that the aged asphalt in the RAP still has active cohesion although its cohesion strength is much lower than the binder in the hot-mix asphalt mixture.
2. The gradation of RAP is much coarser than the gradation of its extracted aggregates. This leads to much smaller specific surface area of the RAP. It indicates that in the cold recycled asphalt mixture, a large portion of surface area is inside the RAP that cannot be covered and coated by the new binder.
3. The splitting strength of RAP material was estimated to be about 0.5 MPa according to the splitting test data of cement mortar-RAP mixtures with different RAP percentages. Meanwhile, the cement-RAP mixture has much lower splitting strength than the cement-aggregate mixture with the same gradation and cement content. It proves that the strength of RAP material is not the same but much lower than real aggregates.
4. It can be concluded that the RAP in the cold recycled asphalt mixture does not act exactly like “black color” aggregates. The coarse RAP particles formed by agglomeration of fine particles and the aged binder have important influences on the strength of cold recycled asphalt mixtures. It is important to add new aggregate into the recycled mixture to increase the effective aggregate surface area that can be coated with the new binder.

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