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Effect of crumb rubber and nano silica on the durability performance of high volume fly ash roller compacted concrete pavement

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ABSTRACT

In this study, response surface methodology (RSM) was used to evaluate the effect of partial replacement of fine aggregate with crumb rubber and the addition of nano silica by weight of cementitious materials on the durability performance of HVFA RCC pavement. The experiments were designed and analysis executed using the face centered central composite design method. After executing the experimental works, regression analysis was used to develop models for predicting the Vebe time and water absorption of HVFA RCC pavement. The analysis of variance for the developed models showed that the Vebe time and water absorption of HVFA RCC pavement can be predicted using quadratic model type with higher degree of correlation and predictability. The results of multi-objective optimization showed that an optimum HVFA RCC pavement with minimum Vebe time and water absorption values can be achieved with 17.09% crumb rubber as replacement to fine aggregate by volume, 50% fly ash as replacement to cement by volume, and 1.01% nano silica as addition by weight of cementitious materials. The experimental results showed that the Vebe time of HVFA RCC pavement increases with increase in partial replacement of cement with fly ash, and addition of nano silica. While the rate of water absorption of HVFA RCC pavement increases with increase in partial replacement of cement with fly ash, and increase in partial replacement of fine aggregate with crumb rubber, and decreases with the addition of nano silica by weight of cementitious materials.

1. Introduction

Roller compacted concrete (RCC) causes a major development to the mass concrete construction industries by fastening and easing the traditional methods of placement, compaction, and consolidation (Omran et al., 2017). In simple terms, RCC can be defined as a dry lean concrete of zero slump consistency that is constructed using a similar process as in pavement construction (ACI, 2011b) . Therefore RCC must be dry enough to be able to support the weight of vibratory roller in its fresh state so as to achieve full compaction and consolidation and yet wet enough to allow for adequate mortar distribution during mixing and placement (Mehta and Monteiro, 2006; Adamu et al., 2016).

The durability performance of roller compacted concrete (RCC) pavement can be measured in several ways such as; its resistance to abrasion, water permeation and porosity. The Permeability of RCC pavement is one of its durability factors, and can be defined as ease with which fluid such as water or chemicals penetrates into and out of its interconnected pores. The higher the permeability the less durable the RCC pavement will be and vice-versa. Several factors affect the permeability of RCC pavement these includes; voids or capillary pores in the compacted RCC paste and aggregates, degree of compaction, method of mixture proportioning placement, proportion of materials finer than 75 µm, water-to-binder ratio, paste contents, water and cementitious materials contents, and gradation and quality of aggregates. The permeability of RCC pavement is similar to that of conventional concrete (ACI, 2011a). The permeability index of RCC pavement can be measured through several ways

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which includes water absorption, water penetration, sorptivity, chloride ion penetration, chloride diffusivity, porosity (cumulative pore volume and pore diameters of interconnected pores), etc.

Fakhri (2016) reported decrease in water absorption of RCC pavement when fine aggregate was partially replaced with crumb rubber. This is as a result of lower water absorption of rubber particles compared to natural aggregates. They further found a decrease in water absorption of RCC when silica fume partially replaced cement. This is due to pore filler effect of silica fume. Chi and Huang (2014) reported increase in water absorption of RCC pavement when circulating fluidized bed combustion ash (CFBA) partially replace fine aggregate. This is caused by the irregular and porous surface of CFBA which consequently increases the RCC permeability by increasing its water absorption.

Mardani-Aghabaglou et al. (2013) studied the effect of fly ash as both supplementary cementitious material (SCM) and aggregate on the water absorption of RCC pavement. The water absorption and permeable voids of RCC pavement increased with increase in partial replacement of cement with fly ash. This is due to slow pozzolanic reaction of fly ash at early age which decline the production of C-S-H gel, the product responsible for capillary pore filling. On the contrary, partially replacing fine aggregate with fly ash decreased the water absorption of RCC pavement. This is due to the finer sizes of fly ash compared to fine aggregate thereby acting as filler and reduces the voids in the hardened RCC matrix, another reason is due to contribution of pozzolanic reaction of fly ash apart from serving as fine aggregate, this leads to more C-S-H formation and consequently decreased water absorption. Shaikh and Supit (2015) reported decrease in consistency of high volume fly ash (HVFA) RCC pavement with increase in addition of nano silica. They further reported decrease in the rate of water absorption with addition of nano silica to HVFA concrete. Nano silica modify and decreases the pore volume of HVFA concrete, the total porosity of HVFA concrete decreases by 53.3% with addition of up to 2% nano silica.

Crumb rubber has been used extensively in concrete to improve one or more properties. For example, Adamu et al. (2017a) reported increased flexural toughness and energy absorption in roller compacted concrete when crumb rubber was used as a partial replacement to fine aggregate. However, crumb rubber has negative effect on the mechanical properties and durability of concrete (Mohammed and Azmi, 2011, 2014).

Different statistical models have been used to develop models for mix design or predicting the properties of concrete. For example, Mohammed et al. (2014) developed statistical models using regression analysis for mix design containing wood chippings as fine aggregate replacement. In a similar studies, Abdullahi et al. (2008) also developed models using regression analysis to predict the mix design of concrete containing palm oil clinker as partial replacement to fine aggregate. However, nowadays the response surface methodology (RSM) is the most used and widely accepted statistical method in concrete. RSM is commonly used statistical and mathematical technique used for analyzing and developing models between one or more independent variables and responses (Montgomery, 2017; Adamu et al., 2017b). In addition, RSM can be used for model multi-objective optimization by setting defined desirable goals based on either responses or variables (Montgomery, 2017; Adamu et al., 2018).

Therefore in this study, RSM was used to evaluate the effect of crumb rubber and nano silica on the durability performance of HVFA RCC pavement, where the Vebe consistency and water absorption were considered.

2. Materials and methods

2.1. Materials

Type 1 ordinary Portland cement conforms to the requirements of ASTM (2018a) with properties given in Table 1 was used. Fly ash which conforms to the requirements outlined in ASTM (2018b) was used to partially replace cement in high volume. From Table 1 it can be seen that the summation of SiO_2+ Al_2O_3+Fe_2O_3 (57.06+20.96+4.15) for the fly ash is greater than 70%, therefore it is classified as class F. Natural sand with a specific gravity of 2.65, absorption of 1.24% and fineness modulus of 2.68 was used as fine aggregate. Two nominal maximum sizes of coarse aggregates have been used to achieve the desired combined aggregate gradation. They are 19 mm size with a specific gravity of 2.66 and water absorption of 0.48% and 6.35 mm size having a specific gravity of 2.55 and water absorption of 1.05%. Three different crumb rubber sizes were combined so as to obtain similar gradation to fine aggregate. Several trial sieve analysis has been conducted in accordance with the requirements of ASTM (2018c) and a combination of 40% mesh 30 (0.595 mm), 40% 1-3 mm and 20% 3-5 mm has been selected. In order to achieve the recommended combined aggregate gradation and a more cohesive paste, the percentage of materials finer than 75 μm should be between 2% and 8% of the total aggregates, and materials such as naturally occurring non-plastic silt, fine sand or Pozzolanas can be used (Adamu et al., 2017a, 2017b, 2017c). In this study, class F fly ash has been used as mineral filler. Strong hydrophobic nano silica of size 10-25 nm has been used as an additive to the cement.

2.2. Mix design

The mix design was carried out using the soil compaction geotechnical approach according to ACI (2009). It involves a series of stages. The optimal combinations of fine aggregate, coarse aggregate, and mineral filler were determined so that the combined aggregate grading curve falls within the limit recommended by (ACI, 2009). The combined aggregate gradation curve showed in Fig. 1 was obtained using a proportion of 55% fine aggregate, 20% of 19 mm coarse aggregate, 20% of 6.35 mm chips coarse aggregate, and 5% mineral filler. Subsequently, the optimum moisture content (OMC) and maximum dry density (MDD) were determined in accordance with ASTM (2012).

Table 1: Materials properties

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

The OMC and MDD of four RCC mixes have been produced using different cement contents; 12%, 13%, 14%, and 15% by weight of dry aggregates. For each cement content, five mixes were produced using different water content ranging from 4.5% to 6.5% by weight of dry aggregate, to obtain the moisture content-density relationship. The optimum moisture content for 12%, 13%, 14% and 15% cement contents have been found to be 5.46%, 5.56%, 5.92% and 6.09% respectively. Four RCC mixes have been produced utilizing 12%, 13%, 14% and 15% cement content using their corresponding OMC as the amount of water for the mix. The 28 days flexural strength of each mix have been determined. 13% cement content was then selected based on target flexural strength of 4.8 MPa, and was used to derive the proportion for all the final mixture in this study.

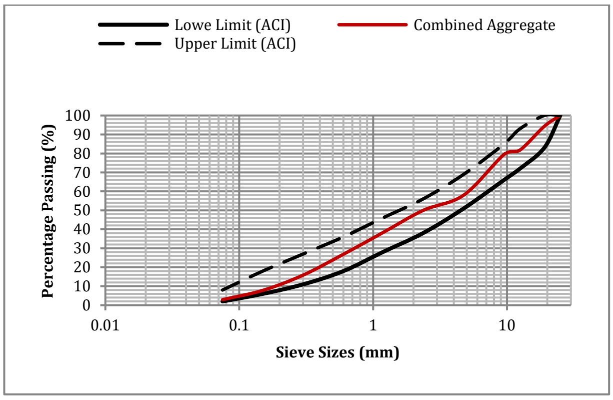


Fig. 1: Combined aggregate grading

2.3. Experimental design and test methods

2.3.1. 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 (Mohammed and Adamu, 2018a; 2018b). The response surface can be expressed mathematically by a single formulation shown in Eq. 1 (Montgomery, 2017).

$$R = f(v_1, v_2) + \varepsilon \quad (1)$$

where ε 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 version 10 was utilized for the RSM analysis, where the face centered central composite design (FCCCD) method was used to develop the model for predicting the Vebe time and water absorption of HVFA RCC pavement. The independent variables used are; crumb rubber (CR) with variation levels 10%, 20%, and 30%; fly ash with variation levels 50%, 60%, and 70%; nano silica (NS) with levels 1%, 2%, and 3%. Based on the different combinations of the variables, 19 runs were developed by the RSM software as shown in Table 2.

2.3.2. Sample preparations and test methods

RCC pavement mixture is very steep, adequate compaction using vibration table cannot be achieved, which can leads to voids and honeycombs in the hardened mix thereby reducing its mechanical energy. Therefore, in order to achieve proper compaction and consolidation, 50 Hz frequency vibration hammer was utilized to simulate the roller compaction in the laboratory in accordance to the guidelines outlined in ASTM (2014a).

The Vebe consistency of the freshly mixed RCC was carried out in accordance with the requirements of ASTM (2014b) using vibration table. The water absorption test was carried out accordance with ASTM (2013). For each mix, three 100 mm^3 cubes were used after curing in water for 28 days before testing.

3. Results and discussions

3.1. Response surface methodology

The result summary of the responses based on the variables combinations using RSM is shown in Table 3. These results were used for the analysis and model development.

The result summary for analysis of variance (ANOVA) for the developed models using RSM is presented in Table 4. The significance of each variable and the responses are evaluated using the 95% confidence interval which corresponds to probability P-value<0.05. All the models have P-values less than 0.05, meaning they are all significant models at 95% confidence level. In addition, the significance of each model term was verified using the 95% confidence level. For both Vebe time and water absorption, quadratic model was more suitable and therefore selected. For Vebe time model, all the model terms were significant except the interaction of crumb rubber and fly ash (A*B), interaction of crumb rubber and nano silica (A*C), interaction of fly ash and nano silica (B*C), square of crumb rubber (A^2), and square of nano silica (C^2). Similarly for water absorption model, all the model terms were significant except the interaction of crumb rubber and fly ash (A*B), interaction of crumb rubber and nano silica (A*C), interaction of fly ash and nano silica (B*C), and square of nano silica (C^2). Furthermore, the lack of fit for both models was not significant; this implies that the experimental results fitted well into the models.

Table 2: Variable combinations and mixture constituent materials

Run	Factors combinations			Quantities for 1 kg/m³ RCR						
	CR	Fly Ash	NS	Cement	Fly ash	NS	Fine Agg	Coarse Agg	Water	CR
1	20	50	1	134.58	102.54	2.37	920.06	833.34	96.87	229.78
2	10	70	2	80.81	143.66	4.49	1135.07	833.93	96.31	114.89
3	20	60	1	107.70	123.09	2.31	920.06	833.63	96.59	229.78
4	30	60	1	107.70	123.09	2.31	805.05	833.63	96.87	344.67
5	20	60	1	107.70	123.09	2.31	920.06	833.63	96.59	229.78
6	10	60	1	107.70	123.09	2.31	1135.07	833.63	96.87	114.89
7	10	50	0	134.58	102.54	0	1135.07	833.34	96.87	114.89
8	20	60	0	107.70	123.09	0	920.06	833.63	96.87	229.78
9	30	50	0	134.58	102.54	0	805.05	833.34	96.87	344.67
10	30	70	2	80.81	143.66	4.49	805.05	833.93	96.87	344.67
11	20	60	1	107.70	123.09	2.31	920.06	833.63	96.59	229.78
12	20	60	1	107.70	123.09	2.31	920.06	833.63	96.59	229.78
13	10	70	0	80.81	143.66	0	1135.07	833.93	96.87	114.89
14	20	60	1	107.70	123.09	2.31	920.06	833.63	96.59	229.78
15	20	60	2	107.70	123.09	4.62	920.06	833.63	96.87	229.78
16	20	70	1	80.81	143.66	2.24	920.06	833.93	96.87	229.78
17	30	50	2	134.58	102.54	4.74	805.05	833.34	96.87	344.67
18	10	50	2	134.58	102.58	4.74	1135.07	833.34	96.87	114.89
19	30	70	0	80.81	143.66	0	805.05	833.93	96.87	344.67

Table 3: Variable combinations and responses

Run	Factors			Responses	
	A: Crumb Rubber (%)	B: Fly Ash (%)	C: Nano Silica (%)	Vebe Time (secs)	Water Absorption (%)
1	20	60	1	33	2.59
2	20	60	0	30	2.73
3	10	50	0	26	2.1
4	30	50	2	24	3
5	20	60	1	31	2.67
6	10	70	0	35	2.86
7	30	70	0	31	4.36
8	20	60	1	30	2.48
9	10	60	1	34	2.3
10	20	70	1	36	3.45
11	20	60	2	33	2.27
12	10	70	2	38	3.07
13	20	60	1	32	2.62
14	20	50	1	24	2.19
15	20	60	1	32	2.5
16	30	70	2	35	3.94
17	10	50	2	29	1.78
18	30	60	1	32	3.6
19	30	50	0	19	3.34

Table 4: Analysis of variance for developed models

Vebe Time (seconds)			Water Absorption (%)		
Source	F Values	P – Values	Source	F Values	P – Values
Model	35.30	< 0.0001	Model	60.83	< 0.0001
A-Crumb Rubber	36.22	0.0002	A-Crumb Rubber	264.49	< 0.0001
B-Fly Ash	230.73	< 0.0001	B-Fly Ash	195.48	< 0.0001
C-Nano Silica	26.61	0.0006	C-Nano Silica	12.45	0.0064
AB	2.57	0.1436	AB	0.071	0.7955
AC	0.92	0.3615	AC	3.72	0.0859
BC	0.10	0.7560	BC	1.78	0.2147
A^2	1.36	0.2736	A^2	23.84	0.0009
B^2	11.08	0.0088	B^2	9.49	0.0131
C^2	1.17	0.3078	C^2	1.84	0.2077
Lack of Fit	0.89	0.5625	Lack of Fit	3.15	0.144

The adequacy of each model was checked and validated using degree of correlation (determination). From Table 5, it can be seen that all the models has a very high degree of correlation (R^2)

which approaches unity (1). Therefore the models has a very good fitness, with the experimental data. To further explain the fitness and validity of the models, for all models, the adjusted R^2 and the predicted R^2 were in reasonable agreement to each other as their differences is less than 0.2. Furthermore, for all the developed models their adequate precision (AP) values are desirable with adequate signal, as they are greater than 4, therefore models can be used in navigating the design space.

Table 5: Models validation

Variables	Vebe Time (sec)	Water Absorption (%)
R^2	0.972	0.984
Adjusted R^2	0.945	0.968
Predicted R^2	0.875	0.803
AP	22.986	29.443
Mean	30.74	2.83

The developed response models for Vebe time and water absorption with all the model terms is presented in Eq. 2a and Eq. 2b respectively. From the developed equations, the negative and positive signs before the terms denote the antagonistic and synergistic effects of the individual variables on the Vebe time and water absorption of HVFA RCC pavement. The developed models were shorten with the insignificant terms removed using backward regression analysis and hierarchical terms added afterwards and presented in Eq. 3a and Eq. 3b for Vebe time and Water absorption respectively.

$$V_T = -67.611 - 0.934A + 3.083B + 3.243C + 0.00625 \times A \times B + 0.038 \times A \times C - 0.0125 \times B \times C + 0.0078A^2 - 0.022B^2 - 0.722C^2 \quad (2a)$$

$$W_A = 7.675 - 0.065A - 0.217B - 0.112C - 0.00011 \times A \times B - 0.0081 \times A \times C + 0.0056 \times B \times C + 0.0035A^2 + 0.0022B^2 - 0.098C^2 \quad (2b)$$

$$V_T = -76.311 - 0.21A + 3.157B + 1.8C - 0.022B^2 \quad (3a)$$

$$W_A = 6.285 - 0.065A - 0.171B - 0.133C + 0.00316A^2 + 0.00186B^2 \quad (3b)$$

where V_T is the Vebe time in seconds, W_A is water absorption in %, A is crumb rubber in %, B is fly ash in %, and C is nano silica in %. NS is nanosilica in %.

The adequacy and degree of correlation of the models are checked graphically by plotting the predicted versus actual data. From Fig. 2a and Fig. 2b, the predicted responses and the actual (experimental) data for all the models are in agreement to each other with a high degree of correlation, as the data points aligned along the straight trend line. Therefore, the developed models in Eq. 2 and Eq. 3 can be used to predict the Vebe Time and Water absorption of HVFA RCC pavement.

3.2. Multi-objective optimization

A multi-objective optimization has been carried to using RSM to determine the best optimum combinations of crumb rubber and nano silica that could yield minimum Vebe time and water absorption. The optimization goals and the results for the multi-objective optimization are presented in Table 6. Based on the optimization goals, the best optimal mixture proportions selected by the RSM software is obtained by combining 17.09% of crumb rubber as a fine aggregate replacement with 50% fly ash as partial replacement to cement and 1.01% of nano silica as addition to cement to give the maximize responses with combined desirability of 82.3%.

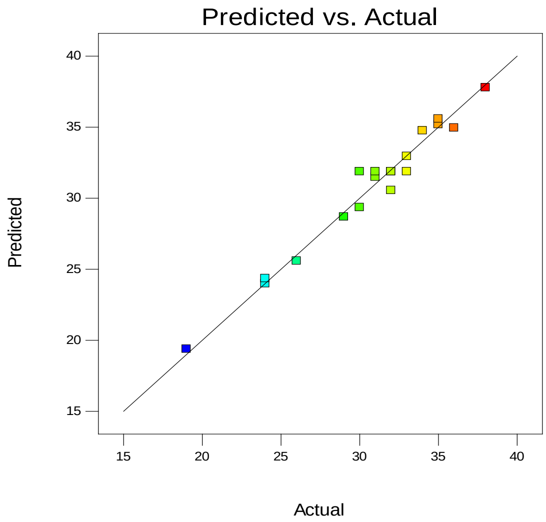


Fig. 2a: Predicted versus actual plots for developed vebe time model

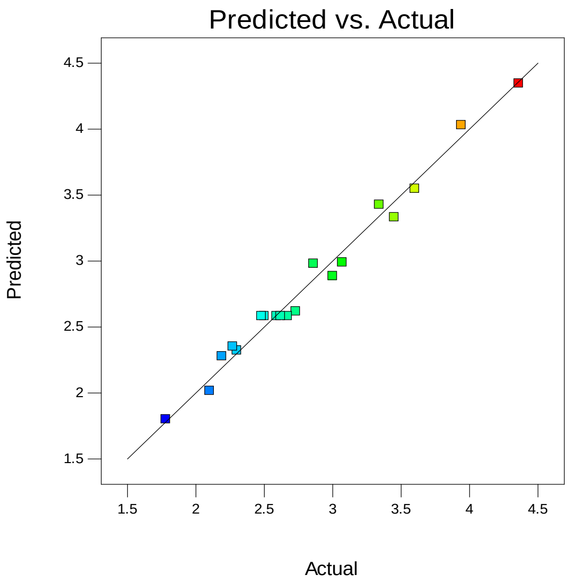


Fig. 2b: Predicted versus actual plots water absorption model

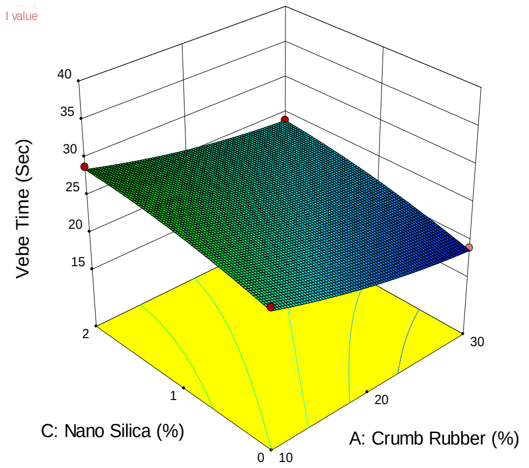
3.3. Effect of crumb rubber and nano silica on the Vebe time of HVFA RCC pavement

The results of Vebe consistency of HVFA RCC pavement with 50%, 60% and 70% fly ash is presented in Fig. 3a, Fig. 3b, and Fig. 3c respectively in 3-dimensional response surface plot. From the results, it can be seen that the Vebe time of HVFA RCC pavement increases with increase in percentage replacement of cement with fly ash. This is to say the higher the fly ash content, the lower the Vebe consistency of HVFA RCC pavement. This effect can be ascribe to the higher surface area of fly ash compared to cement, which makes to absorb more water during mixing and consequently decreases its consistency.

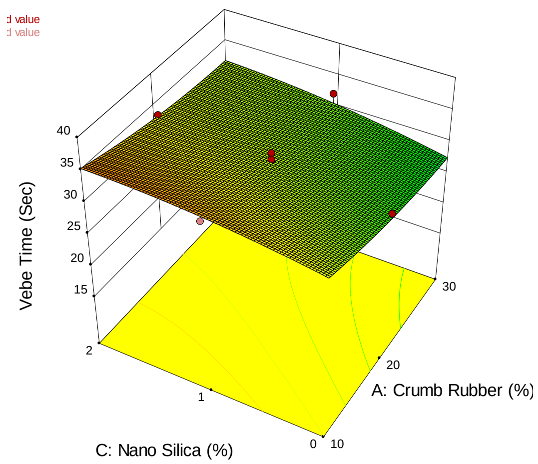
Table 6: Multi-objective optimization goals and result

Variables and Responses	Goal	Upper limit	Lower limit	Optimum ratio and predicted response
Crumb rubber	In range	10	30	17.09
Fly ash	In range	50	70	50
Nano silica	In range	0	2	1.01
Vebe Time	minimize	19	38	22.7
Water absorption	minimize	1.78	4.38	2.19
	Desirability			82%

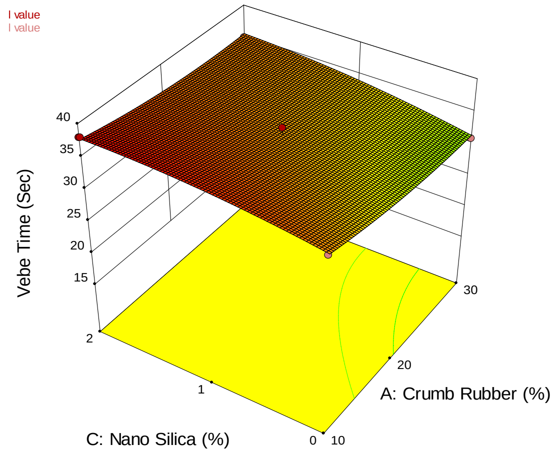
The Vebe consistency of HVFA RCC pavement with any percentage of fly ash increases with increase in crumb rubber content. This can be attributed to the lower water absorption of crumb rubber compared to fine aggregate, thus increasing the amount of free water in the mix, and consequently reducing the compaction time and effort needed (Meddah et al., 2014). On the other hand, the addition of nano silica decreases the consistency of HVFA RCC with any percentage of fine aggregate. This is due to the finer particle size and higher surface area of nano silica making it to absorb part of the free water available in the mixture.



(a) HVFA RCC Pavement with 50% fly ash



(b) HVFA RCC Pavement with 60% fly ash



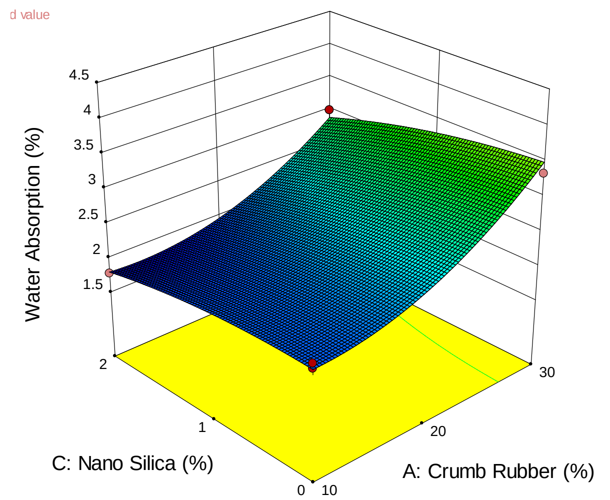
(c) HVFA RCC Pavement with 70% fly ash

Fig. 3: 3D response surface plot for Vebe time of HVFA RCC pavement

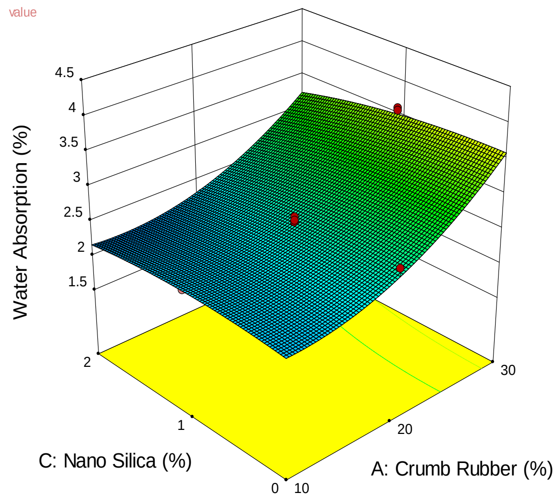
3.4. Effect of crumb rubber and nano silica on the water absorption of HVFA RCC pavement

The results summary for the water absorption of RCC pavement is presented in 3D response surface plot as shown in Fig 4. By comparing Fig. 4a, Fig. 4b, and Fig. 4c, It can be seen that the higher the percentage replacement of cement with fly ash, the higher the water absorption values. This is caused by the reduction in hydration process when fly ash replaced cement, with fly ash having a slow hydration reaction process, this resulted to more crystalline calcium hydroxide and lower calcium-silicate-hydrate in the hardened matrix, leading to more pores and poor bonding between aggregates and cement matrix and causing increased permeability (Gholampour and Ozbakkaloglu, 2017). The water absorption of HVFA RCC with any percentage of fly ash increases with increase in crumb rubber content. This increment is attributed to the increased porosity in the hardened RCC resulting from the non-polar and hydrophobic nature of crumb rubber which makes it to repel water and entrap air in its surface during mixing, this thereby increases voids in the hardened matrix and consequently higher permeability (Mohammed et al., 2011; 2018).

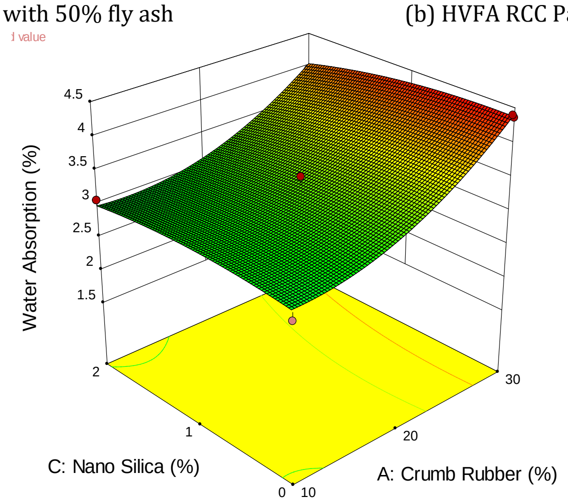
The addition of nano silica by weight of cementitious materials in HVFA RCC pavement with any percentage of fly ash improves the durability performance by decreasing its water absorption. This decrease is due to the finer sizes of nano silica thereby filling the small pores generated by the crumb rubber in the hardened RCC thereby densifying the microstructure hence reducing its permeability (Mohammed et al., 2016; Mohammed and Adamu, 2018a; 2018b). Another mechanism for the decrease in water absorption with addition of nano silica in RCC is due to the high pozzolanic reactivity of nano silica, thereby reacting with the crystalline calcium hydroxide to produce more amorphous calcium-silicate hydrates (C-S-H gel). This C-S-H gels fills up the voids in the hardened matrix and decreases the thickness of the ITZ and increase bonding between cement paste and rubber particles (Mohammed and Nezri, 2015). This leads to a more homogenous and densified.



(a) HVFA RCC Pavement with 50% fly ash



(b) HVFA RCC Pavement with 60% fly ash



(c) HVFA RCC Pavement with 50% fly ash

Fig. 4: 3D response surface plot for Water absorption of HVFA RCC pavement

4. Conclusion

In this study, based on the experimental work and analysis carried out, the following conclusions can be drawn:

- Quadratic model was developed using RSM to predict the Vebe time and water absorption of HVFA RCC pavement using crumb rubber, fly ash and nano silica as the variables. The result of the RSM analysis shows there is a good correlation between the variables and the responses.
- The results of the optimization process using RSM shows that the combination of 17.09% crumb rubber as a fine aggregate replacement by volume and 50% fly ash as replacement to cement and addition of 1.01% nano silica by

weight of cement will yield the minimum Vebe time and water absorption.

- The Vebe time and water absorption of HVFA RCC pavement increases with increase in fly ash content as replacement to cement.
- The Vebe time and water absorption of HVFA RCC pavement with any percentage of fly ash decreases with the addition of nano silica by weight of cementitious materials.

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