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Strength and durability against wetting-drying cycles of geopolymer-stabilized reclaimed asphalt pavement for roadway subgrade materials

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ABSTRACT

Pavement rehabilitation and reconstruction processes result in significant amounts of reclaimed asphalt pavement (RAP). Enhancing the engineering characteristics of RAP is essential to facilitate its utilization as an eco-friendly alternative construction material for roadway construction. In this article, the unconfined compressive strength (USC) and durability of RAP when stabilized with various ratios of fly ash, bottom ash and alkali solutions consisting of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) was investigated under the cyclic wetting-drying (w-d) tests that simulate the changes in weather over a geological age, and are considered capable of simulating critical scenarios that can induce damage to roadway materials. The results showed that the specimens using only fly ash exhibited higher UCS and lower mass loss than those combined with bottom ash in all wet-dry cycles. The use of a NaOH and Na_2SiO_3 mixture resulted in lower mass loss compared to using NaOH alone indicates higher durability of specimens, which is a desirable property for materials used in roadway construction. The results also provide insights into the appropriate ratios for the application of reclaimed asphalt pavement (RAP) in conjunction with geopolymer derived from coal ash for use as roadway materials in the future applications.

1. INTRODUCTION

Roads are considered as essential infrastructure and play a crucial role in the development and prosperity of a country. Constructing roads into rural areas brings development and modernization to remote villages, aiding farmers in transporting their produce. Additionally, roads are vital for national security. Therefore, studying road pavement structure is of great importance. Pavement structure is designed to bear the weight of traffic on the road surface. The materials used in constructing pavement structures must meet standards for physical and engineering properties. However, the increasing demand for road construction, coupled with national development efforts and environmental regulations on mountain blasting, could directly impacts the stone industry which is one of the important sources of roadway material. This results in material shortages and challenges in selecting high-quality materials for roadway construction.

When roads have been in use for a period of time, they can suffer damage due to the excessive load from vehicular traffic or the degradation of materials over time. Such damage includes issues like potholes, rutting and various types of cracking. If repairs and maintenance are not carried out to restore the road to its original condition, the damage will worsen, compromising the safety of road users and increasing repair costs. Consequently, it becomes necessary to rehabilitate asphalt concrete pavements by removing the old surface to create a new, functional driving surface. The repair process involves milling the old pavement down to the base course before replacing the surface layer with new materials. This generates waste from the deteriorated asphalt concrete, which, if simply discarded, accumulates and poses a growing problem for both public and private sectors. In Thailand, there are now standards (DH-S 214/2566, 2023) for reusing old pavement materials to reduce production costs and repurpose waste materials, thus benefiting the environment and mitigating climate change. Using reclaimed asphalt pavement (RAP) as a substitute for coarse aggregate supports the use of recycled materials in road construction and decreases the demand for new natural aggregates. This practice not only promotes recycling but also contributes to sustainability in construction practices.

Electric power is considered a fundamental factor in driving the country's industry and economy. Currently, there are at least 10 coal-fired power plants in Thailand, with 9 privately-owned plants located in 4 provinces: Rayong (6 plants), Prachinburi (2 plants), and Ayutthaya (1 plant). The only plant owned by the Electricity Generating Authority of Thailand is the Mae Moh power plant in Lampang Province. By-products from the electricity generation process include fly ash and bottom ash, which accumulate in large quantities annually, causing issues with storage and disposal, and impacting the environment. Consequently, various public and private sectors have developed ideas to recycle and repurpose these by-products as components or alternative materials for concrete and road construction, which are essential elements of public infrastructure projects.

To date, research on enhancing the strength of Reclaimed Asphalt Pavement (RAP) with geopolymer binders made from fly ash has become widely accepted (Khamtanee, et al., 2024; Suddeepong, *et al.*, 2018; Nanda and Priya, 2024; Adhikari, *et al.*, 2021). However, Thailand is situated in a tropical region and experiences significant climatic variations during the rainy and dry seasons. Therefore, this study aims to investigate the influence of wet-dry conditions on the unconfined compressive strength of subgrade materials. The wet-dry (w-d) cycle test, simulating critical weather conditions that can cause damage to roadway materials, will be conducted over six cycles. The results of this study will be compared with the standards of the Department of Highways (DH-S 214/2566, 2023) to provide data supporting the practical application of these materials as a new alternative for subgrade materials in the future.

2. MATERIALS, MIXING COMPOSITIONS ANS SPECIMENS PREPARATION

2.1 Reclaimed Asphalt Pavement (RAP)

In this study, RAP was obtained from the milling of deteriorated pavement surfaces of the Burapha Withi Expressway, kilometer 6+000 to 9+000, in Bangkok, Thailand. The basic properties of RAP used in this study have been tested and are presented in Table 1. The results indicate that the abrasion test by Los Angeles Machine value is 29.7%, which is within the standard criterion of not exceeding 35% according to DH-S 214/2566, (2023) standard. The maximum dry density is measured at 2.02 g/cm³, and the optimum moisture content is 8% and water absorption value is 4%.

Table 1. Properties of RAP in this study

Testing	Results
Specific Gravity	2.3
Water Absorption of Aggregate	4 %
Abrasion Test by Los Angeles Machine	29.7 %
Dry Density	2.02 g/cm^3
Optimum Moisture Content	8 %

The gradation of the RAP used in this study was tested in accordance with the Ministry of Highways of Thailand Standards DH-S 205/2517, (1974) for sieve analysis of fine and coarse aggregates. According to these standards, the quantity of aggregate passing through the 0.075-millimeter sieve (No. 200) must not exceed two-thirds (2/3) of the total mass passing through the 0.425-millimeter sieve (No. 40). The particle size distribution of the RAP utilized in this research complies with this standard.

2.2 Coal Ash

The coal ash utilized in this study consists of Class C fly ash and bottom ash, sourced from the Mae Moh power plant in Lampang Province, Thailand. These ashes are by-products of coal combustion for electricity generation. The chemical compositions of the fly ash and bottom ash are detailed in Table 2.

Table 2. Chemical composition of coal ash from the Mae Moh power plant

Chemical composition (%)		
	Bottom ash	Fly ash
SiO_2	28.16	29.66
Al_2O_3	13.92	14.42
Fe_2O_3	15.83	15.03
CaO	28.71	29.25
MgO	3.61	3.33
SO_3	5.86	3.29
K_2O	1.31	1.78
Na_2O	1.98	2.57

2.3 Alkaline Activator

The alkaline solution used as a polymerization reaction accelerator in this study consists of two components with a concentration of 10 molar: (1) sodium hydroxide (NaOH) which often utilized as an alkaline activator in geopolymer chemistry. It serves as a crucial component in the activation process, reacting with source materials such as fly ash or metakaolin to initiate the polymerization and formation of the geopolymer matrix and (2) sodium silicate (Na_2SiO_3), also known as water glass, is another common component used in geopolymer formulations. It acts as an alkaline activator alongside sodium hydroxide, contributing to the dissolution of source materials and the formation of the geopolymer gel. Sodium silicate provides silica and alkali ions necessary for the polymerization reaction, helping to establish the desired chemical bonds within the geopolymer structure.

2.4 Mixing Compositions of Subgrade Materials

In this study, the compositions of the subgrade specimens were derived from the proportions of five primary components: Reclaimed Asphalt Pavement (RAP), Fly Ash (FA), Bottom Ash (BA), Sodium Hydroxide (NaOH) solution, and Sodium Silicate (Na_2SiO_3) solution. The combined amount of fly ash and bottom ash was set to constitute 20% of the total weight of the RAP. The specific mixing ratios of fly ash to bottom ash were established at 100:0 and 75:25 by weight. Additionally, an alkaline solution, consisting of NaOH and Na_2SiO_3, was prepared at a concentration of 10 molar. The volume ratios between the NaOH and Na_2SiO_3 solution were set at 100:0, 75:25, and 50:50, respectively. Table 3 provides a detailed breakdown of the mixing ratios for the various specimens used in the study.

Table 3. Mixing ratio of each subgrade specimen

Specimen name	Coal ash (%)		Alkaline solution (%)	
	Fly ash	Bottom ash	NaOH	Na_2SiO_3
RAP-A(100:0)-S(100:0)	100	0	100	0
RAP-A(75:25)-S(100:0)	75	25	100	0
RAP-A(100:0)-S(75:25)	100	0	75	25
RAP-A(75:25)-S(75:25)	75	25	75	25
RAP-A(100:0)-S(50:50)	100	0	50	50
RAP-A(75:25)-S(50:50)	75	25	50	50

Note: RAP-A(100:0)-S(75:25) represents using RAP as the coarse material with a fly ash to bottom ash ratio of 100:0 and an alkaline solution ratio of NaOH:Na_2SiO_3 of 75:25.

2.5 Specimens Preparation

The procedures for preparing pavement specimens are detailed as follows:

- Determine the optimum moisture content and maximum dry density for each composition by conducting modified compaction tests in accordance with the Department of Highways standard DH-S 108/2517, (1974) and ASTM D 1557, (2021). These tests should utilize a compaction machine with a mold diameter of 101.6 millimeters (4 inches) and a height of 116.8 millimeters (4.584 inches). Perform the compaction tests to ascertain the maximum dry density and optimum moisture content for each composition.

- Prepare sample specimens by mixing Reclaimed Asphalt Pavement (RAP), Fly Ash (FA), and Bottom Ash (BA) in the predetermined proportions as described in Table 3. Subsequently, mix these components with a 10-molar alkaline solution, adjusting the mixture to the optimum moisture content for each component. Compact and cure the specimens in a laboratory environment for a duration of 7 days.

- After 7 days of curing, conduct wet-dry cycles as depicted in Fig.1, performing 1, 3, and 6 cycles according to ASTM D559/D559M-15, (2023) standards, as follows:

a) submerge the specimens
b) allow the surface to dry
c) oven drying
d) rest at room temperature for 3 hours

Fig. 1 Curing the specimens under wet-dry cycles

- Submerge the specimens in room temperature water for 5 hours.
- Remove the specimens from the water and allow the surface to dry at room temperature.
- Place the specimens in an oven at 70 degrees Celsius for 48 hours.
- Remove the specimens from the oven and allow them to rest at room temperature for 3 hours.
- Completing all these steps constitutes one cycle. Repeat the process for the desired number of cycles.
- After completing the specified number of cycles, immerse the specimens in water for 2 hours to ensure full saturation before testing their Unconfined Compressive Strength (UCS).

3. THE STUDY RESULTS AND DISCUSSION

3.1 Unconfined Compressive Strength of Specimens

Figure 2 and Table 4 illustrate the unconfined compressive strength (USC) values of specimens subjected to 0, 1, 3, and 6 wet-dry cycles. In the first cycle, the group of samples treated solely with NaOH solution exhibited a slight decrease in UCS, ranging from -3.42% to -12.73%. The samples treated with a NaOH:Na_2SiO_3 solution ratio of 75:25 showed UCS values that were similar to the 0 cycle state, with a slight tendency to increase, and the differences in strength ranged from -3.42% to 12.73%. On the other hand, the samples treated with a NaOH:Na_2SiO_3 solution ratio of 50:50 exhibited a significant increase in UCS, with values rising by 34.52% to 44.30%.

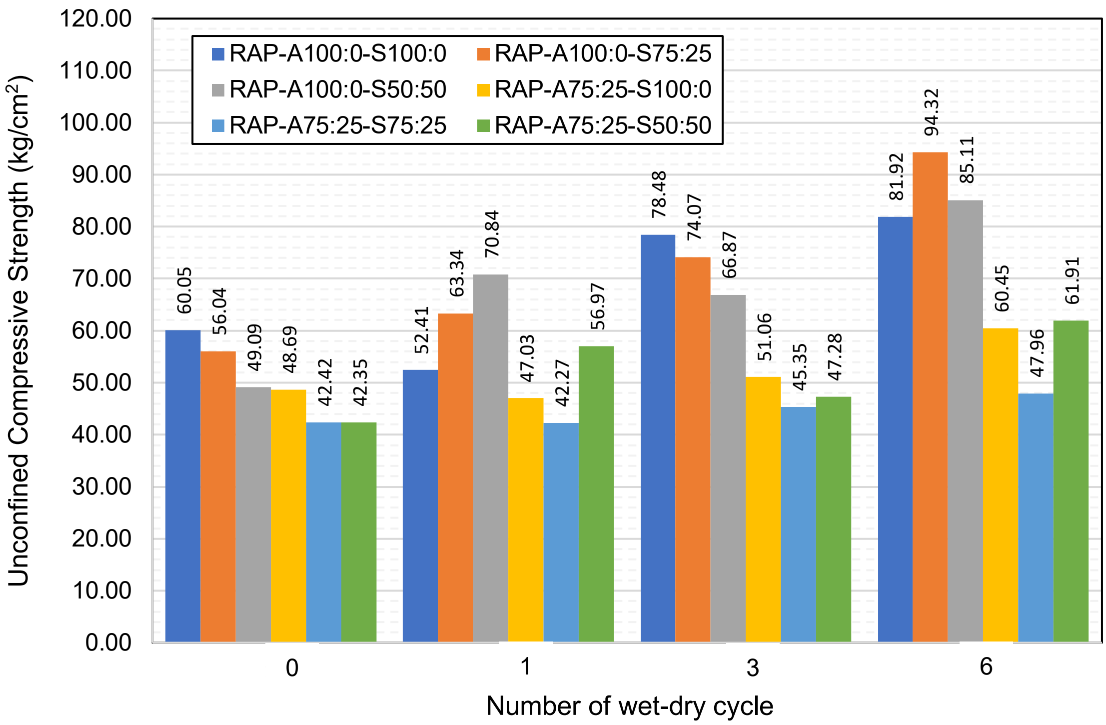

Fig. 2 Unconfined compressive strength of specimens under various wet-dry cycles

Table 4 Unconfined compressive strength of specimens under various wet-dry cycles

Name of Specimens	Unconfined compressive strength (kg/cm^2) – (% increased compared to 0 cycle)			
	0 cycle	1 cycle	3 cycles	6 cycles
RAP-A100:0-S100:0	60.05	52.41 (-12.73)	78.48 (30.69)	81.92 (36.42)
RAP-A100:0-S75:25	56.04	63.34 (13.03)	74.07 (32.18)	94.32 (68.33)
RAP-A100:0-S50:50	49.09	70.84 (44.30)	66.87 (36.21)	85.11 (73.38)
RAP-A75:25-S100:0	48.69	47.03 (-3.42)	51.06 (4.87)	60.45 (24.15)
RAP-A75:25-S75:25	42.42	42.27 (-0.36)	45.35 (6.89)	47.96 (13.06)
RAP-A75:25-S50:50	42.35	56.97 (34.52)	47.28 (11.65)	61.91 (46.19)

After completing three cycles of wet-dry cycles, it was observed that all samples exhibited an increase in UCS compared to the initial (0 cycles) state, with increases ranging from 4.87% to 36.21%. Furthermore, it was found that samples with higher amounts of Na_2SiO_3 solution had greater increases in UCS compared to those with lower amounts or none at all.

After completing six cycles of wet-dry cycles, all samples showed a significant increase in UCS compared to the initial (0 cycles) state, with increases ranging from 13.06% to 73.38%. Additionally, it was also observed that samples with higher amounts of Na_2SiO_3 solution exhibited greater increases in UCS compared to those with lower amounts or none at all, similar to the behavior observed after 1 and 3 cycles as previously described. This indicates that the inclusion of Na_2SiO_3 solution could contributes to the improvement of strength, enhancing the material's resistance to wet-dry conditions.

3.2 Mass Loss

Table 5 presents the mass and mass loss of specimens subjected to various wet-dry cycles. The percentage of mass loss is calculated by comparing the mass lost after each cycle to the mass at cycle 0, or the initial state before exposure to wet-dry conditions.

Table 5 Mass and mass loss of specimens under various wet-dry cycles

Cycles	RAP A100:0-S100:0		RAP A100:0-S75:25		RAP A100:0-S50:50		RAP A75:25-S100:0		RAP A75:25-S75:25		RAP A75:25-S50:50	
	Mass (g)	Mass Loss (%)	Mass (g)	Mass Loss (%)	Mass (g)	Mass Loss (%)	Mass (g)	Mass Loss (%)	Mass (g)	Mass Loss (%)	Mass (g)	Mass Losse (%)
0	2284.00	0.00	2255.01	0.00	2159.50	0.00	2195.67	0.00	2241.25	0.00	2187.36	0.00
1	2261.55	0.98	2233.29	0.96	2141.61	0.83	2158.12	1.71	2202.23	1.74	2155.17	1.47
2	2258.85	1.10	2229.92	1.11	2138.53	0.97	2153.35	1.93	2196.05	2.02	2150.89	1.67
3	2255.55	1.25	2226.89	1.25	2135.79	1.10	2148.90	2.13	2191.37	2.23	2148.43	1.78
4	2250.98	1.45	2223.17	1.41	2133.71	1.19	2143.65	2.37	2186.46	2.44	2145.12	1.93
5	2247.97	1.58	2219.24	1.59	2131.25	1.31	2138.82	2.59	2183.45	2.58	2141.59	2.09
6	2245.21	1.70	2214.93	1.78	2129.57	1.39	2134.06	2.81	2180.45	2.71	2140.37	2.15

Fig. 3 shows the mass loss of all specimens, in the case where the ratio of fly ash to bottom ash is 100:0, it can be observed that the mass loss increased rapidly in the first cycle and continued to increase steadily up to the sixth cycle. Notably, after six cycles, the specimens with a NaOH:Na_2SiO_3 ratio of 50:50 exhibited the least mass loss, amounting to 1.39% of the initial mass. The specimens with NaOH:Na_2SiO_3 ratios of 100:0 and 75:25 showed similar mass loss from the first to the sixth cycle. Among these, the NaOH:Na_2SiO_3 ratio of 75:25 had the highest mass loss in the sixth cycle, with a total mass loss of 29.924 grams, equivalent to 1.78% of the initial mass.

In the case where the ratio of fly ash to bottom ash is 75:25. The mass loss also increased rapidly during the first cycle and continued to rise steadily up to the sixth cycle. Notably, after six cycles, the specimens with a NaOH:Na_2SiO_3 ratio of 50:50 exhibited the least mass loss, amounting to 2.151% of the initial mass. The specimens with NaOH:Na2SiO_3 ratios of 100:0 and 75:25 showed similar mass loss from the first to the sixth cycle. Among these, the 100:0 ratio had the highest mass loss in the sixth cycle, with a total mass loss of 61.61 grams, equivalent to 2.806% of the initial mass.

Minimizing mass loss is advantageous as it indicates greater durability of the specimens. When comparing the specimens using only fly ash to those with a mixture of fly ash and bottom ash, it was found that the addition of bottom ash resulted in greater mass loss in all cycles of wet-dry conditions. This may be due to the larger particle size of bottom ash, which leads to less effective chemical reactions compared to the finer fly ash, ultimately affecting the durability of the samples.

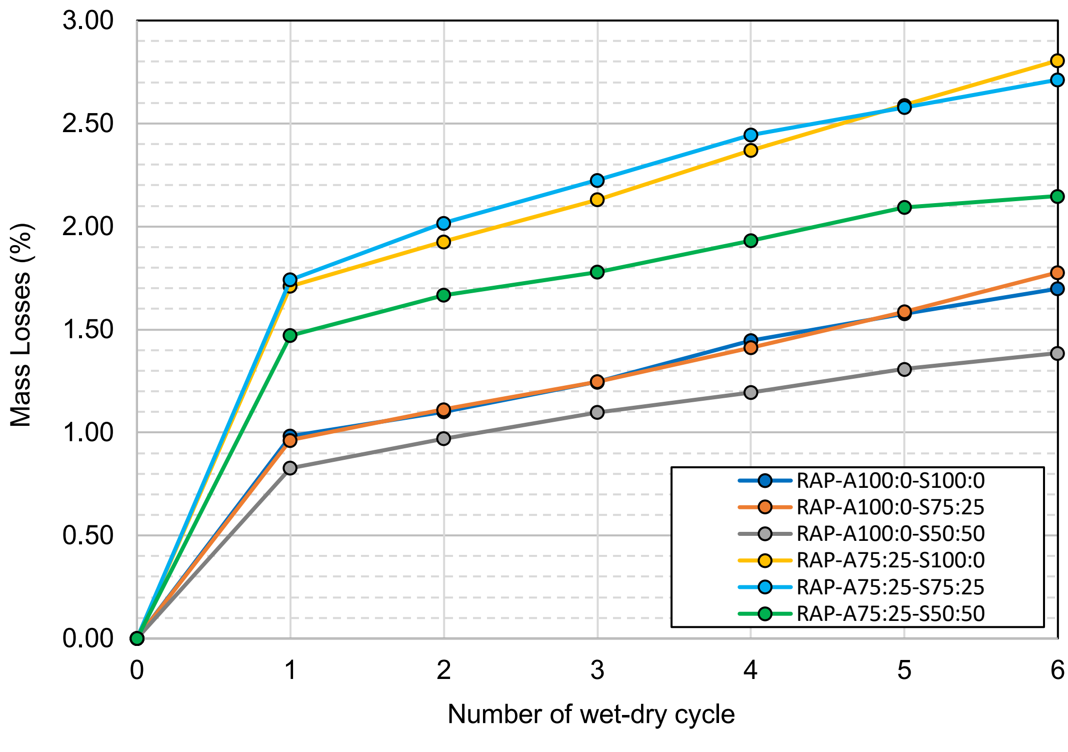

Fig. 3 Mass loss of specimens under various wet-dry cycles

4. CONCLUSIONS

This research investigates the use of reclaimed asphalt concrete pavement (RAP) stabilized with geopolymer from coal ash for use as roadway material. The study examines the impact on the unconfined compressive strength and mass loss of the material subjected to wet-dry cycles. The findings of the study can be summarized as follows:

From the unconfined compressive strength (UCS) test results, it was found that with an increasing number of wet-dry cycles, the UCS of all specimens increased. Specifically, after six cycles of wet-dry cycles, the sample RAP-A100:0-S75:25, which used only fly ash and had a NaOH:Na_2SiO_3 solution ratio of 75:25, exhibited the highest UCS of 94.32 kg/cm². When comparing the use of fly ash alone to the use of a mixture of fly ash and bottom ash, it was found that samples using only fly ash exhibited higher UCS than those with bottom ash in all cycles of wet-dry cycles. Regarding the solution composition, using NaOH alone resulted in a smaller increase in UCS compared to using a combination of NaOH and Na_2SiO_3. Specifically, after six cycles of wet-dry cycles, using NaOH alone increased the UCS of the samples by 24.15% to 36.42%, whereas using NaOH combined with Na_2SiO_3 in a 50:50 ratio increased the UCS by 46.19% to 73.38% compared to the initial state before exposure to wet-dry conditions.

The mass loss test results indicate that as the number of wet-dry cycles increases, all specimens experience greater mass loss. A common behavior observed is a rapid mass loss in the first cycle, followed by a steady increase from the second cycle through the sixth cycle. After six cycles of wet-dry cycles, the sample RAP A75:25-S100:0, which used a mixture of 75% fly ash and 25% bottom ash with NaOH solution alone, exhibited the highest mass loss at 2.81%. In contrast, the sample RAP A100:0-S50:50, which used only fly ash with a NaOH:Na_2SiO_3 solution ratio of 50:50, had the lowest mass loss at 1.39%.When comparing the use of fly ash alone to the mixture with bottom ash, it was found that samples using only fly ash had lower mass loss than those with bottom ash. Additionally, the use of a NaOH and Na_2SiO_3 mixture resulted in lower mass loss compared to using NaOH alone. Lower mass loss indicates higher durability, which is a desirable property for materials used in construction.

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