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Effect of wetting–drying cycles on compressive strength and microstructure of recycled asphalt pavement – Fly ash geopolymer

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HIGHLIGHTS

- Effect of w–d cycles (C) on the strength and microstructural changes of RAP-FA blend and RAP-FA geopolymer.
- Micro-structure analyzed using XRD and SEM.
- For $C < 6$, the w–d cycles stimulate the chemical reaction and hence strength improvement.
- For $C > 6$, the significant macro- and micro-cracks developed during w–d cycles cause strength reduction.
- UCS after w–d cycles of RAP-FA geopolymers and RAP-FA blends were compared with road authorities' requirements.

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ABSTRACT

The usage of recycled asphalt pavement (RAP) and fly ash (FA) in pavement applications contributes to the sustainable usage of such waste by-products. Although RAP-FA geopolymer and RAP-FA blend without liquid alkaline activator have been proven as a pavement material based on strength and leachate requirement, the durability of these by-products when exposed to an aggressive environment has not been investigated to date. This research investigates the effect of wetting–drying (w–d) cycles on the strength and microstructural changes of RAP-FA blend and RAP-FA geopolymer. The strength characteristics of these materials were determined by unconfined compression strength (UCS) test. The microstructure of the compound pavement material was 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 wetting–drying (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. For RAP-FA geopolymer, geopolymerization products [Sodium Alumino-Silicate Hydrate, N-A-S-H] co-existed with C-(A)-S-H results in increased UCS within the first 6 w–d cycles. The macro- and micro-cracks when $C > 6$ cause strength reduction of RAP-FA geopolymers. A better durability performance is observed when RAP-FA geopolymers are prepared with higher NaOH content that can be attributed to formation of a stable cross-linked alumino-silicate polymer structure. The outcome from this research confirms the viability of using RAP-FA blends and RAP-FA geopolymer as alternative sustainable pavement materials.

1. 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

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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].

Several geotechnical researchers have evaluated recycled waste materials as an alternative construction material in civil infrastructure applications. Surplus clay and fly ash (FA) were used for developing a sustainable lightweight cellular cemented construction material [3]. Waste carpet fibers were used to increase the strength and reduce the swelling pressure of expansive soils [4,5]. Calcium carbide residue (CCR), a waste by-product of the acetylene gas production process, has been established as a green soil stabilizer [6–8], to develop non-bearing masonry units [9], and stabilized subgrade materials [10], additives of grouting materials used in tunneling and groundwater sealing [11–13].

From a geoenvironmental perspective, FA based geopolymer is an environmentally friendly additive for improving the mechanical and durability characteristics of problematic soils [14–16]. Geopolymer using FA and CCR as alkali activator is a low-carbon method to stabilize clayey soil [17,18]. Water treatment sludge, FA, and rice husk ash have furthermore been used to manufacture sustainable geopolymer masonry units [19–22]. The strength and durability of sludge-geopolymer masonry units were found to be significantly higher than those of sludge-cement masonry units.

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 [23,24]. RAP contains asphalt binder (3–7%) and aggregates (93–97%) by weight [25], 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 [26,27]. An evaluation of FA-stabilized RAP as pavement base/sub-base material has been investigated by Saride et al. [28] 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. Further studies on the mechanical and microstructural properties of a stabilized RAP, virgin aggregate (VA) and FA blend as a pavement base/sub-base [26,29] indicated that RAP:VA = 80:20 with 40% FA replacement satisfied the strength, stiffness, and California Bearing Ratio requirements for low volume roads. Mohammadinia et al. [30] explored a sustainable stabilization solution for RAP by using FA and blast furnace slag geopolymers and reported that the 7-day strength of geopolymer stabilized RAP could meet pavement sub-base specification requirements.

Hoy et al. [31,32] have evaluated the strength development and leachate characteristics of RAP-FA geopolymers and RAP-FA blends as sustainable stabilized pavement base/sub-base materials, in which up to 80% RAP was used as aggregates. Liquid alkaline activator (L), a mixture of sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH), was used to activate the alumino-silicate FA to produce FA-geopolymer binder, while RAP, FA, and water (RAP-FA blend) were mixed as a control material. The authors reported that both the RAP-FA blends and RAP-FA geopolymers could be used in pavement base applications as the strength requirements met the specifications of the Department of Highways, Thailand. Furthermore, the waste by-products were found to pose no significant environmental and leaching hazards into soil and ground water resources, and geopolymer stabilization was also found to reduce the leaching of heavy metals from RAP-FA mixture significantly.

Besides strength and environmental requirements as investigated previously, the durability of RAP-FA blends and RAP-FA geopolymers under severe climatic conditions is a crucial parameter when used in road construction applications. The study on durability of RAP-FA blends and RAP-FA geopolymers is however still in its infancy. Dempsey and Thompson [33] 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 [34,35]. The durability study against w–d cycles of the chemically treated RAP with VA have been reported by Game (2009) [36] and indicated that the strength loss was approximately 10–15% on an average for all the mixes studied after 14 cycles of w–d test. The authors reported that weight loss and strength drop of the mixture composed of RAP:VA = 75:25 with 2% cement were low even after 14 w–d cycles, while higher volumetric change and lower strength were observed when the same RAP mixed with 7% FA after 7 w–d cycles. In addition, Kampala et al. [37] have investigated the influence of w–d cycle on the durability of CCR-FA stabilized clays as a pavement application to ascertain its serviceability. It is concluded that the optimal CCR and FA contents were found at about 7 and 20%, respectively. The excessive FA contents cause the strength reduction. Furthermore, although the input of FA can enhance the pozzolanic reaction, the strength of the CCR stabilized clay reduced significantly with the number of w–d cycles. In recent year, the study on the green material by using FA activated NaOH to treat the RAP and VA mixture demonstrated that the assessment of durability is highly important when secondary material like RAP was used in the pavement applications [38]. The study concluded that the strength of the mixes RAP:VA = 60:40 + 4%NaOH + (20% or 30% FA) was found to be higher than the minimum strength requirements specified by Indian road congress even after 12 cycles of w–d test. Al-Obaydi et al. [39] and Al-Zubaydi [40] indicated that the cyclic w–d cycles cause crack propagation, 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 durability of RAP-FA blends and RAP-FA geopolymers when subjected to cyclic wetting–drying tests. The change in the strength and physical properties of both RAP-FA blends and RAP-FA geopolymers at various cyclic w–d cycles 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 to explain their strength development. The outcome of this research will enable the development of construction guidelines for researchers, pavement engineers and end-users in assessing suitable RAP-FA blends and RAP-FA geopolymers in future road construction applications.

2. Materials and methods

2.1. Materials

In this research, RAP samples were collected from a mill asphalt pavement stockpile in Nakhon Ratchasima province, Thailand. A cold milling machine was used to remove the existing old asphalt pavement for resurfacing. In Thailand, the used cold in-place recycling machine has a narrow tooth spacing milling drum with a lower speed and the milled pavement thickness is approximately 20–25 mm. The maximum size of RAP aggregate studied was approximately 10 mm as the max-