Abrasive Resistance of Nano Silica Modified Roller Compacted Rubbercrete: Cantabro Loss Method and Response Surface Methodology Approach

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Abstract. Roller compacted concrete (RCC) when used for pavement is subjected to skidding/rubbing by wheels of moving vehicles, this causes pavement surface to wear out and abrade. Therefore, abrasion resistance is one of the most important properties of concern for RCC pavement. In this study, response surface methodology was used to design, evaluate and analyze the effect of partial replacement of fine aggregate with crumb rubber, and addition of nano silica on the abrasion resistance of roller compacted rubbercrete (RCR). RCR is the terminology used for RCC pavement where crumb rubber was used as partial replacement to fine aggregate. The Box-Behnken design method was used to develop the mixtures combinations using 10%, 20%, and 30% crumb rubber with 0%, 1%, and 2% nano silica. The Cantabro loss method was used to measure the abrasion resistance. The results showed that the abrasion resistance of RCR decreases with increase in crumb rubber content, and increases with increase in addition of nano silica. The analysis of variance shows that the model developed using response surface methodology (RSM) has a very good degree of correlation, and can be used to predict the abrasion resistance of RCR with a percentage error of 5.44%. The combination of 10.76% crumb rubber and 1.59% nano silica yielded the best combinations of RCR in terms of abrasion resistance of RCR.

1. Introduction
Roller compacted concrete (RCC) is one of the special concretes with zero slump consistency at fresh state, whose transportation, placement, and compaction methods are similar to the methods used in asphaltic pavement construction [1]. One of the major advantages of RCC when used for pavement is economy, the reduction in cost can be as high 30% and 20% compared to asphaltic pavement and conventional concrete pavement respectively [2]. RCC pavement surface is subjected to heavy duty and low-speed vehicular operations [3]. The sliding, skidding and rubbing of the vehicular wheels on the surface of RCC pavement causes wearing, tearing and abrasion on the pavement. Therefore, for any RCC pavement, its abrasion resistance is an important property to put into consideration [4]. Different factors affect the abrasion resistance of concrete such as; aggregate type, the proportion of aggregate, mix proportioning, fiber content (if any), compressive strength, pozzolanic materials, curing and surface finishing [5]. The abrasion resistance of concrete is used to measure its durability performance and is directly proportional to compressive strength. In addition, the pore structure and the micro hardness of the surface finishing of concrete significantly affect its abrasion resistance [6].
The abrasion resistance of concrete was found to decrease with partial replacement of fine aggregate by crumb rubber, as it was reported by Ozbay, et al. [7], where a reduction of up to 23.19% was reported with replacing 15% fine aggregate with crumb rubber. Similarly, Ganesan [8] found an increase in abrasion resistance of concrete by 20% with replacement of 15% fine aggregate using crumb rubber. Thomas, et al. [9], reported an increase in abrasion resistance by up to 15.16% when 20% crumb rubber was used in concrete for a water/cement ratio of 0.3. They found the increase in abrasion resistance to be higher for concrete with 0.5 water/cement ratio.

Nano silica addition to concrete has been found to improve its abrasion resistance. For example according to Nazari and Riahi [10], the abrasion resistance of concrete increases with addition of up to 2% nano silica. Similarly, Li, et al. [6] reported an increase in surface index abrasion resistance of concrete by 157% and 100.8% with addition of 1% and 3% nano silica respectively.

The Cantabro loss method was used to evaluate the abrasion resistance of RCC pavement and it was found to be an effective method. Rao, et al. [5] used the Cantabro loss method to study the abrasion resistance of RCC pavement.

On the other hand, response surface methodology (RSM) is commonly used statistical and mathematical technique used for analysing and developing models between one or more independent variables and responses [11]. In addition, RSM can be used for model multi-objective optimization by setting defined desirable goals based on either responses or variables [11]. Mohammed, et al. [12], has utilized RSM to model the compressive strength of concrete containing paper mill as additives. Mtarfi, et al. [13], have optimized and developed model for predicting mortar compressive strength with RSM. Güneyisi, et al. [14] have developed models and optimized high-performance concrete by minimizing the durability factors and maximizing compressive strength using metakaolin and fly ash as variables. Mohammed, et al. [15] developed mix design model for self-compacting engineered cementitious composites (SC-ECC) using RSM. They also optimized ECC mixtures by maximizing modulus of elasticity and energy absorption.

It is therefore worth mentioning that incorporating crumb rubber as partial replacement to fine aggregate in RCC pavement and addition of nano silica will improve its abrasion resistance. Therefore, in this study the Cantabro loss method has been used to evaluate the abrasion resistance of RCC pavement with incorporation of crumb rubber and nano silica. Response surface methodology (RSM) has been used to design the experiments and execute the analysis.

2. Materials and Methods

2.1. Materials

In this study, Type I general purpose ordinary Portland cement, which conforms to ASTM C150M-1. Natural sand having nominal maximum size aggregate of 4.75 mm, specific gravity 2.65, fineness modulus 2.86, water absorption 1.24%, was used as fine aggregate. Two sizes of coarse aggregate which are 19 mm maximum size aggregate having a specific gravity 2.66 and water absorption 0.48%, and chips of 6.35 mm maximum size with a specific gravity 2.55 and water absorption 1.05% was used. Three sizes of crumb rubber were combined so as to achieve gradation similar to fine aggregate. After several series of trial combinations, using sieve analysis according to ASTM D5644, final proportion of 40% of 0.595 mm (mesh 30) size, 40% of 1 – 3 mm size, and 20% of 3 – 5 mm size were used. As one of the basic requirement for any RCC pavement is that 2 to 8 % of the aggregate should be materials finer than 75 µm so as to produce a cohesive paste with lower void contents, in this study, class F fly ash which conforms to ASTM C612 was used as mineral filler. Strong hydrophobic nano silica of size 10 - 25 nm was used as an additive to the cement.
2.2. Mix Procedure, Experimental design and Test Methods

2.2.1. Mix Procedure.

The mix proportioning has been carried out using the soil compaction geotechnical approach according to ACI 211.3R. The first step is to obtain a combined aggregate grading falling within the limits recommended by the US Army corps of Engineers [16]. A combination of 55% fine aggregate, 20% 19 mm inch coarse aggregate, 6.35 mm coarse aggregate and 5% mineral filler gave the best-combined aggregate grading. Next is optimum moisture content and maximum density determination according to ASTM D1557-12e. Here four different RCC mix were prepared using with cement contents of 12%, 13%, 14% and 15% by weight of dry aggregates. For each cement content, five submixes were produced by varying the water content from 4.5% to 6.5% by dry mass of RCC. Finally, the optimum moisture contents of 5.46%, 5.56%, 5.92% and 6.09% were found for 12%, 13%, 14% and 15% cement contents respectively, and they are used for determination of final water/cement ratio of the mix. Next is a selection of appropriate cement content based on the target flexural strength, this was achieved by making another RCC mixes with 12%, 13%, 14%, and 15% cement contents with their corresponding OMC respectively and testing their 28 days compressive and flexural strengths. From the cement content versus compressive/flexural strengths relationship plot in Fig 3 and based on the target flexural strength of 4.8 MPa, 13% cement content was selected and used for the final mix computation. After series of calculations, a final water/cement ratio of 0.42 was obtained for the mix, which was further lowered to 0.37 due to the addition of 1% Superplasticizer.

2.2.2. Response Surface Methodology.

Response surface methodology (RSM) is the most suitable statistical and mathematical technique that can be used. In addition, RSM can be used for model multi-objective optimization by setting defined desirable goals based on either the responses or the variables. The response surface can be expressed mathematically by a single formulation shown in Eqn 1 [11].

\[ r = f(v_1, v_2) + \varepsilon \]  

Where \( \varepsilon \) is the observed error for the response \( r \), \( v_1 \) and \( v_2 \) are the variables. The predictable response can be rewritten as \( G(r) = f(v_1, v_2) = \beta \). Then \( \beta = f(v_1, v_2) \) is called the response surface.

In this study, the Design expert software was utilized for the RSM analysis, where the Box-Behnken model was used to develop the model for predicting the 28 days Cantabro abrasion loss of RCR. Three variables were taken into consideration; crumb rubber (CR) with variation levels 10%, 20%, and 30%; nano silica (NS) with levels 1%, 2%, and 3%; and number of revolutions (R) varied at 100, 200, and 300. Based on the different combinations of the variables, 17 runs were developed by the RSM software as shown in Table 1. Other constituent materials which were fixed for each mix include; cement (268.69 kg/m³), filler (103.76 kg/m³), 19 mm coarse aggregate (415.03 kg/m³), 6.35 mm coarse aggregate (416.85 kg/m³), and water (98.24 kg/m³).
Table 1. Experimental combinations, variable constituent materials and Response

| Run | CR: Crumb Rubber (%) | NS: Nano Silica (%) | Revolutions | Fine Aggregate (kg/m$^3$) | Nano Silica (kg/m$^3$) | Crumb rubber (kg/m$^3$) | Cantabro Loss (%) |
|-----|----------------------|---------------------|-------------|---------------------------|-----------------------|------------------------|------------------|
| 1   | 20                   | 0                   | 100         | 918.44                    | 0                     | 229.78                 | 4.38             |
| 2   | 30                   | 1                   | 300         | 803.64                    | 2.69                  | 344.67                 | 7.79             |
| 3   | 20                   | 2                   | 300         | 918.44                    | 5.37                  | 229.78                 | 6.51             |
| 4   | 20                   | 1                   | 200         | 918.44                    | 2.69                  | 229.78                 | 5.98             |
| 5   | 20                   | 2                   | 100         | 918.44                    | 5.37                  | 229.78                 | 3.57             |
| 6   | 20                   | 1                   | 200         | 918.44                    | 2.69                  | 229.78                 | 5.52             |
| 7   | 20                   | 1                   | 200         | 918.44                    | 2.69                  | 229.78                 | 5.6              |
| 8   | 30                   | 2                   | 200         | 803.64                    | 5.37                  | 344.67                 | 6.66             |
| 9   | 20                   | 0                   | 300         | 918.44                    | 0                     | 229.78                 | 7.33             |
| 10  | 10                   | 1                   | 300         | 1033.25                   | 2.69                  | 114.89                 | 6.46             |
| 11  | 20                   | 1                   | 200         | 918.44                    | 2.69                  | 229.78                 | 5.7              |
| 12  | 10                   | 1                   | 100         | 1033.25                   | 2.69                  | 114.89                 | 3.42             |
| 13  | 20                   | 1                   | 200         | 918.44                    | 2.69                  | 229.78                 | 5.7              |
| 14  | 10                   | 0                   | 200         | 1033.25                   | 0                     | 114.89                 | 5.95             |
| 15  | 30                   | 0                   | 200         | 803.64                    | 0                     | 344.67                 | 6.72             |
| 16  | 10                   | 2                   | 200         | 1033.25                   | 5.37                  | 114.89                 | 5.53             |
| 17  | 30                   | 1                   | 100         | 803.64                    | 2.69                  | 344.67                 | 4.14             |

2.2.3. Cantabro Abrasion Loss

An abrasion resistance of RCR was determined after 28 days curing using the Cantabro test method, where Los Angeles abrasion machine was used with the steel balls removed. This test method is in accordance to ASTM C1747. Cylindrical samples with diameter of 150 mm and height 100 mm were used. The initial weight of each specimen was measured prior to inserting into the Los Angeles abrasion machine recorded as $W_1$ (g). The abrasion resistance was measured after 100, 200 and 300 revolutions at a speed of 30-33 revolution per minute. At the end of each revolution interval, the abraded specimen was removed from the machine and cleaned by removing any dust or loose particles. Its weight is then measured and recorded as $W_2$ (g). The Cantabro loss (abrasion resistance) after each revolution is then calculated using Eqn 2.

$$C_{loss} (%) = \left[ \frac{W_1 - W_2}{W_2} \right] \times 100$$  \hspace{1cm} (2)

where $C_{loss}$ is the Cantabro abrasion loss, $W_1$ is the initial weight of the sample (g), $W_2$ is the final weight of the sample (g).

3. Results and Discussions

3.1. Response Surface Methodology

The results of Cantabro abrasion loss based on the RSM design is shown in Table 1. The summary of the analysis of variance (ANOVA) result for the developed response model i.e. 28 days Cantabro loss is shown in Table 2. The model type was quadratic having 95% confidence interval (P<0.05), with F value of 50.54, thus significant. Similarly, the significance of all the model terms was verified using the 95% confidence interval. Model terms CR, NS, V, and $V^2$, were all significant with their P-values...
less than 0.05. While all other model terms not listed were not significant having P-values greater than 0.05 as shown in Table 2. The developed model equation with all the model terms is shown in Eqn 3a. The positive and negative signs before a model term designate synergistic and antagonistic effect of the individual variable on the Cantabro loss of RCR respectively.

\[ C_{\text{loss}} = 1.881 - 0.094CR - 0.949NS + 0.033V - 0.009*CR*NS + 0.000153*CR*V - 2.5 \times 10^{-5} * NS*V + 0.00026CR^2 + 0.255NS^2 - 5.075 \times 10^{-5}V^2 \]  
\[ (3a) \]

Removing the insignificant terms reduces the overall model and also noise. As shown in Eqn 3b model reduction was done using hierarchical terms.

\[ C_{\text{loss}} = 1.096 - 0.055CR - 0.774NS + 0.036V + 0.0026CR^2 + 0.255NS^2 - 5.075 \times 10^{-5}V^2 \]  
\[ (3b) \]

Where \( C_{\text{loss}} \) = Cantabro loss in %, CR=crumb rubber, NS=nano silica, and V=number of revolution

From Table 2, it can be seen that the model has a very high degree of correlation (\( R^2=0.985 \)), meaning only about 1.5% of the experimental data cannot fit into the model. The adequacy validity of the model was verified. Furthermore, for the adjusted \( R^2 \) is in agreement with the predicted \( R^2 \) as their differences are less than 0.2 [11]. In addition, as shown in Table 3 the model has a low standard deviation value, this implies that the experimental data closely fit the overall mean. The coefficient of variation explains the percentage variation of the experimental data to the mean, and it can be seen that only 4.03% of the experimental data not fitted to the overall mean.

The adequacy and degree of correlation of the models are checked graphically by plotting normal probability against residuals and the predicted versus actual data as shown in Figures 1 and 2 respectively. From both figures it can be seen that the data points were fitted and aligned along the straight line, this implies the predicted model is in agreement with the experimental data and can be used to predict the Cantabro abrasion loss for RCR.
3.2. Effect of Crumb rubber and Nanosilica on the Abrasion Resistance of RCR
The results for Cantabro loss of RCR after 100, 200, and 300 revolutions are shown in 3–dimensional plots in Figures 3a, 3b, and 3c respectively. The abrasion resistance was found to decrease with increase in percentage replacement of fine aggregate with crumb rubber for all number of revolutions, and attributed to the poor bond between hardened cement matrix and rubber particles, and coarse aggregate-hardened matrix. This makes the cement paste or rubber particle to wear out easily from the concrete matrix when subjected to rubbing, grinding or skidding. It is also due to reduction in compressive strength caused by crumb rubber in RCR, as the abrasion resistance of concrete is directly proportional to its compressive strength [17]. The abrasion resistance of RCR on the other hand increases with increase in percentage addition of nano by decreasing its Cantabro loss. This is due to the pozzolanic reactivity of nano silica, with the SiO$_2$ from nano silica reacting with the excess Ca(OH)$_2$ from hydration process and producing more calcium-silicate-hydrate which densify the rubbercrete microstructure, increases strength, enhanced the bonding between hardened cement paste and crumb rubber, and consequently abrasion resistance [18].
3.3. Multi-Objective Optimization

An optimization has been carried out using RSM to find the best combination of CR and NS that could yield minimum 28 days Cantabro abrasion loss of RCR, when CR and number of revolutions are maximized, and NS kept in range of 0% to 2%. The optimization goals are summarized in Table 3. It can be seen that CR is maximized; this is due to the fact that it is a bye-product from scrap tire.

The results for the multi-objective optimization are presented in Table 3 showed that 10.76% volume replacement of fine aggregate with CR, and 1.59% addition of NS by weight of cementitious materials, tested at 300 revolutions yielded the optimum response based on the desired optimization criteria.

**Table 3. Optimization criteria and results**

| Variables & Responses | Goal       | Lower limit | Upper limit | Optimized ratio and predicted response |
|-----------------------|------------|-------------|-------------|---------------------------------------|
| Crumb rubber (%)     | In range   | 10          | 30          | 10.76                                 |
| Nano Silica (%)      | In Range   | 0           | 2           | 1.59                                  |
| Revolutions           | Maximize   | 100         | 300         | 300                                   |
| Cantabro loss (%)    | Minimize   | 3.42        | 7.79        | 6.27                                  |

In order to validate the model developed, series of supplementary experiments were carried out in the laboratory using the same mix design and materials. The percentage error or variations between the predicted responses and the experimental results were calculated. A desirable compatibility exists between the theoretical (predicted) and experimental results with average percentage error of 5.44%, as shown in Table 4.

**Table 4. Model verification**

| S/N | CR (%) | NS (%) | Revolution | Theoretical Cantabro loss (%) | Experimental Cantabro loss (%) | Error (%) |
|-----|--------|--------|------------|-------------------------------|-------------------------------|-----------|
| 1   | 10     | 0      | 200        | 6.45                          | 6.23                          | 3.41      |
| 2   | 10.76  | 1.59   | 300        | 6.27                          | 6.69                          | 6.28      |
| 3   | 30     | 1.5    | 100        | 4.14                          | 4.51                          | 8.2       |
| 4   | 20     | 1.45   | 200        | 5.33                          | 5.08                          | 4.92      |
| 5   | 25     | 0.95   | 300        | 6.87                          | 6.58                          | 4.41      |
4. Conclusion
The following conclusions can be drawn from this study
- The abrasion resistance of RCR can be determined using the Cantabro loss method
- The abrasion resistance of RCR decreases with increase in percentage replacement of fine aggregate with crumb rubber
- The abrasion resistance of RCR increases with increase in percentage addition of nano silica by weight of cementitious materials.
- A quadratic model has been developed using RSM to predict the Cantabro loss of RCR using crumb rubber, nano silica, and revolutions as the variables. The result of the RSM analysis shows there is a good correlation between the predicted and experimental response.
- The results of the optimization process using RSM shows that the combination of 10.76% crumb rubber as a fine aggregate replacement by volume and addition of 1.59% NS by weight of cement, and tested at 300 revolutions yielded the best result when Cantabro loss is minimized. The model verification showed that the predicted Cantabro model and the experimental results were in agreement with percentage error of 5.44%.

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