Multiple Optimization of Cold Reclaimed Asphalt Pavement Mixture

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Abstract: Many asphalt pavements fail structurally after having performed well for some years. In China, when low volume of traffic highway is recycled, the asphalt surface course and the base course stabilized by inorganic stabilizers are sometimes recycled and mixed together to form a new base. Portland cement, lime-fly ash, lime or Portland cement-fly ash is added to improve the strength of the new base, but they are not used at the same time, so it is difficult for a road engineer to select an effective and economical stabilizer. To evaluate the effect and economical efficiency of different stabilizers comprehensively, this paper used Portland cement, lime-fly ash, lime and Portland cement-fly ash to form four kinds of cold recycled mixtures and every kind of cold recycled mixture has 3 mix proportions. The unconfined compression strength, flexural tensile strength, splitting strength, compression resilient modulus, shrinkage performance, water stability performance, fatigue failure and engineering cost of 12 cold recycled mixtures were compared. Finally, the Portland cement-fly ash stabilized mixture with proportion of 5:15:80 was recommended.

1 INTRODUCTION

In addition to its environmental benefits, pavement recycling technologies provide cheaper, faster, and less traffic disruptions alternatives to conventional reconstruction strategies [1]. Cold recycling is one of the most popular pavement recycling methods [2]. It is suggested to use 100% reclaimed materials from asphalt pavement (RMAP) to design cold recycled mixture [3].

Cold recycling has been used in America with a long history. The guide for American asphalt pavement recycling was published in 2005, which elaborated pavement recycling technologies. Later, Japan, Germany, Australia and other countries investigated the effect of recycling agent and the performance of regeneration asphalt mixture deeply, emphasized the practical application of the regeneration technology specially, and achieved the normalization and standardization of regeneration technology [4]. Chen conducted a study on the structural combination and material properties of cold recycled asphalt materials to use cold recycled asphalt mixtures for pavement distress repair [5]. Tang and Wu investigated the relationship between the strength characteristics of the cement cold-recycled base materials and the amount of cement binding material, the amount of emulsified asphalt and the thickness of the structural layer [6]. Stimilli, Ferrotti and Graziani studied the mixture which was formed in a central plant employing high-reclaimed asphalt (RA) content and used it to construct two experimental sections along an in-service Italian motorway [7]. Loizos, Papavasiliou and Plati focused on the in situ estimation of the fatigue cracking characteristics / tendencies of CIR pavements, used in situ Non Destructive Tests (NDTs) and facilitated with advanced analysis tools [8]. Xiangguo, Xiaobo and Baoguo Ma showed that the maximum dry density and the optimum moisture content of the mixture changed significantly with the RAP/S proportion and Portland cement-fly ash content [9]. Marek, Przemyslaw and Marek presented the results from the tests performed on the recycled base mixes manufactured in full-depth declamation technology with bitumen emulsion and different types of binding agent [10]. Chomicz and Maciejewski presented an approach for identifying the optimum range of foamed bitumen and Portland cement contents in recycled mineral-bitumen road base mixtures using simultaneous optimization of response variables (i.e. properties of mixtures estimated from statistical models) with the use of desirability functions [11]. Niazi and Jalili showed that both Portland cement and lime could increase Marshall stability, resilient modulus, tensile strength, resistance to moisture damage and resistance to permanent deformation of CIR mixtures [12, 13]. Im explored technically sound ways to classify the minimum CIR properties necessary to certificate the placement of an HMA overlay [14]. Zhihao tested the unconfined compressive strength, cleavage strength and resilient modulus of lime-fly ash stabilized cold regeneration mixture, and established the changing law of these indexes related to the content of lime-fly ash and the curing age, and built functional relationship of strength-cleavage strength and functional relationship of strength-resilient modulus [15].

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2 MATERIALS

The RMAP were taken from the Huang’an Road located in Heze city of Shandong Province, China. The structure of original pavement consisted of 4cm asphalt penetration macadam and 30cm lime stabilized soil. The lime dosage of lime stabilized soil is 12 wt. %.

2.1 Recovered Lime Stabilized Soil

According to specification of China (JTG E42-2005) T 0302—2005 [16], the gradation of the recovered lime stabilized soil was tested by water washing method. The test results are shown in Table 1.

The screening test was carried out for the recycled aggregate by water-washing method in accordance with specification of China (JTG E42-2005) T 0302—2005 [16]. The test results are shown in Table 3 It can be seen that the maximum particle size of recycled aggregate meets the specification requirement of the maximum diameter; but the content of the particles whose sizes is less than 0.075mm has reached 10.3 wt.%, which is beyond the upper limit of the specification.

2.2 Recycled Asphalt Surface

According to specification of China (JTG E20-2011) T 0722-1993 [18], the extraction of recycled asphalt mixture was tested by centrifugal separation. The test results show that the content of asphalt in the recycled asphalt mixture is 4.23 wt. %. Penetration (0.1 mm at 25°C, 100 g, 5 s), softening point (R&B) and ductility (5 cm/min, 5°C) of them were measured. The test results are shown in Table 2. The test results show that the asphalt binder has been severely aged, and its penetration and ductility can’t meet the requirements of the specification any more.

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### 2.4 Added Portland Cement

The indexes of the added 42.5# Portland cement were tested according to specification of China (JTG E51-2009) [17]. The test results are shown in Table 5.

#### 2.5 Added Lime

The added lime is quick lime, and the effective contents of CaO and MgO are 68.3 wt. %. The quicklime can be used after digested and passed form 1mm square mesh.

#### 2.6 Added Fly Ash

The added fly ash is the wet ash produced in the Shaanxi Wei Nan power plant. The indexes of the added fly ash were tested according to specification of China (JTG E51-2009) [17]. The test results are shown in Table 6.

### 3 MIX DESIGN

#### 3.1 Determination of Gradation

After the new aggregate is added, the adjusted gradation is shown in Table 7, which can meet the requirements of specification of China (JTG F41-2008) [19].

#### 3.2 The Program of Cold Recycled Mixture

Portland cement, lime fly ash, Portland cement-fly ash and Portland cement-lime are used to form four kinds of cold recycled mixtures. According to experiences, this paper designs twelve cold recycling programs.

The standard proctor compaction tests of twelve cold recycling programs were tested according to specification of China (JTG E51-2009) [17]. The test results are shown in Table 8. The optimum moisture content and maximum dry densities is used to prepare the specimens.

### 4 TEST METHODS

Unconfined compressive strength (UCS) test, flexural tensile strength test, splitting strength test, compression resilient modulus test, dry shrinkage test, temperature shrinkage test and water stability test were conducted according to to specification of China (JTG E51-2009) [17] (similar to ASTM D2166 [11]).
5 ANALYSIS METHOD OF FATIGUE LIFE AND ENGINEERING COST [21]

5.1 Analysis Method of Fatigue Life

According to specification of China (JTG D50-2006) [20], allowable tensile stress of pavement structural materials could be given by

\[ \sigma_R = \frac{\sigma_S}{K_S} \]  

(1)

where \( \sigma_R \) represents allowable tensile stress (MPa); \( \sigma_S \) represents ultimate splitting strength (MPa); \( K_S \) represents coefficient of tensile strength structure, \( K_S \) of grained soil stabilized with inorganic binding materials could be given by

\[ K_S = 0.45N_e^{0.11} / A_C \]  

(2)

where \( N_e \) represents a cumulative equivalent axle load (times / lane) during the whole design life; \( A_C \) represents coefficient related to highway grade. For freeway, first-class highway, second-class highway, and other class highway, the values of \( N_e \) are 1.0, 1.0, 1.1, and 1.2 respectively.

It can be deduced from Eq. (1) and Eq. (2) that

\[ N_e = 0.11 \sqrt{\frac{A_C \sigma_S}{0.45k_R}} \]  

(3)

The relationship between compressive strength \( \sigma_C \) and splitting strength \( \sigma_S \) is

\[ \sigma_C = k \sigma_S \]  

(4)

It can be deduced from Eq. (3) and Eq. (4) that

\[ N_e = 0.11 \sqrt{\frac{A_C \sigma_C}{0.45k_R}} \]  

(5)

For the same highway, the value of \( A_C, k, \) and \( \sigma_R \) are same, so \( 0.11 \sqrt{\frac{A_C \sigma_C}{0.45k_R}} \) is a fixed value.

If let \( 0.11 \sqrt{\frac{A_C \sigma_C}{0.45k_R}} = \Lambda \), then

\[ N_e = A \cdot \frac{0.11}{\sigma_C} \]  

(6)

Thus the cumulative equivalent axle load during the whole design life is merely related to compressive strength.

5.2 Analysis of Engineering Cost

Assuming that the milling depth of the original road is 30cm. The economical efficiency is related to cost and fatigue life, so the cost divided by fatigue life named as cost per standard axle load is used to evaluate the economical efficiency.

6 RESULTS AND DISCUSSION

The 7-day unconfined compressive strength of cold recycled mixture is the primary index to select program of cold recycled mixture. According to it, one mixing proportion is recommended for each type of cold recycled mixture; then, the optimal scheme will be recommended according to the bending tensile strength, shrinkage performance, compressive resilient modulus, softening coefficient, fatigue life and cost per standard axle load.

The performances and cost of Portland cement stabilized cold recycled mixture are shown in table 9. From table 9, it can be seen that 7-day unconfined compressive strength of 2.244MPa when the mix proportion of Portland cement: RMAP is 4: 96 is less than specification limit of 2.5—3MPa. So this proportion is deleted firstly. The 7-day unconfined compressive strength, 28-day flexural tensile strength, 28-day softening coefficient and fatigue life for the proportion of 5:95 are greater than those for the proportion of 6:94. The cost per standard axle load, dry shrinkage coefficient, temperature shrinkage coefficient and 60d compressive resilient modulus for the proportion of 5:95 are less than those for the proportion of 6:94. Mainly according to fatigue life and engineering cost, the recommended proportion of Portland cement stabilized cold recycled mixture is 5:95.


<table>
<thead>
<tr>
<th>Mix Proportion</th>
<th>4:96</th>
<th>5:95</th>
<th>6:94</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-Day Unconfined Compressive Strength (MPa)</td>
<td>2.244</td>
<td>2.843</td>
<td>2.623</td>
</tr>
<tr>
<td>28-Day Flexural Tensile Strength (MPa)</td>
<td>0.437</td>
<td>0.633</td>
<td>0.590</td>
</tr>
<tr>
<td>28-Day Splitting Strength (MPa)</td>
<td>0.223</td>
<td>0.254</td>
<td>0.353</td>
</tr>
<tr>
<td>Shrinkage Performance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dry Shrinkage Coefficient (10^-6)</td>
<td>147.44</td>
<td>152.17</td>
<td>164.74</td>
</tr>
<tr>
<td>Temperature Shrinkage Coefficient(10^-6/℃)</td>
<td>9.4</td>
<td>9.6</td>
<td>9.9</td>
</tr>
<tr>
<td>60d Compressive Resilient Modulus(MPa)</td>
<td>809</td>
<td>881</td>
<td>934</td>
</tr>
<tr>
<td>Softening Coefficient</td>
<td>1.025</td>
<td>1.091</td>
<td>0.916</td>
</tr>
<tr>
<td>Fatigue Life(Times)</td>
<td>2.5E+05A</td>
<td>5.3E+05A</td>
<td>2.6E+05A</td>
</tr>
<tr>
<td>Cost Per Standard Axle Load (¥)</td>
<td>4.43E-02</td>
<td>2.48E-02</td>
<td>5.86E-02</td>
</tr>
</tbody>
</table>

The performance and cost of lime-fly ash stabilized cold recycled mixture, Portland cement-fly ash stabilized cold recycled mixture and Portland cement-lime stabilized cold recycled mixture are shown in table 10.
According to the method shown in the recommended proportion of Portland cement stabilized cold recycled mixture, the recommended proportion of lime-fly ash stabilized cold recycled mixture, Portland cement-fly ash stabilized cold recycled mixture and Portland cement-lime stabilized cold recycled mixture are determined as 5:12.5:82.5, 5:15:80 and 5:10:85 respectively.

Table 10. The Performance and Cost of Lime-Fly Ash Stabilized Cold Recycled Mixture.

<table>
<thead>
<tr>
<th>Mix Proportion</th>
<th>5:10:85</th>
<th>5:12.5:82.5</th>
<th>5:15:80</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-Day Unconfined Compressive Strength (MPa)</td>
<td>0.487</td>
<td>0.985</td>
<td>1.606</td>
</tr>
<tr>
<td>28-Day Flexural Tensile Strength (MPa)</td>
<td>0.540</td>
<td>0.700</td>
<td>0.760</td>
</tr>
<tr>
<td>28-Day Splitting Strength (MPa)</td>
<td>0.383</td>
<td>0.357</td>
<td>0.502</td>
</tr>
<tr>
<td>Shrinkage Performance</td>
<td>Dry Shrinkage Coefficient (10^-6)</td>
<td>209.71</td>
<td>246.74</td>
</tr>
<tr>
<td></td>
<td>Temperature Shrinkage Coefficient(10^-6/°C)</td>
<td>8.6</td>
<td>8.4</td>
</tr>
<tr>
<td>60d Compressive Resilient Modulus(MPa)</td>
<td>963</td>
<td>1052</td>
<td>1108</td>
</tr>
<tr>
<td>Softening Coefficient</td>
<td>1.06</td>
<td>0.935</td>
<td>0.971</td>
</tr>
<tr>
<td>Fatigue Life(Times)</td>
<td>9.8E+05A</td>
<td>6.0E+06A</td>
<td>2.9E+06A</td>
</tr>
<tr>
<td>Cost Per Standard Axle Load ($)</td>
<td>1.62E-02</td>
<td>2.89E-03</td>
<td>1.10E-04</td>
</tr>
</tbody>
</table>

Table 11. The Performance and Cost of Cement-Fly Ash Stabilized Cold Recycled Mixture.

<table>
<thead>
<tr>
<th>Mix Proportion</th>
<th>5:10:85</th>
<th>5:15:80</th>
<th>5:20:75</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-Day Unconfined Compressive Strength (MPa)</td>
<td>3.458</td>
<td>3.872</td>
<td>4.096</td>
</tr>
<tr>
<td>28-Day Flexural Tensile Strength (MPa)</td>
<td>1.073</td>
<td>1.177</td>
<td>1.233</td>
</tr>
<tr>
<td>28-Day Splitting Strength (MPa)</td>
<td>0.625</td>
<td>0.783</td>
<td>0.727</td>
</tr>
<tr>
<td>Shrinkage Performance</td>
<td>Dry Shrinkage Coefficient (10^-6)</td>
<td>352.33</td>
<td>357.63</td>
</tr>
<tr>
<td></td>
<td>Temperature Shrinkage Coefficient(10^-6/°C)</td>
<td>9.3</td>
<td>9.1</td>
</tr>
<tr>
<td>60d Compressive Resilient Modulus(MPa)</td>
<td>1136</td>
<td>1205</td>
<td>1347</td>
</tr>
<tr>
<td>Softening Coefficient</td>
<td>0.994</td>
<td>0.938</td>
<td>1.004</td>
</tr>
<tr>
<td>Fatigue Life(Times)</td>
<td>2.6E+06A</td>
<td>6.3E+06A</td>
<td>5.2E+06A</td>
</tr>
<tr>
<td>Cost Per Standard Axle Load ($)</td>
<td>7.55E-03</td>
<td>3.57E-03</td>
<td>4.90E-03</td>
</tr>
</tbody>
</table>

Table 12. The Performance and Cost of Cement-Lime Stabilized Cold Recycled Mixture.

<table>
<thead>
<tr>
<th>Mix Proportion</th>
<th>5:5:90</th>
<th>5:7.5:87.5</th>
<th>5:10:85</th>
</tr>
</thead>
<tbody>
<tr>
<td>7-Day Unconfined Compressive Strength (MPa)</td>
<td>2.693</td>
<td>2.509</td>
<td>2.056</td>
</tr>
<tr>
<td>28-Day Flexural Tensile Strength (MPa)</td>
<td>0.892</td>
<td>0.854</td>
<td>0.769</td>
</tr>
<tr>
<td>28-Day Splitting Strength (MPa)</td>
<td>0.447</td>
<td>0.379</td>
<td>0.298</td>
</tr>
<tr>
<td>Shrinkage Performance</td>
<td>Dry Shrinkage Coefficient (10^-6)</td>
<td>286.67</td>
<td>287.69</td>
</tr>
<tr>
<td></td>
<td>Temperature Shrinkage Coefficient(10^-6/°C)</td>
<td>9.3</td>
<td>9.7</td>
</tr>
<tr>
<td>60d Compressive Resilient Modulus(MPa)</td>
<td>982</td>
<td>1046</td>
<td>1126</td>
</tr>
<tr>
<td>Softening Coefficient</td>
<td>0.927</td>
<td>0.91</td>
<td>0.931</td>
</tr>
<tr>
<td>Fatigue Life(Times)</td>
<td>1.7E+05A</td>
<td>5.9E+04A</td>
<td>4.2E+05A</td>
</tr>
<tr>
<td>Cost Per Standard Axle Load ($)</td>
<td>1.28E-01</td>
<td>4.38E-01</td>
<td>7.19E-02</td>
</tr>
</tbody>
</table>

In summary, the mix proportions of recommended for each cold recycled mixture are shown in table 13. From table 13, it can be seen that 7-day unconfined compressive strength, 28-day flexural tensile strength, 28-day splitting strength, 60d compressive resilient modulus and fatigue life when the mix proportion of Portland cement-fly ash-RMAP is 5:15:80 are largest. In terms of temperature shrinkage coefficient and softening coefficient, Portland cement-fly ash stabilized cold recycled mixture with the proportion of 5:15:80 is the second-best; and in terms of cost per standard axle load for all recommended cold recycled mixtures, Portland cement-fly ash stabilized cold recycled mixture with the proportion of 5:15:80 is the third-best. Finally, Portland cement-fly ash stabilized cold recycled mixture with the proportion of 5:15:80 is recommended the optimal mixture.
7 CONCLUSIONS

To help road engineers to select appropriate cold recycled scheme, this paper presented an approach for identifying the optimum type and content of stabilizer. To evaluate the effect and economical efficiency of different stabilizers comprehensively, this paper used Portland cement, lime-fly ash, lime and Portland cement-fly ash to form four kinds of cold recycled mixtures and every kind of cold recycled mixture has 3 mix proportions. According to unconfined compression strength, flexural tensile strength, splitting strength, compression resilient modulus, shrinkage performance, water stability performance, fatigue failure and engineering cost of 12 cold recycled mixtures, the recommended mix proportion are as follows: Portland cement: RMAP = 5:95; lime: fly ash: RMAP = 5:12.5:82.5; Portland cement: fly ash: RMAP = 5:15:80; Portland cement: lime: RMAP = 5:10:85. Finally, Portland cement-fly ash stabilized cold recycled mixture with the proportion of 5:15:80 is recommended the optimal mixture.

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