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Mechanical properties and performance of high volume fly ash roller compacted concrete containing crumb rubber and nano silica

Musa Adamu [a,b,*], Bashar S. Mohammed [a,*], Mohd Shahir Liew [a]

[a] Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak, Malaysia
[b] Department of Civil Engineering, Bayero University Kano, PMB 3011, Kano, Nigeria

HIGHLIGHTS

- A sustainable HVFA RCC pavement with improved performance is developed.
- Response surface methodology (RSM) was used to design the experiments.
- RSM was used to develop models for predicting strengths and optimization of HVFA RCC pavement.
- Nano silica partially mitigated loss of strengths in HVFA RCC due to negative effect of crumb rubber.
- Nano silica increases early strength development in HVFA RCC pavement.

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ABSTRACT

This study deals with the development of an environmentally sustainable roller-compacted concrete (RCC) using high-volume fly ash (HVFA) and crumb rubber as partial replacement for cement and fine aggregate respectively, and nano-silica as an additive to cementitious materials. Response surface methodology (RSM) was used to design, develop statistical models, and carry out the optimization for the mixtures using the variables crumb rubber, HVFA, and nano-silica. The responses used for the RSM are compressive, flexural, and splitting tensile strengths. The proposed models demonstrated a high correlation among the variables and responses. An optimised HVFA RCC mix can be achieved by partially replacing 10% fine aggregate with crumb rubber by volume, replacing 53.72% of cement with fly ash by volume, and the addition of 1.22% nano-silica by weight of cementitious materials. Further experimental investigations showed that the HVFA RCC pavement exhibited lower fresh density, Vebe time, compressive strength, splitting tensile strength, flexural strength, modulus of elasticity, abrasion resistance, and impact resistance compared to conventional (control) RCC pavement. These effects further escalate with increase in partial replacement of fine aggregate with crumb rubber. On the other hand, nano-silica increases the mechanical properties and performance of HVFA RCC pavement with or without crumb rubber. This is because of the ability of nano-silica to partially mitigate the negative effect of crumb rubber on the properties of HVFA RCC by densifying the interfacial transition zone between the cement matrix and crumb rubber and filling the pores in the hardened cement matrix. Furthermore, nano-silica partially ignited the pozzolanic reactivity of fly ash at early ages which leads to higher performance of HVFA RCC pavement at early age.

1. Introduction

The world is currently focusing on environmental sustainability by reducing CO_2 emissions, with approximately 10% of CO_2 emissions emanating from cement production. Therefore, the construction industry is striving to shift from conventional concrete methods to green concrete by reducing the usage of cement in concrete, which will lead to a reduction in cement production. This can be achieved by using supplementary cementitious materials including silica fume, rice husk ash, fly ash, and ground granulated blast furnace slag (GGBS) as partial replacements for cement in concrete during mixing, or blended during cement production to produce Pozzolan cement [1]. A concrete containing fly ash equal

* Corresponding authors at: Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, 32610 Bandar Seri Iskandar, Perak, Malaysia.

E-mail addresses: madamu.civ@buk.edu.ng (M. Adamu), bashar.mohammed@utp.edu.my (B.S. Mohammed).

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to, or greater than, 50% by weight of cement is regarded as a high-volume fly ash [2].

Roller-compacted concrete (RCC) is a zero-slump concrete which is transported, placed, and compacted using equipment used in earth and rock fill operations. The RCC is mixed in a central plant, typically a pug mill mixing plant and hauled to the construction site in non-agitated haul trucks. Class F fly ash improves the workability, increases placement time, and may be used to replace up to 50% by volume in RCC [3]. Fly ash usage in RCC applications continues to gain acceptance because of its significant advantages, such as the reduction in overall cost, increased long-term strength and durability, and a reduction in adiabatic temperature rise during mixing [4].

Rao, et al. [5] prepared the same three series mixtures (i.e. Series A, B, and C), and in each series, they partially replaced cement with fly ash at 0%, 20%, 40%, and 60% levels. They reported that the flexural and compressive strengths, abrasion resistance, and ultrasonic pulse velocity of RCC pavement for each series of mixtures decreased with increasing fly ash content up to 90 d. They attributed this decrease to the slow pozzolanic reactivity of fly ash in the early ages, which caused a reduction in C-S-H formation, and subsequently decreased strength. Mardani-Aghabaglou, et al. [6] replaced cement with fly ash at 20%, 40%, and 60% levels by weight of cementitious materials in RCC pavement. They reported that compressive, splitting tensile, and flexural strengths all decreased with increasing fly ash content for up to 180 d, but the rate of decrease reduced with age. In a similar study, Yerramala and Babu [7] studied the effect of high-volume fly ash (HVFA) on the durability performance of RCC pavements. They replaced cement with fly ash at 40% and 85% levels by weight. Their findings showed that the consistency of RCC pavement increased with increasing fly ash content. However, the permeability in terms of water permeability, water absorption, and sorptivity all increased for up to 90 days. They concluded that a less permeable RCC pavement can be produced with 60–70% HVFA. It can be observed that HVFA decreases the early strengths and durability of RCC pavement, thereby negating its advantages, i.e. early load carrying capacity. Therefore, in order to use HVFA in RCC pavement effectively, nano-silica needs to be incorporated, either as a partial replacement, or as an additive to cementitious materials [8].

Previous studies showed that the addition of nano-silica to HVFA concrete resulted in a greater densification, with a reduction in total pore volume and reduced pore diameters. Nano-silica reacted faster with the surplus lime than fly ash during hydration, producing a higher amount of C-S-H gel, which densified both the cement aggregate paste and the interfacial transition zone (ITZ), and fills the voids in the matrix [9]. Zhang and Islam [10] added 1% nano-silica by weight of cementitious materials to HVFA concrete with 50% fly ash content, and the nano-silica accelerated the cement hydration of the paste. The early strength improved by 30% and 25%, at 3 and 7 days respectively, while the long term strength improved by 13% and 18% at 28 and 91 days respectively, when compared to the HVFA without the addition of nano-silica. Supit and Shaikh [11] added 2% and 4% nano-silica to HVFA concrete with 40% and 60% fly ash as a cement replacement, and reported significant improvements in the short term compressive strengths. At 3 d and 7 d, the compressive strength improved by 25% and 15%, respectively, for 40% fly ash and 2% nano-silica, but for 60% fly ash and 2% nano-silica the compressive strength increase was only significant at 3 d, with no significant increase at greater ages. They reported similar results for concrete with 60% HVFA and 4% nano-silica. This was a result of the contribution of the pozzolanic reaction by nano-silica being greater at early ages than fly ash because of its finer particles and greater surface area. Shaikh and Supit [12] added 2% nano-silica to concrete containing 60% HVFA. They reported that the fly ash increased the workability of the concrete, while nano-silica increased water demand, thereby decreasing the workability because of its greater surface area. The strength of HVFA concrete increased by 166.7%, 0%, 0%, and 4.55% at 3, 7, 28, and 90 d, respectively, with the addition of nano-silica. The rate of water absorption decreased with the addition of nano-silica to HVFA concrete, with a decrease of 7.32% and 22.97% at 28 and 90 d, respectively. Nano-silica also modified and decreased the pore volume of HVFA concrete, and the c by 53.3% with the addition of nano-silica.

Crumb rubber can be used in RCC pavements to improve one or more properties and increase the environmental sustainability. Numerous studies have shown that the incorporation of crumb rubber as fine aggregate in RCC has a number of advantages, such as improved toughness and energy absorption, reduced brittleness, improved fatigue life, increased thermal conductivity, improved sound absorption, and a significant reduction in the rate of propagation of cracks under flexural and tensile loading [13,14]. However, the primary disadvantage of using crumb rubber in concrete is a reduction in mechanical properties and durability performance [15], resulting from increased pore volume in the hardened cement matrix. As crumb rubber is hydrophobic and nonpolar by nature, it entraps air on its surface and repels water in the fresh concrete mixture, thereby increasing the air content. Once the concrete hardens, the mixing water evaporates, leaving voids in the hardened matrix [16,17]. The entrapped air on the crumb rubber increases the thickness of the interfacial transition zone (ITZ), and causes weak bonding between the cement matrix and crumb rubber. With load application, microcrack formation begins to form across the weak porous ITZ, thereby leading to premature failure and a reduction in strength [18,19]. A number of studies attempted to find a method of totally, or partially, mitigating the negative effect of crumb rubber on the mechanical properties and durability of concrete, but these methods proved ineffective and uneconomical. However, the use of nano-silica as an additive to cementitious materials was successful in partially mitigating the loss in mechanical properties and durability of concrete with the incorporation of crumb rubber [18].

Therefore, this study is aimed at investigating the effect of crumb rubber and nano silica on the properties of HVFA RCC pavement. Crumb rubber was used to partially replace the fine aggregate. High-volume fly ash has been used as a partial replacement to cement to reduce costs, improve environmental sustainability, and decrease the possibility of thermal cracking. Nano-silica has been added by weight of cementitious materials to mitigate the loss of mechanical properties and durability due to the effect of crumb rubber, and to improve early strength development in HVFA RCC by igniting the pozzolanic reactivity of fly ash at early ages.

2. Materials and mix proportioning

2.1. Materials

In this study, ordinary Portland Type I cement, conforming to the requirements of ASTM C150M, with a specific gravity of 3.15 and chemical properties as presented in Table 1, was used. Natural sand with particle gradation as shown in Fig. 1, a specific gravity (saturated surface dry (SSD)) of 2.65, a fineness modulus of 2.86, and water absorption of 1.24% was used as fine aggregate. Two nominal maximum sizes aggregates (NMSA), with particle size gradation as shown in Fig. 1, were used as coarse aggregate: 19 mm NMSA with a specific gravity (SSD) of 2.66 and absorption of 0.48%, and 6.35 mm NMSA coarse chips with a specific gravity (SSD) of 2.55 and absorption of 2.55%. Three sizes of crumb rubber were combined so as to achieve gradation similar to fine aggregate. After several series of trial combinations, using a sieve analysis according to ASTM D5644, a final proportion of 40% of 0.595 mm (mesh 30) size, 40% of 1–3 mm size, and 20% of 3–5 mm size was selected. The combined particle size curve is shown in Fig. 1. Fly ash meeting the requirements of ASTM C612 and ASTM C311, and with properties as presented in Table 1, was used as a high-volume cement replacement. Nano-silica with sizes 10–25 nm and strong hydrophobicity, was used as an additive to cemen-