STABILIZATION OF RECYCLED ASPHALT PAVEMENT BY FLY ASH AS A SUSTAINABLE PAVEMENT MATERIAL

Menglim Hoy¹, Suksun Horpibulsuk², Runglawan Rachan³ and Arul Arulrajah⁴

¹²School of Civil Engineering and Center of Excellence in Innovation for Sustainable Infrastructure Development, Suranaree University of Technology, Thailand; ³Department of Civil Engineering, Mahanakorn University of Technology, Thailand; ⁴Department of Civil and Construction Engineering, Swinburne University of Technology, Australia;

ABSTRACT

This paper presents the results of the evaluation of Recycled Asphalt Pavement (RAP) and Fly Ash (FA) blend as a sustainable pavement material. The strength characteristic of RAP-FA blend was determined by Unconfined Compression Strength (UCS) test. The effect of wetting-drying (w-d) cycles on the strength and microstructural changes of this material was also investigated. The micro-structure of the compound pavement material was analyzed using X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM). The leachability of the heavy metals is measured by Toxicity Characteristic Leaching Procedure (TCLP) and compared with international standards. Test results show that the compacted RAP-FA blend can be used as a base course material as its UCS values meet the minimum strength requirement specified by national road authorities of Thailand. The durability test results show that the UCS of RAP-FA blend increases with increasing the number of w-d cycles (C), reaching its peak at 6 w-d cycles. The XRD and SEM analyses indicate that the increased UCS of RAP-FA blend is due to stimulation of the chemical reaction between the high amount of Calcium in RAP and the high amount of Silica and Alumina in FA during w-d cycles leading to production of more Calcium (Aluminate) Silicate Hydrate [C-(A)-S–H]. For C > 6, the significant macro- and micro-cracks developed during w-d cycles cause strength reduction. The TCLP results demonstrate that there is no environmental risk for RAP-FA blend in road construction. The outcome from this research confirms the viability of using RAP-FA blend as alternative sustainable pavement materials.

Keywords: Recycled Asphalt Pavement, Wetting-Drying Cycles, Durability, Microstructure, Pavement Structure.

INTRODUCTION

Sustainable infrastructure is a key strategic initiative in many developed and developing countries. Research on the usage of alternative sustainable materials is at the forefront of many governments, researchers, and pavement industries worldwide [1]. The usage of waste by-products in civil infrastructure enables a more durable alternative to quarried materials resulting in conservation of natural resources, decreased energy use, and reduced greenhouse gas emission. In recent years, extensive research works on innovative and environmentally friendly solutions have resulted in the applications of green technologies in pavement construction, which have led to more efficient use of natural resources and recycled materials [2].

Meanwhile, roads are a central component of many nation’s infrastructure and present a wide array of opportunities for the usage of vast quantities of recycled materials. Recycled Asphalt Pavement (RAP), is obtained from spent asphalt extracted from roads that have reached the end of their design life [3, 4]. RAP contains asphalt binder (3–7%) and aggregates (93–97%) by weight [5], and is an ideal recycled material for reuse in pavement applications. RAP often exhibits low strength and stiffness performances, hence chemical stabilization of RAP is used extensively for developing bound pavement base/sub-base material [6, 7]. Several researchers have reported that the performance of cement stabilized RAP satisfied the requirements of pavement base/subbase application [8]. Cement-stabilized RAP is however not considered as an environmentally friendly material, as the production of Portland cement contributes significantly to global warming.

These shortcomings have led to an attempt to explore novel low carbon stabilization methods. An evaluation of FA-stabilized RAP as pavement base/sub-base material has been investigated by Saride, et al. [9] whom reported that the Unconfined Compression Strength (UCS) and resilient modulus (M₅₀) properties can be improved by FA replacement. However, the 7-day UCS of RAP was reported to be lower than the strength requirement specified for pavement base materials. Further studies on the mechanical and microstructural properties of a stabilized RAP, Virgin Aggregate (VA) and FA blend as a pavement base/sub-base [10] indicated that RAP:VA = 80:20 with 40% FA replacement satisfied the strength, stiffness, and California Bearing Ratio requirements for low volume roads.
The RAP stabilized with FA for pavement base course is presented in this study, which a large amount of RAP, of up to 80% could be used as aggregate. Though the utilization of recycled waste materials in highway construction can be considered as having significant impacts on resource management, the hazardous compounds that can leach out and pollute the water resource should also be considered [11].

Besides strength and environmental requirements, the durability of stabilized material under severe climatic conditions is a crucial parameter when used in road construction applications. The study on durability of RAP-FA blends is however still in its infancy. Dempsey and Thompson [12] defined durability as the ability of the materials to retain their stability and integrity and to maintain adequate long-term residual strength to provide sufficient resistance to climate conditions.

Cyclic wetting-drying (w-d) test, simulates weather changes over a geological age, and is considered to be one of the most appropriate simulation that can induce damage to pavement materials [13,14]. Al-Obaydi, et al. [15] and Al-Zubaydi [16] indicated that after repeated w-d cycles, crack propagation would occur, resulting in severe effects on the engineering properties of the materials, particularly in terms of their residual strength and stability. This research attempts to study the possibility of using FA stabilized RAP as a sustainable pavement material, which divided into three main objectives. First, an investigation of the strength development of the RAP-FA blend. Then, its durability when subjected to cyclic wetting-drying tests. The changes in material properties, microstructure and mineralogy during cyclic w-d tests were examined. The change in materials’ strength/physical properties were examined using UCS and weight loss tests, while the mineralogical and microstructural changes were examined by the application of X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) analyses at various repeated w-d cycles. Finally, the leachate test to estimate the contaminant concentration from the RAP-FA blend is also investigated. The outcomes of this research will have significant impact on construction guidelines and specifications for using RAP-FA blends and RAP-FA geopolymers in road construction applications.

MATERIALS AND METHODS

Materials

In this research, RAP samples were collected from a mill asphalt pavement stockpile in Nakhon Ratchasima province, Thailand. The gradation and the engineering properties of air-dried RAP are shown in Figure 1 and Table 1, respectively. The chemical and mineral composition of RAP, obtained by X-Ray Fluorescence (XRF) and X-Ray Diffraction (XRD) analyses, are presented in Table 2 and Figure 2, respectively. The XRD analyses indicated that the predominant mineral components in RAP were calcite-magnesium and dolomite, while the XRF results indicated that the main chemical compositions in RAP were 41.93% CaO and 36.18% MgO.
FA used in this study was obtained from Mae Moh powerplant, the largest lignite power plant in the northern region of Thailand. The grain size distribution curve of FA, obtained by a laser particle analyzer, is also shown in Figure 1.

The specific gravity of FA was 2.50. Table 2 summarizes the chemical composition of FA using XRF analysis. FA was composed mainly of 40.13% SiO₂, 20.51% Al₂O₃, 5.83% Fe₂O₃, and 12.45% CaO. In accordance with ASTM C 618 [17], FA was classified as Class C because the total chemical composition of SiO₂+Al₂O₃+Fe₂O₃ was greater than 50% and CaO greater than 10%.

The peaks of main amorphous phases, including calcium sulfate, quartz, calcite, mulite, and hematite were detected by XRD analysis in region of 15-40°20 as demonstrated in Figure 2. The SEM image in Figure 3b indicates that variety sizes of FA particles were in fine and spherical shape.

Sample preparation

The RAP-FA blend was a combination of RAP, FA, and water. FA replacement ratios were 10%, 20%, and 30% by weight of RAP.

The mixing procedure started with mixing air-dried RAP and FA for 5 min, then mixed with water for an additional 5 min to ensure homogeneity. The mixture was next compacted in a cylindrical mold (101.6 mm in diameter and 116.3 mm in height) under the modified Proctor energy [19] for the Unconfined Compression Strength (UCS) test. The samples were dismantled, wrapped within vinyl sheet and then cured at room temperature (RT) (20 – 25°C) for 7 days and 28 days.

Table 1. Geotechnical Properties of RAP.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
<th>ASTM</th>
</tr>
</thead>
<tbody>
<tr>
<td>USCS classification</td>
<td>SP</td>
<td>D2487-11</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>2.70</td>
<td>D1883-07</td>
</tr>
<tr>
<td>CBR (%)</td>
<td>10-15</td>
<td>D557-12</td>
</tr>
<tr>
<td>Water absorption (%)</td>
<td>6.80</td>
<td>-</td>
</tr>
<tr>
<td>Swelling ratio (%)</td>
<td>0.20</td>
<td>-</td>
</tr>
<tr>
<td>Dry unit weight (kN/m³)</td>
<td>17.50</td>
<td>D1557-12</td>
</tr>
<tr>
<td>Optimum water content (%)</td>
<td>4.10</td>
<td>D1557-12</td>
</tr>
</tbody>
</table>

Table 2. Chemical composition of RAP and FA by using XRF analysis.

<table>
<thead>
<tr>
<th>Chemical Formula</th>
<th>RAP</th>
<th>FA</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>3.15</td>
<td>40.13</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>4.78</td>
<td>20.51</td>
</tr>
<tr>
<td>Fe₂O₃</td>
<td>0.10</td>
<td>5.83</td>
</tr>
<tr>
<td>CaO</td>
<td>41.93</td>
<td>12.45</td>
</tr>
<tr>
<td>MgO</td>
<td>36.18</td>
<td>3.11</td>
</tr>
<tr>
<td>SO₃</td>
<td>0.89</td>
<td>0.42</td>
</tr>
<tr>
<td>K₂O</td>
<td>0.04</td>
<td>1.61</td>
</tr>
<tr>
<td>LOI</td>
<td>-</td>
<td>0.40</td>
</tr>
</tbody>
</table>

UCS is considered as one of the most important design parameters in road construction and earthwork applications [20]. The UCS of the samples was determined in accordance with ASTM D1633 [21] using a compression machine with a strain rate of 0.5%/min. The samples after 7 and 28 days of curing were soaked in water for 2 hours and then were air-dried for 1 hour prior to UCS test according to the specifications of the Department of Highways, Thailand [45]. The water absorption of 28 days cured samples was also measured every one hour during soaking.

Wetting and Drying (w-d) Test

Standard wetting and drying test methods for compacted soil-cement mixtures [22] was adopted for the sample preparations. 28-day samples were selected for wetting and drying (w-d) tests and were submerged in potable water at room temperature for 5 hours. They were then dried in an oven at 70°C for 42 hours and air-dried for 1 hour. This procedure constitutes one w-d cycle (48 h). The weight loss of the samples were recorded by weighing at each w-d cycle. At the targeted w-d cycles, the samples again were immersed in water for 2 hour and then air-dried for at least 1 hour prior to the UCS test. The UCS of the samples were measured at 1, 3, 6, 9, 12, 15 and 20 w-d cycles and compared with that of the samples without w-d cycle to investigate the effect of w-d cycles on the UCS.

Mineralogical and Microstructural Analyses

The micro-structure change of RAP-FA blend samples was examined using X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) to indicate the mineralogical and microstructural changes before and after the w-d cycles. Small fragments were taken from the broken portion of the UCS samples and separated into two portions. One was frozen at -195°C by immersion in liquid nitrogen for 5 minutes and coated with gold for SEM analysis using JEOL JSM-6400 device [23]. The other portion was air-dried and further processed to produce finer than 75 um powder for XRD analysis. The traces were obtained by scanning at 0.1°(20) per min and at steps of 0.05°(20).
Toxicity Characteristic Leaching Procedure (TCLP) Test
The Toxicity Characteristic Leaching Procedure (TCLP) test is the method prescribed by the U.S. EPA guidelines (Method 1311) to determine if the solid waste is hazardous [24]. The TCLP tests were carried out on 100% RAP and RAP-FA blend for different types of heavy metal by using Inductively Coupled Plasma – Optical Emission Spectrometry (ICP-OES).

RESULTS AND DISCUSSION
Unconfined Compression Strength (UCS)
Figure 4 shows the relationship between dry unit weight and water content (WC) of the compacted RAP-FA blends. The dry unit weight of 100% RAP (without FA) are insensitive to WC. On the other hand, the dry unit weight of RAP and FA bends is sensitive to WC and maximum dry unit weight is at OWC. The maximum dry unit weight tends to increase with increasing FA replacement ratios. However, the FA replacement ratio up to 20% insignificantly affects the compaction curve of RAP and FA blends as seen that the compaction curves of RAP+20%FA and RAP+30%FA blends are similar.

Figure 5 summarizes the UCS results of RAP+FA blends (at 20%FA and 30%FA) at the age of 7 days and 28 days. It clearly indicates that the UCS values of the RAP+FA blends increase with curing time.

This is notably similar to previous studies on strength development of cement-stabilized RAP [25, 26]. The 7-day UCS value of both RAP+20%FA blend and RAP+30%FA blend are higher than RAP results reported by Saride et al. and greater than the strength requirement specified by the Thailand national road authorities in which UCS > 1,724 kPa and UCS > 2,413 kPa for both low and high volume roads, respectively [27,28].

Wetting-Drying Cycled Strength
FA replacement ratio at 20% by weight of RAP shows to be optimal, hence the durability against wetting-drying (w-d) cycles was performed on RAP+20%FA blend after 28 days of curing to investigate the strength, mineralogical, and microstructural properties.

The UCS of RAP+20%FA blend at various number of w-d cycles, C is presented in Figure 6. The UCS of RAP+20%FA blend evidently increases with increasing C, up to C = 6 and then decreases when C > 6. Previous research, which investigated the effect of w-d cycles on strength development of an FA stabilized with lime and gypsum, also indicated the strength increase due to the development of cementitious compounds during the w-d process [29].

Figure 7 shows the relationship between water absorption and soaking time of RAP+20%FA blend after 28 days of curing. Evidently, the water absorption of RAP+20%FA blend is very low and lower than 1% for all tested C. Kuosa and Niemeläinen [51] reported that the water absorption for pavement materials is normally < 1%.

Fig. 4 Compaction results of 100%RAP and RAP-FA blends.

Fig. 5 Compressive strength of RAP+20%FA blend and RAP+30%FA blend at age of 7 days and 28 days.

Fig. 6 Relationship between strength and number of w-d cycles of RAP+20%FA blend.
The relationship between the weight loss of the RAP+20%FA blend versus number of w-d cycles, C is illustrated in Figure 8. The weight loss of RAP+20%FA blend remarkably increases within the first w-d cycle and thereafter gradually increases with an increase in C. The effect of cyclic w-d cycles on the external surface of the RAP+20%FA blend is evident in Figure 9a and b respectively at a particular C = 0 and C = 20. Large macro-cracks and surface deterioration on the RAP+20%FA blend are clearly observed, which leads to strength loss. However, even with the strength reduction after C = 6, its 20 days cycle UCS value is still greater than the minimum strength requirement specified by Thailand national road authorities. From the cyclic w-d results and the photos, it is evident that RAP+20%FA blend provides a fairly good durability when subjected to w-d cycles.

Mineralogical and Microstructural Changes

The XRD patterns of RAP+20%FA blend at various C are shown in Figure 10. Without w-d cycle (C = 0), the RAP+20%FA blend (Figure 10a) contains the amorphous phases of Calcium Magnesium as the predominant minerals in RAP as well as new cementitious minerals (Silica- and Alumina-products), such as Anorthite, Diopsite, Ladradorite, and Ettringite. These new minerals are formed when RAP is mixed with FA (RAP-FA blend), as evidenced by comparing Figure 3 (RAP) and Figure 10a (RAP-FA). In other words, the chemical reaction between the high amount of silica and alumina of FA and high amount of Calcium of RAP results in the formation of Calcium Silicate Hydrate (C-S-H) and Calcium Aluminate Hydrate (C-A-H), similar to the hydration of Portland cement [30,31], that can enhance the strength development.

The increase in peaks corresponded to Anorthite, Diopsite, and Ladradorite with increasing C to 6 is observed by comparing Figure 10b (C = 1) with Figure 10c (C = 6), that indicates the increase of C-S-H and C-A-H. Drying at 70°C for w-d test evidently enhances the cementitious products (C-A-S-H) [32,33]; i.e., an increased temperature results in a faster moisture diffusivity of the cementitious materials and hence cement hardening [34-36]. The same is however not true for C > 6. The temperature affects the water physical properties (density and surface tension) [37] and causes the coarsening of the pore structure in relation to Ettringite dissolution and C-S-H alteration [32]. The XRD patterns of RAP+20%FA blend in Figure 10d indicates the presence of Ettringite and the decreased intensity of Anorthite and Diopside minerals when the samples are subjected to 12 w-d cycles. Ettringite is a hydrous mineral that exhibits expansive behavior upon wetting [38, 39] and makes the RAP-FA blends potentially volumetrically unstable [40, 41].

Besides the XRD results, SEM images of RAP+20%FA blend at various C are illustrated in Figure 11. The growth of C-A-S-H gels inner and on the spherical surface of FA with increasing C (C = 0 to 6, see Figure11a-c) is observed while reduction in cementitious gel at the C = 12 (Figure 11d) is detected, which confirms the XRD results.

Toxicity Characteristic Leaching Procedure (TCLP) Analysis

From an environmental perspective, recycled material or solid inert waste material can be accepted in field applications, even due to rainfall or storm water events, if RAP-FA blends will not pose any risk to the ground water tables or water stream beyond. Therefore, in order to use the RAP-FA
blends in road construction, the environmental risk assessment needs to be ascertained.

![Fig. 10 XRD patterns of RAP+20%FA blend samples at: (a) C = 0, (b) C = 1, (c) C = 6, and (d) C = 12.](image)

![Fig. 11 SEM images of RAP+20%FA blend samples at: (a) C = 0, (b) C = 1, (c) C = 6, and (d) C = 12.](image)

Table 3. Leachate analysis of 100%RAP and RAP+20%FA blend.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Sample of acid leachate extraction (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100%RAP</td>
</tr>
<tr>
<td>pH</td>
<td>5.12</td>
</tr>
<tr>
<td>Arsenic</td>
<td>&lt;0.01</td>
</tr>
<tr>
<td>Cadmium</td>
<td>BDL</td>
</tr>
<tr>
<td>Chromium</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td>Copper</td>
<td>BDL</td>
</tr>
<tr>
<td>Lead</td>
<td>BDL</td>
</tr>
<tr>
<td>Mercury</td>
<td>BDL</td>
</tr>
<tr>
<td>Nickel</td>
<td>&lt;005</td>
</tr>
<tr>
<td>Zinc</td>
<td>1.348</td>
</tr>
</tbody>
</table>

Note: BDL = Below Detection Limit

Table 3 shows the leachate analysis of 100%RAP and RAP+20%FA blend by using acetic leachate extraction. According to benchmark mandated by the U.S. Environment Protection Agency (EPA) for storm-water sampling, pH values should be in the range of 6 to 9 (EPA, 2005). Leachate results show that pH level in 100%RAP is 5.12 and 5.59 for RAP+20%FA blend, which are within allowable limits. Table 4 presents the prescribed limits for drinking water and the threshold for hazardous waste defined by the U.S. Environmental Protection Agency (EPA, 1999, 2009).

Wartman et al. (2004) [42] reported that a material is designated as a hazardous waste in accordance to U.S. EPA if any detected mental is present in concentrations > 100 times the drinking water standards. Based on this criterion, the comparison of TCLP results between Tables 3 and 4 indicated that all mental contaminates are within acceptable limits.

From a geotechnical engineering perspective, the research results indicate that RAP is mechanically and economically viable for use in pavement base applications, when it stabilized with 20% of FA. Besides having a high UCS, the RAP-FA blend exhibits good durability against w-d cycles, which can be attributed to the growth of C3-S-H and C-A-H during the w-d processes. Furthermore, these materials provide a positive environmental impact as environmental test results show no significant risk to the ground water or stream water line.

**CONCLUSIONS**

The present study investigated the possibility of using the RAP-FA blend as a sustainable pavement material. The outcome of this research is to promote the use of recycled waste material in road construction, with economic and environmental benefits. The following conclusions can be drawn from this study:
Table 4. Comparison of TCLP data analysis with U.S. EPA Requirements.

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Drinking water standards (EPA, 1999) (mg/L)</th>
<th>Threshold for solid inert waste (EPA, 2009) (mg/L)</th>
<th>Hazardous waste designation (Wartman et al., 2004) (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arsenic</td>
<td>0.05</td>
<td>0.35</td>
<td>5.0</td>
</tr>
<tr>
<td>Barium</td>
<td>2.0</td>
<td>35.0</td>
<td>100.0</td>
</tr>
<tr>
<td>Cadmium</td>
<td>0.005</td>
<td>0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Chromium</td>
<td>0.1</td>
<td>2.5</td>
<td>5.0</td>
</tr>
<tr>
<td>Lead</td>
<td>0.015</td>
<td>0.5</td>
<td>5.0</td>
</tr>
<tr>
<td>Mercury</td>
<td>0.002</td>
<td>0.05</td>
<td>0.2</td>
</tr>
<tr>
<td>Selenium</td>
<td>0.05</td>
<td>0.5</td>
<td>1.0</td>
</tr>
<tr>
<td>Silver</td>
<td>0.05</td>
<td>5.0</td>
<td>5.0</td>
</tr>
</tbody>
</table>

The 7-days UCS of the compacted RAP-FA blend at OWC meets the strength requirement for base course specified by Thailand national road authorities for both 20% and 30% FA replacement. The UCS improves insignificantly when the FA replacement ratio exceeds 20%, indicating this to be the optimal blend.

When subjected to w-d cycles, the UCS of RAP+20%FA blend increases with increasing the number of w-d cycles (C) up to 6 cycles and then decreases. The XRD and SEM analyses indicated that for C ≤ 6, the w-d cycles increase the strength of RAP+20%FA blend due to the growth of C-S-H and C-A-H due to the chemical reactions between high amount of calcium oxide in RAP with high amount of silica and alumina in FA. With C > 6, large cracks due to the loss of moisture content during drying stage, lead to reduction in UCS of RAP+20%FA blend. However, even with the strength reduction after C = 6, its 20 days cycle UCS value is still greater than the minimum strength requirement specified by Thailand national road authorities.

From an environmental perspective, the TCLP results indicate that RAP-FA blends can be safely used in sustainable pavement base application, as this material pose no significant environmental risk. In addition, the RAP-FA blend is found to be durable and with a positive impact that enables its application in sustainable civil engineering infrastructures. The use of these recycled materials furthermore results in significant energy saving and reduction in greenhouse gas emission.

ACKNOWLEDGMENT

The first author is grateful to a financial support from Suranaree University of Technology under SUT-Ph.D. program for his Ph.D. studies. This work was financially supported by the Thailand Research Fund under the TRF Senior Research Scholar program Grant No. RTA5980005, Suranaree University of Technology and the Higher Education Research Promotion and National Research University Project of Thailand, Office of Higher Education Commission.

REFERENCES


[19] ASTM-D1557-12, Standard test methods for laboratory compaction characteristics of soil using modified effort (56,000 ft-lbf/ft3 (2,700 kN/m3)), in West Conshocken, PA, ed. 2012.


