Wetting and Drying Characteristics of Recycled Asphalt Pavement-Fly Ash Blend as a Sustainable Pavement Material

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ABSTRACT: The usage of Recycled Asphalt Pavement (RAP) and Fly Ash (FA) blend in pavement applications contributes to the sustainable usage of such waste by-products. Although RAP-FA blend has been proven as a pavement material based on strength and leachate requirement, the durability of this blend when exposed to an aggressive environment has not been investigated to date. This research presents the effect of wetting-drying (w-d) cycles on the strength and microstructural changes of RAP-FA blend. The strength characteristic of this material was determined by Unconfined Compression Strength (UCS) test. The mineralogical and microstructural changes of the compound pavement material were also analyzed using X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM). 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 Silicate Hydrate (C-S-H) and Calcium Aluminate Hydrate (C-A-H). For C > 6, the significant macro-cracks due to the loss of moisture content during drying stage cause strength reduction. However, its reduced UCS is still greater than the minimum strength requirement even at C = 20. The outcome from this research confirms the viability of using RAP-FA blends as an alternative sustainable pavement material.

INTRODUCTION

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 (Moreno et al., 2012).

Roads are a central component of many nations’ 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 (Arulrajah et al., 2014; Rahman et al., 2014). RAP contains asphalt binder (3–7%) and aggregates (93–97%) by weight (Han & Thakur, 2015), and is an ideal recycled waste 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 (Hoyos et al., 2011; Saride et al., 2015). Several researchers have reported that the performance of cement stabilized RAP satisfied the requirements of pavement base/subbase application (Hoyos et al., 2011; Suebsuk et al., 2014). 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., (2014) whom reported that the Unconfined Compression Strength (UCS) and resilient modulus (M_R) 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.

Hoy et al. (2016a; 2016) have evaluated the strength development and leachate characteristics of RAP-FA blends as sustainable stabilized pavement base/subbase materials, in which up to 80% RAP was used as aggregates and indicated that it can be used as a base pavement material as the strength requirement met the specifications of the Department of Highways, Thailand. In addition, this product was found to pose no significant environmental and leaching hazards into soil and ground water resources.

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 (1967) 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 (Sobhan & Das, 2007).

This research attempts to study the durability of RAP-FA blends 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 Unconfined Compressive Strength (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. 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 Fig. 1 and Table 1, respectively. The chemical and mineral composition of RAP, obtained by X-Ray Fluorescence (XRF) and XRD analyses, are presented in Table 2 and Fig. 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. This high CaO in RAP can react with silica and alumina in FA for an enhanced pozzolanic reaction. The irregular shape of RAP particles covered by amorphous asphalt binder, obtained by SEM analysis, is presented in Fig. 3a.

FA used in this study was obtained from Mae Moh power plant, 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 Fig. 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 and it was classified as Class C according to ASTM C 618 (ASTM-C618-12, 2012). The peaks of main amorphous phases, including calcium sulfate, quartz, calcite, mulite, and hematite were detected by XRD analysis in region of 15°-40°2θ as demonstrated in Fig. 2. The SEM image in Fig. 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. In order to find the optimal water content (OWC), the water ratio was varied by the total weight of RAP and FA prior to compaction test. Once the compaction curves of RAP-FA blends were obtained, the samples at OWC were prepared for unconfined compression test (UCS). 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 (ASTM-D1557-12, 2012) for the 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.

The UCS of the samples was determined in accordance with ASTM D1633 (ASTM-D1633, 2007) 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 (DOH, 2000). 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 (ASTM-D559/D559M-15, 2015) 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 RT 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 was recorded by weighing at each w-d cycle. At the targeted w-d cycles, the samples again were immersed in water for 2 hours and then air-dried for at least 1 hour prior to the UCS test. The
UCS of the samples was 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.

Figures 1, 2. XRD pattern of RAP and FA. Figure 3. SEM image of: (a) RAP and (b) FA.

Mineralogical and microstructural analyses

The micro-structural change of RAP-FA blend samples was examined using XRD and SEM 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 (Sukmak et al., 2013a). The other portion was air-dried and further processed to produce finer than 75 µm powder for XRD analysis. The traces were obtained by scanning at 0.1°(2θ) per min and at steps of 0.05°(2θ).

RESULTS AND DISCUSSION

Unconfined compression strength (UCS)

Fig. 4 shows the relationship between the dry unit weight and water content (WC) of the compacted RAP-FA blends. The dry unit weight of 100% RAP (without FA) is 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.
Table 1. Geotechnical Properties of RAP.

<table>
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<tr>
<th>Parameters</th>
<th>Values</th>
<th>ASTM</th>
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<tbody>
<tr>
<td>USCS classification</td>
<td>SP</td>
<td>D2487-11</td>
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<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>D557-12</td>
</tr>
<tr>
<td>Swelling ratio (%)</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>Dry unit weight (kN/m$^3$)</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>
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</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>
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<tbody>
<tr>
<td>SiO$_2$</td>
<td>3.15</td>
<td>40.13</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>4.78</td>
<td>20.51</td>
</tr>
<tr>
<td>FeO$_3$</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>SO$_3$</td>
<td>0.89</td>
<td>0.42</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>0.04</td>
<td>1.61</td>
</tr>
<tr>
<td>LOI</td>
<td>-</td>
<td>0.40</td>
</tr>
</tbody>
</table>

Fig. 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 (Suebsuk et al., 2014; Taha et al., 2002). The 7-day UCS values of both RAP+20%FA blend and RAP+30%FA blend are higher 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 (DOH, 2000; DRR, 2013).

Wetting and drying cycled strength

FA replacement ratio at 20% by weight of RAP shows to be optimal, hence the durability against 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 Fig. 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 (Sivapullaiah & Moghal, 2010).

Fig. 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 \( C \), though it may gradually increase with soaking time. Kuosa and Niemeläinen (2013) reported that the water absorption for pavement materials is normally < 1%.

The relationship between the weight loss of the RAP+20%FA blend versus number of w-d cycles, \( C \), is illustrated in Fig. 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 Fig. 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 Fig. 10. Without w-d cycle (C = 0), the RAP+20%FA blend (Fig. 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, Ladadorite, and Ettringite. These new minerals are formed when RAP is mixed with FA (RAP-FA blend), as evidenced by comparing Fig. 3 (RAP) and Fig. 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 (Cristelo et al., 2012; Hanjitsuwan et al., 2014), that can enhance the strength development.

The increase in peaks corresponded to Anorthite, Diopsite, and Ladadorite with increasing C to 6 is observed by comparing Fig. 10b (C = 1) with Fig. 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) (Brue et al., 2012; Jiang & Yuan, 2013); i.e., an increased temperature results in a faster moisture diffusivity of the cementitious materials and hence cement hardening (Drouet et al., 2015; Wang, Fall, & Wu, 2016).

The same is however not true for C > 6. The temperature affects the water physical properties (density and surface tension) (Wu et al., 2014) and causes the coarsening of the pore structure in relation to Ettringite dissolution and C-S-H alteration (Brue et al., 2012). The XRD patterns of RAP+20%FA blend in Fig. 10d indicates the presence of Ettringite and the decreased intensity of Anorthite and Diopsite minerals when the samples are subjected to 12 w-d cycles. Ettringite is a hydrous mineral that exhibits expansive behavior upon wetting (Celik & Nalbantoglu, 2013; Little et al., 2009) and makes the RAP-FA blends potentially volumetrically unstable (Aldaood et al., 2014).

Besides the XRD results, SEM images of RAP+20%FA blend at various C are illustrated in Fig. 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 Fig. 11a-c) is observed while reduction in cementitious gel at the C = 12 (Fig. 11d) is detected, which confirms the XRD results.

From a geotechnical engineering perspective, the research results indicate that RAP is mechanically and economically viable for use in pavement base applications, when it is...
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 C-S-H and C-A-H during the w-d processes.

CONCLUSION

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:

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, this study confirms the potential use of the recycled and waste materials such as RAP and FA in term of the RAP-FA blend as a sustainable pavement base material, with high durability performance. The use of these recycled materials furthermore results in significant energy saving and reduction in greenhouse gas emission.
Figure 10. XRD patterns of RAP+20% FA blend samples at: (a) $C = 0$, (b) $C = 1$, (c) $C = 6$, and (d) $C = 12$.

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

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