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Strength development of Recycled Asphalt Pavement – Fly ash geopolymer as a road construction material

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HIGHLIGHTS

- Evaluation of Fly Ash (FA) based geopolymer stabilized Recycled Asphalt Pavement (RAP).
- Role of L, $NaOH/Na_2SiO_3$, FA, and curing temperature and duration are investigated.
- Microstructural development was examined via XRD and SEM analyses.
- UCS of RAP-FA geopolymers and RAP-FA blends were compared with road authorities' requirements.

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ABSTRACT

This paper investigates the strength development of Recycled Asphalt Pavement (RAP)-Fly Ash (FA) geopolymer as a road construction material. A mixture of sodium hydroxide solution (NaOH) and sodium silicate solution (Na_2SiO_3) is used as a liquid alkaline activator (L). Unconfined Compression Strength (UCS) is used as an indicator to measure the strength development of RAP-FA geopolymer and RAP-FA blend (without L). The UCS development is analyzed via Scanning Electron Microscopy (SEM), and X-ray Diffraction (XRD) analyses. Test results show that the compacted RAP-FA blend can be used as a base course material as its UCS values meet the specified strength requirements. The UCS of RAP-FA blends increases with time due to the formation of Calcium Silicate Hydrate (C-S-H) and Calcium Aluminate Hydrate (C-A-H), as detected from XRD and SEM analyses. The UCS of RAP-FA geopolymer increases as the $NaOH/Na_2SiO_3$ ratio decreases and is higher than those of compacted RAP-FA blends. When the $NaOH/Na_2SiO_3$ ratios are less than 90:10. At an early stage of 7 days and room temperature curing, XRD and SEM analyses indicate that low geopolymerization products (N-A-S-H) in RAP-FA geopolymer are detected when only NaOH ($NaOH/Na_2SiO_3$ = 100:0) is used as L, hence the UCS of RAP-FA geopolymer at $NaOH/Na_2SiO_3$ = 100:0 is lower than that of RAP-FA blends. With increasing curing time and temperature, NaOH solution dissolves more silica and alumina from FA in the geopolymerization reaction, hence the UCS developed with time and temperature. The highly soluble silica from Na_2SiO_3 incorporates with leached silica and alumina from FA into a N-A-S-H gel which co-exists with C-S-H and C-A-H from RAP and FA reaction. Therefore, the 7-day UCS values of RAP-FA geopolymer increase with decreasing $NaOH/Na_2SiO_3$ ratios for both room temperature and 40 °C curing. This research study confirms the potential of RAP-FA blends and RAP-FA geopolymers as an alternative stabilized pavement material.

1. Introduction

There is increasing global interest to use recycled materials in the construction and rehabilitation in the infrastructure sectors. Recycled Asphalt Pavement (RAP) is obtained from spent asphalt extracted from roads that have reached the end of their design life [1,2]. RAP is predominantly a combination of aggregates and aged bituminous additives. RAP has successfully been reused as a

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construction material in road bases, road subbase, asphalt concrete aggregates, embankments and backfills [3–5]. The utilization of RAP materials in civil engineering infrastructure works has led to significant environmental benefits, as well as a vast reduction of construction and demolition debris being disposed to landfills.

RAP is increasingly becoming a popular material in unbound base and subbase applications due to its lower cost compared to that of natural quality aggregates. The sustainable usage of RAP also leads to significant economical savings for the construction of new highway pavements [6]. Large quantities of RAP are however not taken up whole-heartedly by industry, due to their often low strength and stiffness characteristics [3,7–11]. Though some efforts have been made to blend RAP with other higher quality natural or recycled materials in pavement base/subbase applications, these RAP blends often do not meet the minimum local road authorities specified requirements [4,8]. Saride et al. [12] evaluated fly ash stabilized RAP, with different percentages of fly ash (FA) replacement contents. The authors reported that in the short-term (curing periods of 1 day and 7 days), the Unconfined Compression Strength (UCS) and resilient modulus (M_R) values increased with an increase in FA content with up to 30% replacement, thereafter further increases in FA content resulted in a decrease in the UCS and M_R values. This investigation showed that 7-day UCS values (maximum 1497 kPa) did not meet the strength requirements specified for base materials. The utilization of RAP substitution in Virgin Aggregate (VA) stabilized by FA have been evaluated by Saride et al. [13] whom reported that RAP: VA = 80:20 with 40% FA mix satisfies the strength, stiffness, and California Bearing Ratio requirements for low volume roads. Mohammadinia et al. [14] recently evaluated the behavior of geopolymer stabilized RAP with FA and blast furnace slag precursors and reported that geopolymer stabilized RAP, with 7 days of curing, could only meet subbase requirements.

Several researchers have reported that the performance of cement stabilized RAP satisfied the requirements of pavement base/subbase applications [3,10,15–17]. Cement-stabilized RAP is however not considered as an environmentally friendly material, as the production of Portland Cement (PC) contributes significantly to global warming. The energy-intensive process for the production of PC emits a large amount of greenhouse gas – carbon dioxide (CO_2) into the atmosphere [18–23]. Davidovits [20] demonstrated that the production of 1 ton of PC clinker directly produces about 0.55 tons of CO_2 and requires the combustion of carbon-fuel, which results in an additional 0.40 tons of CO_2. The production of 1 ton of PC releases approximately 1 ton of CO_2.

These shortcomings have led to an attempt to explore novel low carbon stabilization methods. Geopolymer is an inorganic aluminosilicate material synthesized by alkaline activation of materials rich in alumina (Al_2O_3) and silica (SiO_2) and is considered as a green cementing agent. Geopolymerization involves the chemical reaction of alumino-silicate oxides by alkaline activation, yielding the polycondensation of the material in the three-dimensional silico-aluminate structure [21,24]. Three typical structures of geopolymer are: Poly (sialate) type (-SiO-Al-O-), the Poly (sialate-siloxo) type (-Si-O-Al-O-Si-O-) and the Poly (sialate-disiloxo) type (-Si-O-Al-O-Si-O-Si-O-).

Geopolymer is made of alkali-activated aluminosilicate materials such as FA, slag, rice husk ash and bottom ash. Geopolymers are reported to produce low CO_2 emission and energy consumption [25]. In Thailand, power plants produce a total output of 4.0 million tons of FA and bottom ash annually. However, only approximately 1.8 million tons of FA is used as a pozzolanic material in the concrete industry [26] with the balance being stockpiled as waste materials. Since FA contains a high percentage of amorphous silica and alumina, it is suitable as a precursor for manufacturing geopolymers [27].

Geopolymer has in recent years been used to stabilize natural soils to develop green building materials such as masonry products. It was reported that geopolymer based materials possess higher compressive strength and durability against sulfate than cement based materials [28–30]. Recently, Suksiripattanapong et al. [31] and Horpibulsuk et al. [32] successfully stabilized water treatment sludge using fly ash based geopolymer to develop sustainable non-structural and bearing masonry units. It was illustrated that the geopolymer is more effective than PC in stabilizing the water treatment sludge with high alum content. The strength and durability of sludge-geopolymer masonry units is significantly higher than sludge-cement masonry units.

The RAP stabilized with FA based geopolymer for pavement applications is currently limited due to the lack of laboratory and field evaluation of this novel material. This research aims to study the possibility of using geopolymer to stabilize RAP as a sustainable stabilized pavement material. An extensive suite of laboratory experimental programs was carried out to investigate the strength development of RAP-FA geopolymer. The RAP-FA geopolymer samples were prepared using modified Proctor compaction energy. UCS is used as an indicator to evaluate strength development in this research. The role of various influence factors on UCS development is examined via Scanning Electron Microscopy (SEM), and X-ray Diffraction (XRD) analyses. The various influential factors studied in this research included liquid alkaline activator (L) content, $NaOH/Na_2SiO_3$ ratio, FA content, and heat condition (temperature and duration). This study has significant impacts on pavement applications by using RAP stabilized with FA-geopolymer binder, a sustainable alternative to ordinary PC, in pavement base and subbase courses.

2. Materials and methods

2.1. Recycled Asphalt Pavement (RAP)

RAP, collected from a milled asphalt pavement stockpile in Nakhon Ratchasima province, Thailand was used in this research. A cold milling machine was used to remove the asphalt pavement for resurfacing in the cold in-place recycling process. Fig. 1a shows a photo of RAP from the stockpile. The low water content of RAP (less than 0.3%) was detected. The gradation of air-dried RAP was determined by a sieve analysis in accordance with ASTM-D422-63 [33] and is shown in Fig. 2. The cold in-place recycling process used a narrow tooth spacing milling drum with a lower speed and therefore result in the maximum size of approximately 10 mm. The RAP contains approximately 99.8% coarse-grained particles (retained on No. 200 sieve). The specified gravity of RAP is 2.7. The RAP is classified as poorly graded sand (SP) according to the Unified Soil Classification System (USCS) [34].

The gradation of the RAP was compared with that specified for base materials (ASTM-D1241-15 [35] and AASTHO-M147-65 [36] and is shown in Fig. 2. It is noted that RAP gradation does not meet the specification requirements. Although this gradation specification is used for unstabilized base materials in several countries, it is however not applied to stabilized materials in India and Thailand. For instance, Saride et al. [12] reported that in India, RAP which did not meet specified requirements could still be used as aggregate for stabilized base material. The modified Proctor compaction test was performed to determine the maximum dry unit weight (γ_{dmax}) and Optimum Water Content (OWC) of RAP in accordance with ASTM D 1557-12, 2012 [37]. The γ_{dmax} and OWC values of RAP were 17.5 kN/m^3 and 4.1%, respectively. California Bearing Ratio (CBR) test followed the ASTM D1883-07 [38] was carried out on RAP samples under the modified Proctor compaction effort at OWC and soaked for 4 days. Water absorption and swelling after 4 days of soaking were also measured. The soaked CBR value was approximately 10–15%, while water absorption and swelling values were 6.8% and 0.2%, respectively. These values indicate that this RAP did not meet the requirements for base and subbase materials, as specified by the Department of Highways (DOH), Thailand [39].

This research aims to study the stabilization of RAP with FA-geopolymer to meet the specified requirements for stabilized pavement material. The mineral and chemical compositions of RAP, obtained by X-ray Diffraction (XRD) and X-ray Fluorescence (XRF) analyses, are depicted in Fig. 3 and Table 1, respectively. Since the RAP (consisting of aggregates and aged bituminous additives) was removed by a cold milling machine, the amorphous asphalt was not fully covered by aggregates, as presented in Fig. 1a. Hence, the predominant mineral components in RAP were calcite-magnesium and dolomite. The main chemical composition detected in RAP was 41.93% CaO and 36.11% MgO. This high CaO in RAP can react with silica and alumina in FA for a suitable pozzolanic reaction.