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# ESTABLISHING RELATIONSHIP BETWEEN MODULUS OF ELASTICITY AND STRENGTH OF NANO SILICA MODIFIED ROLLER COMPACTED RUBBERCRETE

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**ABSTRACT:** Roller compacted concrete (RCC) pavement is subjected to repetitive loadings and bending stresses from moving vehicles. Therefore, they are susceptible to cracks due to fatigue. Dowel bars, tie rods, or steel reinforcement cannot be placed on RCC pavement due to the way they are placed, compacted and consolidated, Therefore, all loads and deformations are resisted by the concrete alone. One of the ways of reducing such effect is producing a more durable RCCP that will undergo higher deformation before cracking. This can be done by partially replacing fine aggregate with crumb rubber (CR) in RCC to produce roller compacted rubbercrete (RCR). In this study, RCR was produced by partially replacing fine aggregate with CR at levels 0%, 10%, 20%, and 30% by volume. Nano silica (NS) was then added at 0%, 1%, 2%, and 3% by weight of cementitious materials to mitigate loss in strength, and their effect on modulus of elasticity (MOE) was studied. The MOE of RCR decreases with increase in CR and increases with NS addition. Also at 10% CR the MOE of RCR increases. Conversely, NS decreases the ductile behavior of RCR by making it more rigid. Power function was not suitable for the relationship between MOE and compressive strength of RCR as recommended by ACI 318, therefore linear model was developed.

*Keywords: Crumb rubber, Nano silica, Roller compacted rubbercrete, Modulus of elasticity, Compressive strength*

## 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 [1]. 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 [2]. 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 [3]. The major advantage of RCC over conventional concrete is the faster construction speed and reduced construction cost. For example, the construction time of RCC dams can be reduced by 1-2 years compared to conventional concrete or gravity dams, and the cost reduced by 25 -50 % in comparison to conventional concrete [1]. When used for pavement, RCC has many advantages over asphaltic pavement which include; high rutting resistance, can be laid over soft subgrade, high resistance to concentrated and heavy loads without softening, resist fuel and hydraulic fluid spillage without deteriorating [4].

Due to the way RCC pavement is placed, compacted and consolidated, steel reinforcement, dowel bars or tie rods cannot be placed [5]. Therefore loads and stresses are transferred using aggregate interlock down to the bottom layers [6]. Stresses in RCC pavement can be due to loads and due to adiabatic temperature caused mainly by the heat of hydration of cementitious materials during mixing which can result to thermal cracking. There is a direct proportionality between the thermal stresses and modulus of elasticity of RCC pavement, thus lower elastic modulus in RCC is of higher desirability. However, factors which affect the elastic modulus of RCC pavement include type and volume of aggregate, water/cement ratios and rate of hydration [3]. The modulus of elasticity can also be used for estimation of the bending deflections and calculating the deformation of the RCC pavement [7].

One of the ways of achieving a lower modulus of elasticity in RCC pavement is by using crumb rubber as a partial replacement material to fine aggregate to produce roller compacted rubbercrete (RCR) pavement. Several studies showed that the modulus of elasticity of concrete decreases with increase in partial replacement of fine aggregate with crumb rubber in concrete [8-11]. This is due to the higher deformation, lower stiffness, strength, and lower elastic modulus of crumb rubber compared to fine aggregate [10, 12]. However, the addition of CR reduces compressive and flexural strengths in RCR pavement [13, 14]. Therefore, to achieve an RCR with lower elastic modulus without much effect of strength reduction, possible ways of mitigating the strength loss with CR needed to be utilized, one of which is using Nano silica (NS) in small percentage as addition to cementitious materials [15], another option is use of silica fume as partial replacement of cement [11].

Previous study by Settari, et al. [16] shows that replacing 50% and of 100% fine aggregate with recycled aggregate pavement (RAP) decreases modulus of elasticity of RCC pavement by 30% and 41% respectively, their findings was in agreement to that of Fakhri and Amoosoltani [17], similarly, Lopez-Uceda, et al. [18] reported a decrease of elastic modulus by 23.4% and 36.9% when they replaced 50% and 100% coarse aggregate with RAP respectively for 100 kg/m$^3$ cement content, and for 250 kg/m$^3$ cement elastic modulus decreased by 21.6% and 29.1% for 50% and 100% RAP respectively. LaHucik, et al. [19] incorporated macro fibers of different types to RCC pavement, they found that for an embossing fibers of 48 mm length, elastic modulus increases by 4.4% for 0.2% fiber content and a decreases by 8.2% for 0.4% fiber content, while for smooth fibers of 40 mm length elastic modulus decreases by 4.4% and 3.8% for 0.2% and 0.4% fiber contents respectively, while Yazici, et al. [20], found that addition of 0.25% polypropylene fibre to RCC pavement increases its elastic modulus by 5.1%, and addition of 0.5% and 0.75% PP decreases the elastic modulus by 19.3% and 26.3% Respectively. Hesami, et al. [21], reported an increase elastic modulus of RCC pavement by 3.3%, 5.5% and 4.7% for partial replacement of 5% cement with coal waste ash (CWA), coal waste powder (CWP), and blend of coal waste ash and limestone (CWA-LS) respectively, while the modulus of elasticity decreased by 17.4%, 12.4% and 14% for 20% cement replacement with CWA, CWP, and CWA-LS respectively.

Based on the available literature reviewed, no related work was found in the study of the effect of crumb rubber and nano silica addition on the elastic modulus of roller compacted concrete pavement. Therefore, this study aimed at investigating the effect of partial replacement of fine aggregate with crumb rubber and addition of nano silica by weight of cement on the elastic modulus and deformation properties of roller compacted concrete pavement.

## 2. MATERIALS AND METHODS

### 2.1 Materials

The materials used in this study are cement, sand, coarse aggregate, fly ash and nano silica. The cement is Type I Portland cement with a specific gravity of 3.15 and conforms to the requirements of ASTM C150M-15. The sand is natural river sand with a maximum size of 4.75 mm and has a specific gravity of 2.65, water absorption 1.24% and fineness modulus 2.86. Two nominal maximum size aggregates (NMSA) have been used, which are19 mm (3/4 Inch) with specific gravity and water absorption of 2.66 and 0.48%, respectively, and 6.25 mm (1/4 inch) with specific gravity and water absorption of 2.55 and 1.05%, respectively. Three sizes of crumb rubber have been blended to achieve gradation similar to that of fine aggregate. After several series of trial combinations, using sieve analysis according to ASTM D5644, final proportion of 40% of 0.595 mm, 40% of 1 – 3 mm, and 20% of 3 – 5 mm has been used. The particles size distribution of crumb rubber and aggregates used is shown in Fig. 1. One of the requirements for RCC pavement production is using materials finer than 75 µm (No 200) sieve to achieve a more cohesive paste with reduced void volume, and the recommended amount should be between 2% to 8% of the aggregate [22], therefore class F Fly ash conforms to ASTM C612 and ASTM C311 has been used as mineral filler. And the nano silica with size 10 – 25 nm has been used as an addition to cementitious materials. The chemical compositions of cement, fly ash and nano silica is shown in Table 1.

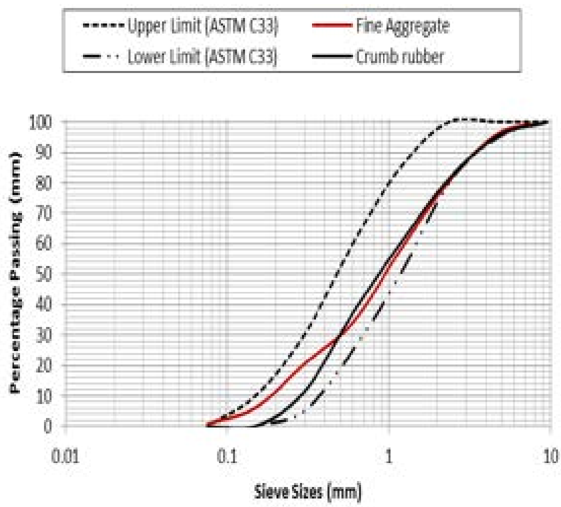


Fig. 1 Sieve analysis of aggregate

Table 1 Materials properties

| Oxides (%) | Cement | Fly ash | Nano silica |
|---|---|---|---|
| $SiO_2$ | 20.76 | 57.06 | 99.8 |
| $Al_2O_3$ | 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 | - |
| LOI | 2.2 | 1.25 | $\leq$ 0.3% (carbon content) |
| Specific gravity | 3.15 | 2.3 | $\leq$ 0.15 g/ml (Surface density) |
| Blaine fineness ($m^2$/kg) | 325 | 290 | 100±25 $m^2$/g |

### 2.2 Mix Design

The geotechnical approach method using the soil compaction concept was used for mixture proportioning of the control RCC. The first step is to obtain a combined aggregate grading falling within the limits recommended by the US Army corps of Engineers [22]. A combination of 55% fine aggregate, 20% 19 mm inch coarse aggregate, 6.25 mm coarse aggregate and 5% mineral filler gave the best-combined aggregate grading. This is followed by optimum moisture content and maximum density determination according to ASTM D1557-12e. Here four different RCC mix were produced with cement contents of 12%, 13%, 14% and 15% by weight of dry aggregates. For each cement content, five sub-mixes 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 4.3 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 [23].

Sixteen mixes were finally prepared as shown in Table 2. Each mix was prepared by varying percentage replacement of fine aggregate with CR at 0%, 10%, 20% and 30% replacement by volume and addition of 0%, 1%, 2% and 3% NS by weight of cementitious materials. Abbreviations were used for each mix, R0C0N is the control mix with 0% CR and 0% NS, R10C3N is a mix with 10% CR and 3% NS, while R30C0N is a mix with 30% CR and 0% NS. This follows the same trend for all other mixes.

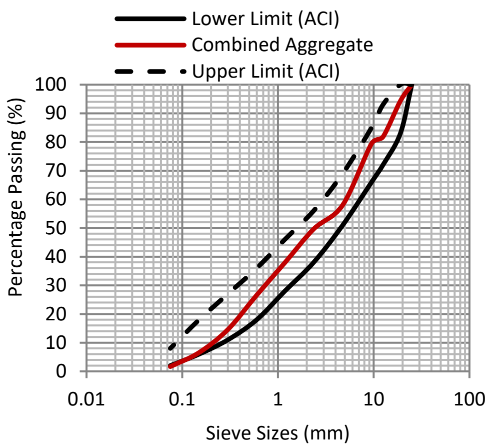


Fig. 2 Combined aggregate grading

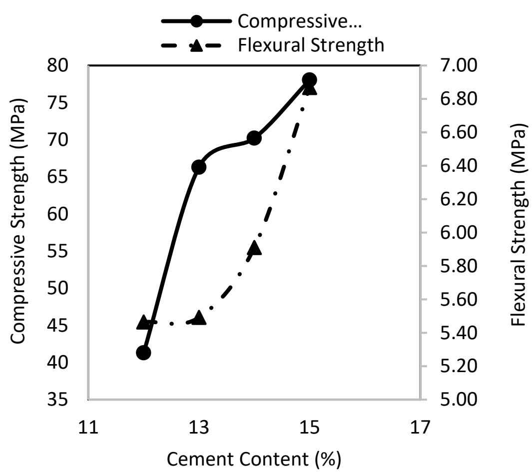


Fig. 3 Cement-strength relationship

Table 2 Mixtures constituent materials

| Mixture | Cement ($kg/m^3$) | Nano silica ($kg/m^3$) | Filler ($kg/m^3$) | Fine aggregate ($kg/m^3$) | Coarse aggregate 19mm ($kg/m^3$) | Coarse aggregate 1/2 –inch ($kg/m^3$) | Water ($kg/m^3$) | CR ($kg/m^3$) |
|---|---|---|---|---|---|---|---|---|
| R0C0N | 268.69 | 0 | 103.76 | 1148.05 | 415.03 | 416.85 | 98.24 | 0 |
| R0C1N | 268.69 | 2.69 | 103.76 | 1148.05 | 415.03 | 416.85 | 98.24 | 0 |
| R0C2N | 268.69 | 5.37 | 103.76 | 1148.05 | 415.03 | 416.85 | 98.24 | 0 |
| R0C3N | 268.69 | 8.06 | 103.76 | 1148.05 | 415.03 | 416.85 | 98.24 | 0 |
| R10C0N | 268.69 | 0 | 103.76 | 1033.25 | 415.03 | 416.85 | 98.24 | 114.89 |
| R10C1N | 268.69 | 2.69 | 103.76 | 1033.25 | 415.03 | 416.85 | 98.24 | 114.89 |
| R10C2N | 268.69 | 5.37 | 103.76 | 1033.25 | 415.03 | 416.85 | 98.24 | 114.89 |
| R10C3N | 268.69 | 8.06 | 103.76 | 1033.25 | 415.03 | 416.85 | 98.24 | 114.89 |
| R20C0N | 268.69 | 0 | 103.76 | 918.44 | 415.03 | 416.85 | 98.24 | 229.78 |
| R20C1N | 268.69 | 2.69 | 103.76 | 918.44 | 415.03 | 416.85 | 98.24 | 229.78 |
| R20C2N | 268.69 | 5.37 | 103.76 | 918.44 | 415.03 | 416.85 | 98.24 | 229.78 |
| R20C3N | 268.69 | 8.06 | 103.76 | 918.44 | 415.03 | 416.85 | 98.24 | 229.78 |
| R30C0N | 268.69 | 0 | 103.76 | 803.64 | 415.03 | 416.85 | 98.24 | 344.67 |
| R30C1N | 268.69 | 2.69 | 103.76 | 803.64 | 415.03 | 416.85 | 98.24 | 344.67 |
| R30C2N | 268.69 | 5.37 | 103.76 | 803.64 | 415.03 | 416.85 | 98.24 | 344.67 |
| R30C3N | 268.69 | 8.06 | 103.76 | 803.64 | 415.03 | 416.85 | 98.24 | 344.67 |

### 2.3 Sample preparations and experimental setup

In this study, the Bosch vibration hammer was used for compaction in accordance to ASTM C1435. For each mix ten, 150 mm by 300 mm cylinders were produced out of which four were tested for compressive strength at 7 days and 28 days and six were tested for modulus of elasticity and Poisson ratio according to ASTM C469 at 7 days and 28 days. Each sample was compacted in five layers so as to achieve adequate compaction. The compressive stress-strain curve for some mixes at 28 days was obtained using strain gauges and loading the samples until failure. Each sample was tested using the universal testing machine of 3000 kN capacity. The load was applied slowly at the rate of 240 $kN/m^2s$. The modulus of elasticity is computed in two ways; taking the slope of the stress-strain curve at 40% of the ultimate compressive stress and using the relation shown in equation 1

$$E_C = (\sigma_2 - \sigma_1)/(\varepsilon_2 - 0.00005) \qquad (1)$$

where Ec is the modulus of elasticity, $\sigma_2$ is the stress equivalent to 40% of ultimate compressive force, $\sigma_1$ is the strain corresponding to a longitudinal strain of 0.00005, $\varepsilon_2$ is the longitudinal stress corresponding to $\sigma_2$

Flexural strength has been determined according to the requirements of ASTM C293M-10 using beams with the size of 100 mm x 100 mm x 500 mm have been produced for each mix and tested at age of 28 days of curing.

## 3. RESULTS AND DISCUSSION

### 3.1 Modulus of elasticity (MOE) of RCR

The results of the modulus of elasticity and Poisson ratio of all the RCR mixes are shown in Fig 4a and Fig 4b respectively. The modulus of elasticity (MOE) for all the mixes increases with age due to increase in hydration. Partial replacement of fine aggregate with CR at higher percentage levels above 10% decreases the brittleness nature and increases the flexibility of RCR hence reduction in modulus of elasticity, and increased Poisson ratio. At 10% CR replacement the 28 days MOE increases by 1.2% and decreases by 41.9% and 45.3% for 20% and 30% CR respectively. These findings are in agreement with results of [8, 24] on rubbercrete. The increment in MOE for 10% CR is due to the higher compaction pressure used which reduces the effect of increased porosity caused by crumb rubber. While the decrease in MOE is attributed to higher deformation and lower elastic modulus of CR compared to fine aggregate [10, 12]. In addition, other factors such as poor bonding between CR and cement matrix, higher porosity and increased the thickness of the interfacial transition zone (ITZ) caused by entrapped air by CR during mixing, affects the stress-strain behavior of RCR as shown in Fig 5, and hence reduce MOE [11, 25].

The addition of NS increases the MOE and Poisson ratio of RCR for all CR replacement ratios as shown in Fig 4b. For Poisson ratio, there is no specific pattern for the increment. At 20% CR replacement level, the 28 days MOE of RCR increases by 16.05% and 6.02% for 1% and 2%, NS addition respectively compared to 0% NS. While at 30% CR replacement level the 28 days MOE increases 28.53%, 8.78%, and 8.28% for 1%, 2%, and 3% NS respectively compared to 0% NS.

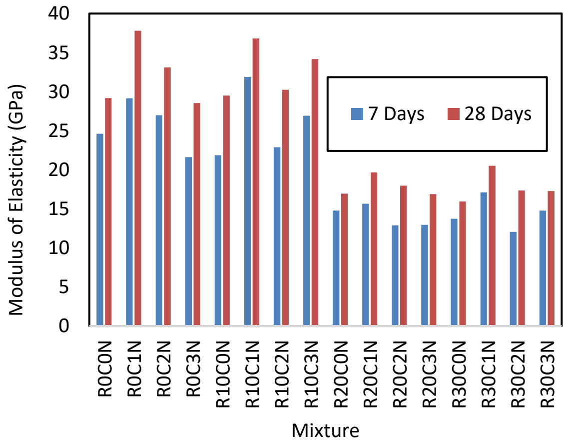


Fig. 4a Modulus of Elasticity of RCR

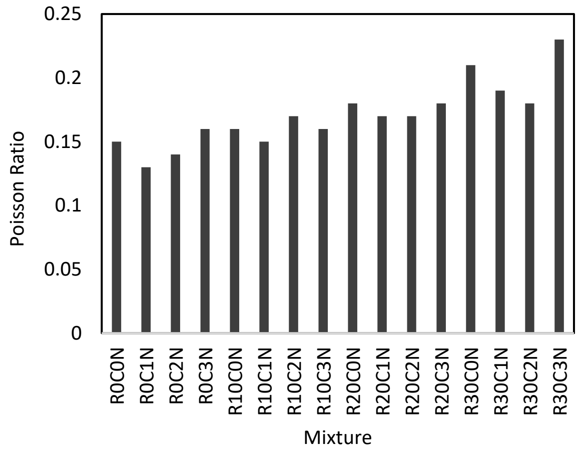


Fig. 4b Poisson’s Ratio of RCR

These findings were in agreement with results by Amin and Abu el-Hassan [26]. This increase is due to the ability of NS to react with $Ca(OH)_2$ from cement hydration to produce more calcium-silicate-hydrate which increases strength and consequently MOE. It is also due to the pore filling ability of NS, making the RCR denser, with microstructure and densified ITZ between CR-cement paste and aggregate-cement paste [27]. This decreases the ductile behavior of RCR and increases its stiffness and subsequently increased MOE [15, 27].

### 3.2 Stress-strain behavior of RCR

The plots of the stress-strain curve of some RCR mixes are shown in Fig 5a and Fig 5b, initially before reaching maximum stress, all the mixes behave similarly. After reaching the maximum stress, mixes with lower CR contents suddenly reach their breaking points without much strain softening; this shows the brittleness nature of the RCR, with lower compressive toughness. While for mixes with higher CR contents, they undergo prolonged strain softening before failure with higher peak strain as shown by the extended parts of the curve after the maximum stress is reached. This further demonstrates how CR increases the ductile behavior of RCR. It can also be seen that although CR increases the peak train of RCR but it decreases its ultimate stress values. On the other hand, it can be seen from Fig 5, NS increases the ultimate stress of RCR, but decreases its peak strain, thereby making it more brittle with lower toughness values

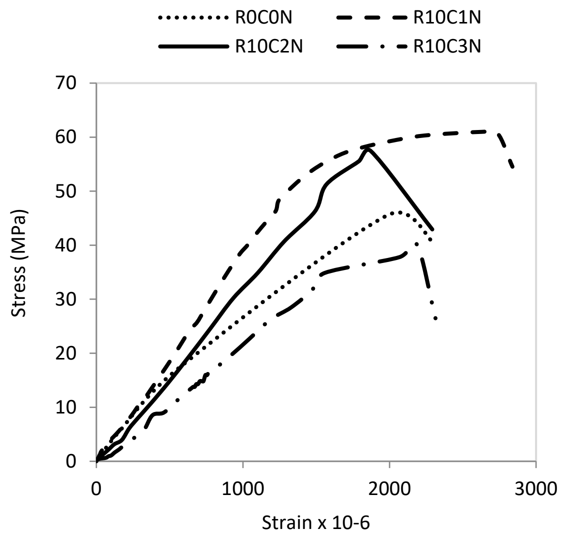


Fig. 5a Stress-strain curve for (a) RCR with 0%-10% CR

### 3.3 Relationship between MOE and mechanical properties of RCR

Several international standards have developed the relationship between compressive strength (Fc) and modulus of elasticity of concrete (Ec) [28, 29]. However, no standard developed the MOE/compressive strength relationship for RCC pavement due to limited available literature [21]. In this study, the power function as shown in Fig 6 is used for the MOE-compressive strength relationship of NS modifies RCR as recommended by ACI 318-14. For comparison and justification, the relationships are compared with previous studies [21, 30].

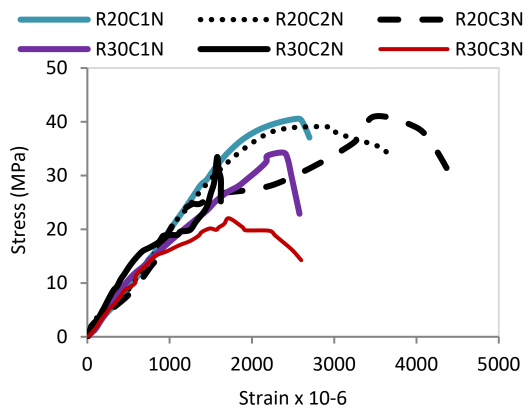


Fig. 5b Stress-strain curve for RCR with 20%-30% CR

As shown in Fig 6, the power models are not good models for the compressive strength of RCR due to the low coefficient of determination ($R^2$), this is due to variation in properties of RCR caused by CR and NS. Therefore to obtain a better MOE-compressive strength relationship for RCR other models were developed as shown in Fig 7. It can be seen that there is good correction between MOE and compressive strength OF RCR when linear relation is used. Therefore the MOE of NS modified RCR can be predicted using its corresponding compressive strength values.

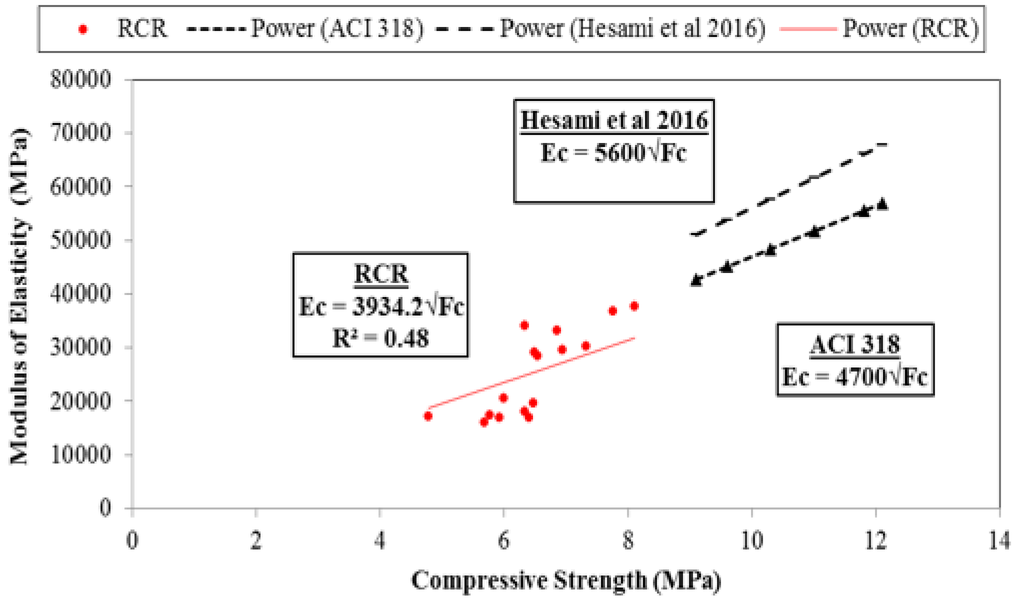


Fig. 6 Power relation between MOE and compressive strength of RCR

### 3.4 Predicting modulus of elasticity of RCR using multivariable regression

The flexural strength and compressive strength are the most important parameters for the design of RCC pavement [31]. The modulus of elasticity of concrete increases with increase in its compressive strength, similarly flexural strength of concrete increases with increase in compressive strength [32-34].

In this study, a multivariable regression model is developed for predicting the 28 MOE of RCR using its corresponding 28 days cylindrical compressive strength and its 28 days flexural strengths. The developed model is shown in equation 2, and its ANOVA is given in Table 3. It can be seen that the model has a high degree of determinations ($R^2$>0.71), with a low standard error (<5), higher F-values and very low F-significance, which explains the fitness, significance and predicting ability of the model.

$$E_C = 0.846F_C - 2.460F_M + 4.357 \qquad (2)$$

where $E_C$ is the modulus of elasticity in GPa, $F_C$ is the compressive strength in MPa, and $F_M$ is the flexural strength in MPa.

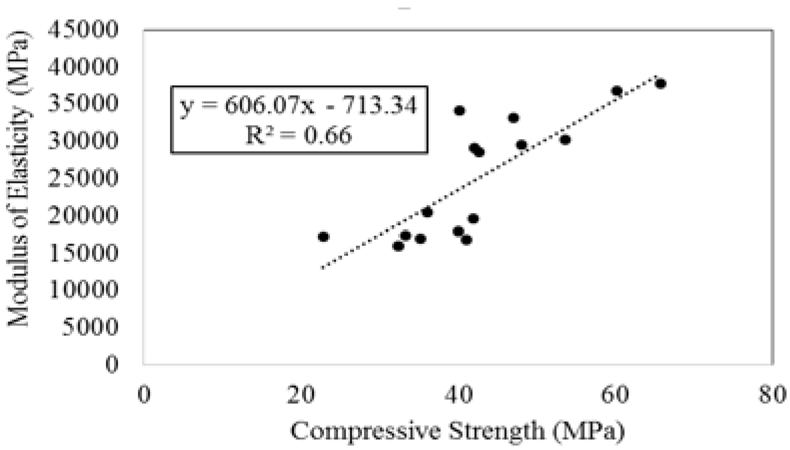


Fig. 7 Recommended relationship between MOE and compressive strength of RCR

Table 3 ANOVA for multivariable model of RCR

| Item | Value |
|---|---|
| $R^2$ | 0.71 |
| Adjusted $R^2$ | 0.66 |
| F-value | 15.604 |
| F-Significance | 0.000351 |
| Sum of squares | 677.527 |
| Mean square | 338.764 |
| Error | 4.569 |

## 4. CONCLUSIONS

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

1) The MOE of RCR increases and its Poisson's ratio decreases at all ages of curing when 10% fine aggregate was replaced with CR. However, at a replacement level above 10%, the MOE of RCR decreases while Poisson ratio increases with increase in percentage replacement of fine aggregate by CR. Therefore CR makes RCR more ductile and therefore more suitable for use in the pavement.

2) The addition of NS increases the MOE of RCR at all ages but decreases its peak strain and compressive toughness, hence making RCR more rigid.

3) The power relationship proposed by the ACI 318 for the relationship between MOE and compressive strength of concrete is not suitable for RCR. The linear model was found to be the most suitable higher degree of correlation.

4) From the results of the multivariable regression analysis, a bilinear function can be used to predict the 28 days MOE of RCR using compressive strength and flexural strength the independent variables.

## 5. ACKNOWLEDGEMENTS

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