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Mechanical performance of roller compacted concrete pavement containing crumb rubber and nano silica

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HIGHLIGHTS

- Nano silica lead to improve properties of RCR.
- Nano silica densifies the microstructure of RCR.
- Models have been developed using RSM to predict the strengths of RCR.

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ABSTRACT

In this study, roller compacted rubbercrete (RCR) was developed by partially replacing fine aggregate with crumb rubber (CR) in roller compacted concrete pavement (RCCP) to improve its flexural resistance, ductile behavior and reduces the environmental effect of waste tires. Due to the fact that crumb rubber reduces strength in concrete, the addition of nano silica (NS) to mitigate the loss in strength of RCR is a possible solution. Sixteen mixtures with four levels of CR (0%, 10%, 20%, and 30%) by volume replacement to fine aggregate and four levels of NS (0%, 1%, 2% and 3%) addition by weight of cementitious materials were prepared and tested. Fresh properties including density and Vebe consistency time have been determined. Hardened properties including unit weight, compressive, flexural and splitting tensile strength, elastic modulus, abrasion resistance and water absorption have been investigated. The findings show that CR increases the consistency of RCR. The compressive strength and abrasion resistance of RCR increases with 10% CR and the flexural strength also increases with replacement of up to 20% fine aggregate with CR. Addition of NS was successful in improving the performance of RCR due to its physicochemical effects which have been verified by carrying out microstructural analysis. Mathematical models developed using Response surface methodology for predicting the strengths and water absorption using CR and NS as the input variables shows a high degree of correlation and predictability. The results of multi-objective optimization showed that, an optimum mixture can be achieved with a 10% volume replacement of fine aggregate and 1.13% NS addition by weight of cementitious materials to have a high strength, durable and ductile RCR for pavement applications.

1. Introduction

The needs in transportation continue to escalate globally due to the rapid increase in human populations. This in conjunction with advancement in technology results to increase in the quantity of vehicle production and usage which consequently results in the rapid generation of waste tires [19]. About 1 billion waste tires are generated annually in more than half of it disposed of without pretreatment, and the number is expected to reach 1.2 billion by 2030 [53]. These waste tires which are mostly disposed of in high volume poses serious environmental and health hazards if they are not properly disposed or recycled [19]. Tires ingredients contain certain chemicals that help in making their service life to last longer. However, these chemicals used make the waste tires generated to be non-biodegradable, and if disposed into landfills leaches toxic substances to the ground thereby causing land pollution, and water pollution in the presence of a nearby water source [47]. Another problem related to waste tires are they are highly flammable with higher calorific properties making them very difficult to extinguish if burnt, with the production of black fume and high temperature causing air pollution and increasing global warming by emitting more CO_2 to the environment [13]. However, if not burnt disposed waste tires provides breeding grounds for all sort

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Table 1
Chemical properties of materials.

Oxides Composition (%)	Cement	Fly ash
SiO_2	20.76	57.06
Al_2O_3	5.54	20.96
Fe_2O_3	3.35	4.15
MnO	–	0.033
CaO	61.4	9.79
MgO	2.48	1.75
Na_2O	0.19	2.23
K_2O	0.78	1.53
TiO_2	–	0.68
Loss of ignition	2.2	1.25
Specific gravity	3.15	2.3
Blaine fineness (m^2/kg)	325	290

Table 2
Properties of nano silica.

Item	Quality
Appearance	High-dispersive white powder
Hear reduction (%) (105 °C 2 h) ≤	3
Loss of ignition (%) (950 °C 2 h) ≤	6
SiO_2 content (dry base) (%) ≥	92
SiO_2 content (%) (950 °C 2 h) ≥	99.8
Specific surface area (m_2/g)	100 ± 25
PH value	6.5–7.5
Surface density (g/ml) ≤	0.15
Dispensability (%) (%) (CCl_4) ≥	80
Oil-absorbed value (ml/100 g) ≥	250
Average particle size (nm)	10–25
Hydrophobicity	Strong

of rodents, mosquitoes, snakes etc. thereby increasing the risk of transferring and spreading deadly diseases such as Zika virus, dengue fever, malaria fever [13]. In order to effectively utilized and manage waste tires, it is mostly used in the production of tire derived fuel (pyrolysis), production of carbon black, fuel for a cement kiln. However, the main disadvantage of tire-derived fuel is that its production involves emission of large amount of CO_2 to the environment and it is less economical compared to fuel from petroleum products [53]. It is also used for ground applications such as; asphalt for paving streets and highways, sports surfacing, animal bedding, fill material for turf grasses [51,9]. The civil engineering industry utilizes a little amount of waste tire generated in the US where it stands at just 7% as of 2015 [48]. With the construction industry been one of the sectors that affect sustainability negatively by consuming a lot of natural resources such as aggregate [8], where river sand which is the commonest material used for fine aggregate is rapidly depleting and becoming scarce and more expensive due to its high demand [6]. In order to remedy the challenges facing the construction industry in terms of sustainability of materials and issues related to waste tire disposal problems, several researchers incorporated the waste tires as partial replacement to aggregate in concrete by grinding the tires into smaller sizes in form of crumb rubber (CR) with the fibers and steel removed [56].

Crumb rubber (CR) when used in concrete has been found to reduce the durability performance and mechanical properties of concrete [59]. The major cause for strength reduction is attributed to the poor adhesion/bonding the hardened cement matrix and CR which is caused by the smooth surface and lower hydraulic conductivity CR. The poor bonding can also be due to the presence of zinc stearate during the production of the tire which consequently diffuses to the rubber surface during mixing in concrete

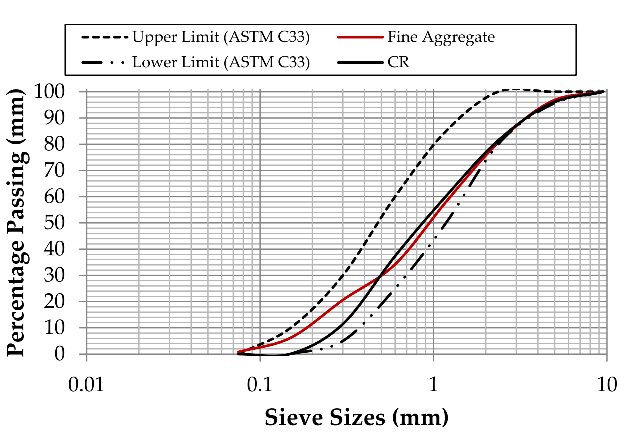

Fig. 1. Particle size analysis of aggregate.

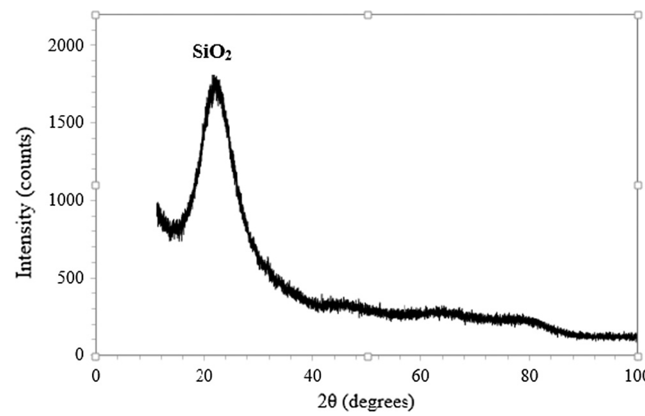

Fig. 2. XRD pattern of nano silica.

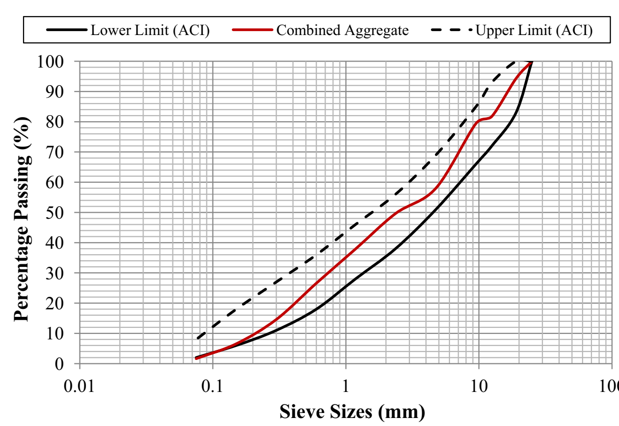

Fig. 3. Combined aggregate gradation.

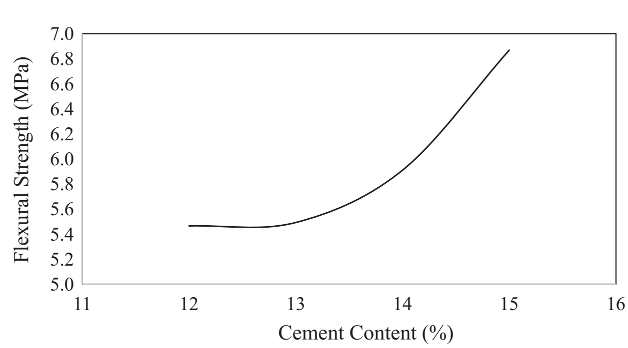

Fig. 4. Relationship between cement content and flexural strength of RCCP.