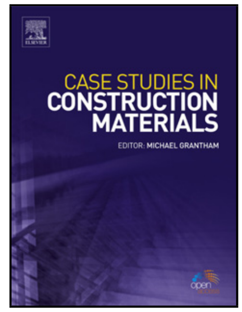

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Evaluating the effect of Crumb rubber and Nano silica on the properties of High volume fly Ash Roller compacted concrete pavement using Non-destructive Techniques

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Abstract

The major problems related to roller compacted concrete (RCC) pavement are high rigidity, lower tensile strength which causes a tendency of cracking due to thermal or plastic shrinkage, flexural and fatigue loads. Furthermore, RCC pavement does not support the use of dowel bars or reinforcement due to the way it is placed and compacted, these also aided in cracking and consequently increased maintenance cost. To address these issues, high volume fly ash (HVFA) RCC pavement was developed by partially replacing 50% cement by volume with fly ash. Crumb rubber was used as a partial replacement to fine aggregate in HVFA RCC pavement at 0%, 10%, 20%, and 30% replacement by volume. Nano silica was added at 0%, 1%, 2% and 3% by weight of cementitious materials to improve early strength development in HVFA RCC pavement and mitigate the loss of strength due to the incorporation of crumb rubber. The nondestructive technique using the rebound hammer test (RHT) and ultrasonic pulse velocity (UPV) were used to evaluate the effect of crumb rubber and nano silica on the performance of HVFA RCC pavement. The results showed that the use of HVFA as cement replacement decreases both the unit weight, compressive strength, rebound number (RN). Furthermore, the unit weight, compressive strength, RN, UPV and dynamic modulus of elasticity of HVFA RCC pavement all decreases with increase in crumb rubber content and increases with the addition of nano-silica. Combined UPV-RN (SonReb) models for predicting the 28 days strength of HVFA RCC pavement based on combining UPV and RN were developed using multivariable regression (double power, bilinear, and double exponential models). The exponential combined SonReb model is the most suitable for predicting the compressive strength of HVFA RCC pavement

using UPV and RN as the independent variable with better predicting ability, higher correlation compared to the single variable models.

Keywords: Crumb rubber; High volume fly ash; Nano silica; Roller compacted concrete pavement; Ultrasonic pulse velocity; Rebound number

1. Introduction

The construction industry has been advancing since the development of RCC causing a significant change in the method of placement, compaction and consolidation of mass concrete which was a slower process for the traditional or conventional concrete method (Mehta and Monteiro 2006). Roller compacted concrete is an extremely dry mix concrete of zero slump consistency in its fresh state, that is conveyed, placed and compacted using rock fill and earth equipment similar to those used for pavement construction (ACI 207.5R-11 2011). The durability, strength development and rate of hydration of RCC mix depend on the selection of constituent materials. Type I (ordinary Portland cement) and Type II (moderate sulfate resistance cement) are more economically used in RCC due to its lower heat of hydration and longer setting times. Pozzolan such as fly ash or slag are commonly used as supplementary cementitious materials and mineral fillers in RCC; they provide a degree of lubrication during placing and fill the voids between aggregates and paste. Class F fly ash improves workability, increases placement time, and may be used to replace up to 50 % by volume in RCC (Fuhrman 2000). However use of fly ash delay setting times in concrete, reduces early strength development, reduces durability at an early age and reduces the resistance to freezing and thawing (Huang, Lin et al. 2013). In order to utilize the advantages of using fly ash in concrete, it should either be used when an early strength development is not required, or where early setting times is to be avoided such as in roller compacted concrete, where delay in setting time is needed to allow for placing and proper compaction of the concrete. A concrete containing 50% or more fly ash by weight of cement is regarded as a high volume fly ash concrete (Mehta and Monteiro 2006). In order to use fly ash efficiently in RCC, one of the ways of solving the problems associated with fly ash is introducing Nanomaterials such as Nano silica to the concrete containing fly ash (Singh, Karade et al. 2013).

The nondestructive testing (NDT) method can be used to evaluate the strength and quality of RCC pavement. The American Society for Nondestructive Testing (NDT) defines nondestructive evaluation as examining an object with technology that does not cause any harm to the object's future function (Shull 2016). To assess the compressive strength of concrete structures, the most commonly used NDT methods are ultrasonic pulse velocity (UPV) and rebound hammer (RH) test (Al-Mufti and Fried 2012). In RH test, the surface hardness is measured in terms of rebound number (RN) using the Schmidt hammer. It consists of a spring-loaded steel hammer mass which slides along the bar, when released it strikes and makes and makes an impact with the help of a steel plunger on the concrete surface. After impact, the mass rebounds back from the steel plunger. The distance of the hammer rebound from the steel plunger is then read on a linear scale in form of rebound number (RN), which is then translated into a compressive strength with the help of a correlation graph (ASTM C805 2013). UPV test is based on measuring the time of pulse wave through a concrete of known path length. Therefore, UPV is usually used to measure the quality, integrity and mechanical properties of concrete. It is also used to calculate the dynamic modulus of elastic and dynamic Poisson's ratio of concrete (Amini, Jalalpour et al. 2016, Rao, Sravana et al. 2016). The UPV method can be used to evaluate the density and voids in hardened concrete, measure the uniformity of concrete, detect cracks and honeycomb, and to estimate the compressive strength (Rao, Sravana et al. 2016).

Few studies have evaluated the quality and performance of RCC pavement using the nondestructive evaluation method. Rao, Sravana et al. (2016), investigated the quality of RCC pavement using the UPV. They investigated the effect of manufactured sand (M-sand) and fly ash on the UPV of RCC pavement. They prepared three series of mixtures. In series A, they used natural aggregates as fine aggregate, series B they used M-sand as fine aggregates, in series C, they used a combination of 50% river sand and 50% M-sand as fine aggregates. In each series they replaced cement with fly ash at varying percentages (10% 20%, 30%, 40%, 50%, 60%). The UPV for all the series mixtures increases with age and decreases with increase in fly ash content due to the slower pozzolanic reaction of fly ash, resulting to a more porous RCC matrix, and consequently increases the path length through which ultrasonic wave travels and consequently decreases it UPV. The quality of series A mixtures was doubtful up to 7 days and was of good quality at 28 to 90 days. For series B mixtures, their quality was doubtful up to 28 days, and at 90 days have good quality except for 60% fly ash content. Series C mixtures have a good quality at 28 days and excellent quality at 90 days. Mardani-Aghabaglou, Andiç-Çakir et al. (2013), investigated the effect of fly ash as both SCM and aggregate on the UPV of RCC pavement. They prepared two series of mixtures (A and B). In series A they partially replaced cement with fly ash at 0%, 20%, 40%, and 60% by weight and in series B they partially replaced fine aggregate with fly ash at 0%, 20%, 40%, and 60%. The UPV of series A mixtures decreases with increase in fly ash content, while the UPV for series B increases with increase in fly ash content. The decrease in UPV with fly ash content is due to the slower pozzolanic reaction of fly ash at an early age. While the increase in UPV with increasing fly ash content for series B is due to a finer size, pore filling ability and contribution of the pozzolanic reaction of fly ash compared to fine aggregate.

Waste tire disposal is a serious problem facing most countries due to its non-biodegradable properties, and will not decompose forever when disposed off. If dumped in the environment, will be stockpiled, causing landfilling problems, and causes so many environmental and health hazards such as high risk of fire, provides shelter to harmful insects, rodents, and animals such as rats, mosquitoes, snakes, mice etc.(Siddique 2007). Burning of the waste tires should have been the perfect solution to their disposal problems, but due to the enormous disadvantage of poisonous smoke and air pollution, this makes it not a good option (Sukontasukkul and Tiamlom 2012).

Due to the rapid growth and development in the construction industries with higher demands of concrete which is the most widely used construction material, the emphasis is been laid on the sustainability of the concrete constituent materials most especially aggregate as it constituent the highest volume percentage in the concrete to prevent or overcome its possible shortage. In order to solve the problems associated with waste tire disposal and the possible shortage of aggregate in the construction industry, incorporating waste tire as partial replacement of aggregate in concrete seems to be a possible solution (Siddique 2007). Several researches have shown that when the waste tire is used in concrete either in form of crumb rubber or chips there is a significant reduction in the mechanical properties and durability of concrete. However, crumb rubber increases the following properties of concrete; ductility and energy absorption capacity, fatigue performance, thermal insulation, electrical resistivity and sound absorption (Siddique 2007).

NDT has been used to evaluate the properties of concrete containing crumb rubber. Mohammed, Azmi et al. (2011) reported a decrease in surface hardness (RN) of concrete when crumb rubber partially replaced fine aggregate. This decrease is due to crumb rubber acting as a tiny spring inside the concrete, thereby absorbing some of the rebound echoes. They further reported decreased UPV values of concrete when fine aggregate was partially replaced with crumb rubber. This was due to increased porosity in the hardened concrete caused by the air entrapped on the crumb rubber surface during mixing. The porosity increases the travel time of the ultrasonic waves, thereby decreasing the UPV. In another study, Guo, Dai et al. (2017) and Marie (2016) also reported a decrease in UPV of concrete with an increase in partial replacement of fine aggregate with crumb rubber.

Therefore, in this study, the nondestructive evaluation techniques have been used to investigate the effect of partial replacement of fine aggregate with crumb rubber and the addition of nano silica by weight of cementitious materials on the properties of HVFA RCC pavement.

2. Materials and Methods

2.1 Materials

In this study, Natural sand was used as a fine aggregate with a maximum size of 4.75 mm, specific gravity 2.65, fineness modulus 2.86 and water absorption of 1.24%. Two nominal maximum sizes of coarse aggregates have been used to achieve the desired combined aggregate gradation. These are 19 mm size having 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 have been combined to obtain similar gradation curve to fine aggregate. Several trials of sieve analysis have been conducted in accordance with the requirements of ASTM D 5644. The combination of 40% mesh 30 (0.595 mm), 40% of 1-3 mm and 20% of 3-5 mm have been selected. The specific gravity of mesh 30, 1 – 3mm and 3 – 5 mm crumb rubber are 0.95, 0.90, and 0.94 respectively. Type 1 ordinary Portland cement which conforms to the requirements of ASTM C150 and having a chemical composition and physical properties as shown in Table 1 was used. Class F fly ash conforming to the requirements of ASTM C618, having physical and chemical properties shown in Table 1 was used as supplementary cementitious materials (SCM). The chemical properties of cement and fly ash were determined using X-ray fluorescence (XRF) analysis. Strong amorphous and hydrophobic nano silica size 10 - 25 nm having properties as shown in Table 2 has been used as an additive to the cement.

Table 1. Physical and Chemical properties of cement and fly ash

Chemical compositions			Physical characteristics		
Oxides (%)	Cement	Fly ash	Property	Cement	Fly ash
SiO_2	20.76	57.06	Specific gravity	3.15	2.3
Al_2O_3	5.54	20.96	Blaine fineness (m^2/kg)	325	290
Fe_2O_3	3.35	4.15	Initial setting time	110	-
MnO	-	0.033	Final setting time	220	-
CaO	61.4	9.79	28 days compressive strength	42.9	-
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			

Table 2. Properties of Nano silica

Property	Quantity
Appearance	High-dispersive white powder
Hear reduction (%) (105ºC 2h) ≤	3
Loss of ignition (%) (950ºC 2h) ≤	6
SiO_2 content (dry base) (%) ≥	92
SiO_2 content (%) (950ºC 2h) ≥	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/100g) ≥	250
Average particle size (nm)	10 – 25
Hydrophobicity	Strong

2.2 *Mixture Proportioning*

The geotechnical approach of the ACI 211.3R (2009) has been used for mix design which involves series of steps as follows.

The first step is to obtain a combined grading of fine and coarse aggregate to be within the upper and lower limits of the gradation curve based on the requirements of ACI 211.3R and US Army Corps of Engineers method (CRD-C 162 1992). In this study, Fig 1 shows the combined aggregate gradation curve and it has been achieved by combining 55% of fine aggregate, 40% of coarse aggregate and 5% of mineral filler. The coarse aggregate consists of 20% of 19 mm maximum size and 20% of 6.35 mm maximum size.

The second step is to determine the optimum moisture content (OMC) and maximum dry density (MDD) according to the requirements of ASTM D 1557-12e. In this study, the OMC and MDD have been determined for four RCC mixes considered using different cement contents (12%, 13%, 14%, and 15%) by weight of dry aggregates. For each cement content, five mixes were proportioned using different water contents ranging from 4.5% to 6.5% by weight of dry aggregate, and the moisture-density curve then has been established. The optimum moisture content for 12%, 13%, 14% and 15% cement contents were found to be 5.46%, 5.56%, 5.92% and 6.09%, respectively.

Four RCC mixes then have been prepared with 12%, 13%, 14% and 15% cement content and water content equal to their OMC. For each RCC mixture, flexural strengths samples have been prepared, cured and tested at age of 28 days to establish a relationship between cement content and flexural strength as shown in Fig 2. A cement content of 13% has been selected for further investigation based on the target flexural strength of 4.8 MPa, and by comparing the outcome of Fig 2 with the recommended values of cement content versus flexural strength relationship given in Table 1 of CRD-C 162 (1992). A water-to-cement of 0.42 has been found to be sufficient based on the quantities of mix ingredients. To reduce the water content and improve the consistency of the mix, superplasticizer (1% by weight of cement) has been added. Therefore, the water content has been reduced by 12% bringing down the water-to-cement ratio to 0.37.

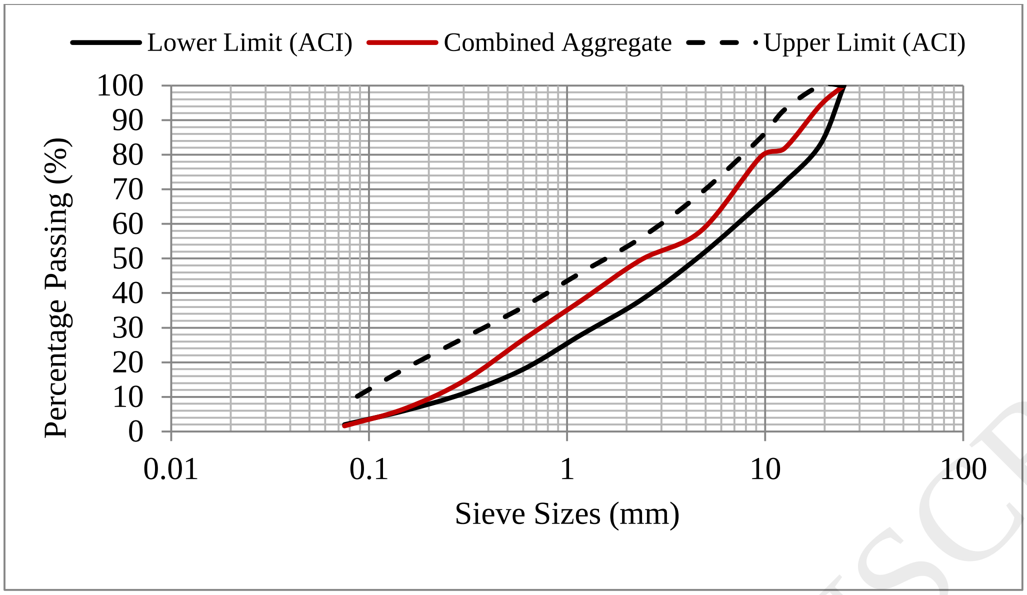

Fig 1. The combined aggregate gradation curve

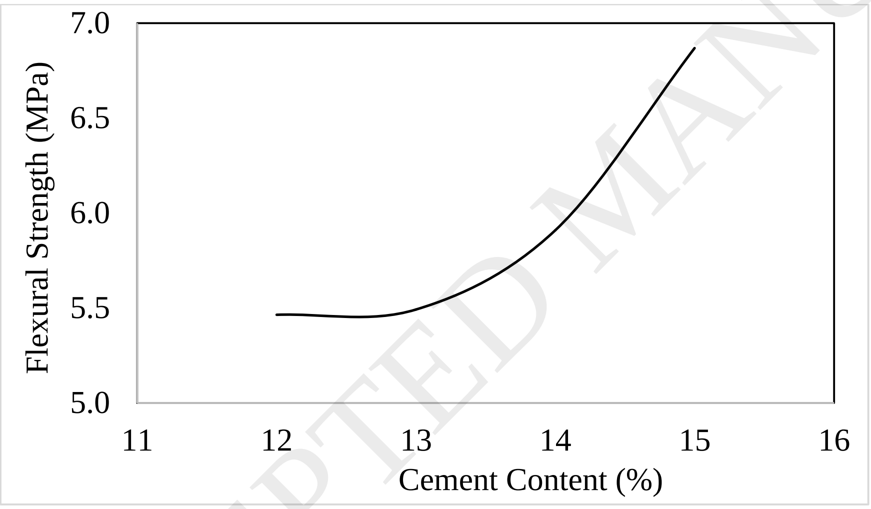

Fig 2. Cement content/Flexural strength relationship

2.2.1 Mix Composition

To investigate the effect of crumb rubber as partial replacement to fine aggregate, and the addition of nano silica as additive to cementitious materials, sixteen mixtures have been prepared by partially replacing cement with HVFA at constant percentage (50%), and varying the percentage replacement of fine aggregates with crumb rubber (at 0%, 10%, 20%, and 30%), and the percentage addition of nano silica at (0%, 1%, 2%, and 3%). Each mixture was assigned a unique ID, for example, mixture M10C50F1N is a mixture containing 10% crumb rubber as partial replacement to fine aggregate, 50% fly ash as a partial replacement to cement, and 1%

nano-silica as an additive to cementitious materials. Mixture M30C50F3N is a mixture containing 30% crumb rubber as partial replacement to fine aggregate, 50% fly ash as a partial replacement to cement, and 3% nano-silica as an additive to cementitious materials. A control (conventional) RCC mixture was also developed for comparison and validation of other mixtures. The control mixture is M0C0F0N i.e. RCC mixture containing 0% crumb rubber, 0% fly ash, and 0% nano-silica. The constituent material for each mixture is shown in Table 3.

Table 3. HVFA RCC pavement mixtures

Mixture	Quantities for 1 kg/m^3 of HVFA RCC							
	Cement	Fly Ash	Nano silica	Filler	Fine aggregate	Coarse aggregate	Water	Crumb rubber
M0C0F0N	268.7	0	0	103.8	1148.1	831.9	98.2	0
M0C50F0N	134.6	102.5	0	103.9	1150.1	833.3	96.9	0
M0C50F1N	134.6	102.5	2.4	103.9	1150.1	833.3	96.9	0
M0C50F2N	134.6	102.5	4.7	103.9	1150.1	833.3	96.9	0
M0C50F3N	134.6	102.5	7.1	103.9	1150.1	833.3	96.9	0
M10C50F0N	134.6	102.5	0	103.9	1035.1	833.3	96.9	115.1
M10C50F1N	134.6	102.5	2.4	103.9	1035.1	833.3	96.9	115.1
M10C50F2N	134.6	102.5	4.7	103.9	1035.1	833.3	96.9	115.1
M10C50F3N	134.6	102.5	7.1	103.9	1035.1	833.3	96.9	115.1
M20C50F0N	134.6	102.5	0	103.9	920.1	833.3	96.9	230.2
M20C50F1N	134.6	102.5	2.4	103.9	920.1	833.3	96.9	230.2
M20C50F2N	134.6	102.5	4.7	103.9	920.1	833.3	96.9	230.2
M20C50F3N	134.6	102.5	7.1	103.9	920.1	833.3	96.9	230.2
M30C50F0N	134.6	102.5	0	103.9	805.1	833.3	96.9	345.3
M30C50F1N	134.6	102.5	2.4	103.9	805.1	833.3	96.9	345.3
M30C50F2N	134.6	102.5	4.7	103.9	805.1	833.3	96.9	345.3
M30C50F3N	134.6	102.5	7.1	103.9	805.1	833.3	96.9	345.3

2.3 *Sample Preparations and Experimental Programs*

2.3.1 *Compaction method*

RCC pavement mixture is very steep, adequate compaction using vibration table cannot be achieved, which can lead to voids and honeycombs in the hardened mix thereby reducing it's mechanical energy. Therefore, in order to achieve proper compaction and consolidation, a vibration hammer of 50 Hz capacity was used to simulate the roller compaction in the laboratory. The compaction of the fresh samples was done in accordance with ASTM C1435. Full compaction was achieved when a ring of mortar forms across the periphery of the base plate.

2.3.2 Test Methods

The hardened unit weight was determined according to the requirements of BS EN 12390-7:2009. For each mixture, three 150 mm^3 cubes were prepared and cured for 28 days prior to determination of the unit weight, and the average results are recorded.

The rebound hammer test was carried out in accordance with the requirements of ASTM C805 using the Schmidt rebound hammer. For each mixture, the three 150 mm^3 cubes were prepared and cured for 28 days prior to testing. The RN was taken at five points spaced equally on four sides of the sample. Across each point, 10 readings were taken and the average value calculated. It was ensured that the readings were not taken exactly at the same point and the impact points were more than 20 mm from the edge of the concrete cubes. Before taking the readings, the Schmidt hammer was held horizontally so that the plunger is perpendicular to the test surface. The RN number for each mix was then taken by calculating the average values of each of the five points on the four faces of the cube. The sample was placed in a Universal Testing Machine (UTM) and a force equivalent to 7 MPa was applied to the sample firm during testing.

The UPV test has been conducted in accordance with the requirements of ASTM C597 (2016) using the PUNDIT with a transducer of 54 KHz after curing the cubes for 28 days. Similar to the RN test, five points were marked on four faces of the cubes. To avoid friction and effects resulting in different velocities, a thin layer of coupling agent was spread on each point. The pulse velocity was then measured on opposite sides (one side with the transducer the other side with the receiver). For each point, three readings were taken. The UPV for each mix was then obtained by calculating the average reading of each of the five points on the four faces.

The dynamic modulus of elasticity (DMOE) for all the mixtures was determined using Eqn 1.

$$E_D = (UPV)^2 \left[\frac{\rho(1+\mu)(1-2\mu)}{1-\mu} \right] \tag{1}$$

where E_D is the 28 days DMOE for HVFA RCC in GPa, ρ is the 28 days hardened density (unit weight) in kg/m^3; μ is dynamic Poisson ratio. The value of μ was assumed to be 0.2 for calculation of DMOE (Lamond 2006).

Finally, the compressive strength test was carried out in accordance with BS EN 12390-3:2009. Cubes of sizes 150 mm x 150 mm x 150 mm were prepared and cured for 7 and 28 days prior to testing. For each mixture, three samples were tested after each curing period and the mean value was reported.

3. Results and Discussions

3.1 *Unit Weight*

The unit weight of RCC pavement is an important parameter for determining its dynamic modulus of elasticity in combination with UPV and dynamic Poisson ratio. The incorporation of

HVFA as a partial replacement to cement decreases the unit weight of RCC pavement as shown in Fig 3 by comparing the value for mixture M0C0F0N with that of M0C50F0N. This is mainly due to the lower specific gravity of fly ash compared to cement it replaced. The unit weight of HVFA RCC pavement decreases with increase in percentage replacement of fine aggregate with crumb rubber. This is due to the specific gravity and density of crumb rubber particles compared to fine aggregate it replaced (Mohammed and Adamu 2018). On the other hand, the addition of nano silica increases the unit weight of HVFA RCC pavement, with 1% being the optimum dosage. For example the unit weight of M10C50F1N, M10C50F2N, and M10C50F3N increases by 1.57%, 0.79%, and 1.51% respectively compared to M10C50F0N. This might be due to the pore filling ability, chemical reactivity of nano silica where it reacts with calcium hydroxide from cement hydration products to produce more calcium silicate hydrate gel which densifies the microstructure and fill the voids and thereby making the RCC pavement more compact and denser (Shah, Hou et al. 2016).

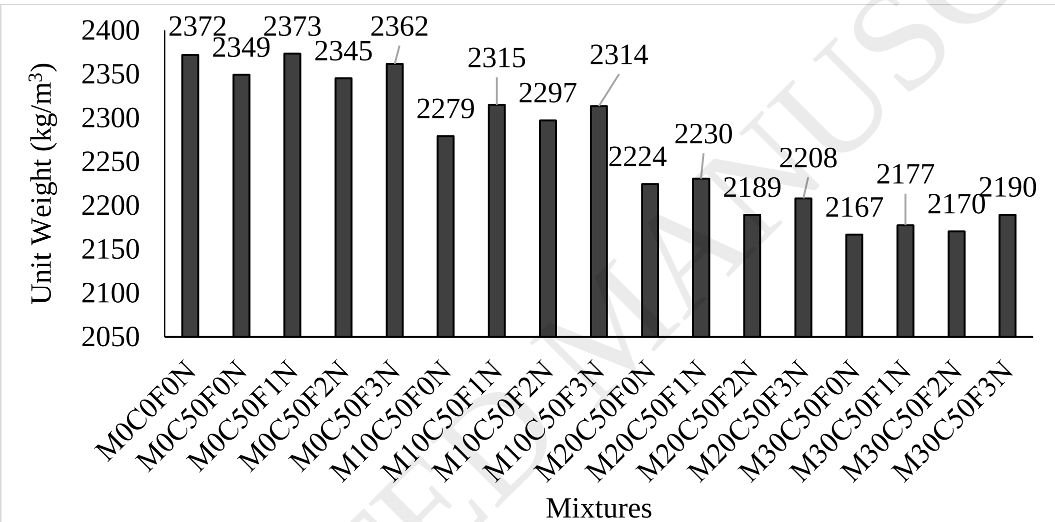

Fig 3. Unit weight of HVFA RCC pavement

3.2 Compressive Strength

The results of compressive strength for all HVFA RCC pavement mixtures is shown in Fig 4. The incorporation of HVFA as a partial replacement to cement resulted to decrease in compressive strength. The compressive strength values for M0C50F0N were lower than that of M0C0F0N by 31% and 9.7% at 7 and 28 days respectively. Therefore, the decrease is more pronounced at the early ages, and this is due to the slower pozzolanic reactivity of fly ash at early ages. This hinders the production of calcium-silicate-hydrate (C-S-H) from the reaction between SiO_2 from fly ash and $Ca(OH)_2$ from cement hydration. This consequently leads to lower strength as C-S-H is the major element for strength development in concrete (ACI 232.2R 2003). The compressive strength of HVFA RCC pavement decreases with increase in percentage replacement of fine aggregate with crumb rubber at both 7 and 28 days as seen in Fig 4. For example, the 28 days compressive strength of M10C50F0N, M20C50F0N, and M30C50F0N were 19.49%, 28.84%, and 36.26% respectively lower compared to M0C50F0N. The decrease in strength of HVFA RCC with the incorporation of crumb rubber is due to the increased thickness of the interfacial transition zone (ITZ) between cement paste – aggregates, and cement paste – crumb rubber, which is caused due to the repulsion of water by crumb rubber during mixing. This consequently causes a weak failure layer in the hardened HVFA RCC matrix, causing rapid premature failure with load applications and subsequently decreasing in the compressive strength (Mohammed and Azmi 2014, Mohammed, Awang et al. 2016). Another reason for the decrease is due to the non-compatibility of crumb rubber with sand, having lower specific gravity, strength, stiffness, and load carrying capacity thus leading to reduced strength when replaced part of fine aggregate (Xue and Shinozuka 2013). It can also be attributed to the increased pore volume in the hardened RCC due to increased air content in the fresh rubbercrete mix, caused by the hydrophobic nature of crumb rubber. Stress concentration occurs across the pores causing micro-cracks formation and consequently reduction in strength (Mohammed and Azmi 2011, Mohammed, Hossain et al. 2012).

To improve the early strength development and mitigate the loss of compressive strength due to the incorporation of crumb rubber in HVFA RCC pavement, nano silica was added as an additive to cementitious materials. As shown in Fig 4, nano silica improve the early strength development in HVFA RCC. This increase might be due to the finer size and larger surface area of nano silica which reacts faster with the surplus lime during hydration and produces more calcium-silicate-hydrates which densify both the cement aggregate paste and the ITZ and fills the voids in the matrix (Supit and Shaikh 2015). The addition of 1% nano silica was successful in a totally mitigating loss in compressive strength in HVFA RCC with the incorporation of 10% crumb rubber as a fine aggregate replacement. This can be observed as the compressive strength of M10C50F1N was higher than that of M0C50F0N at both 7 and 28 days. For incorporation of higher crumb rubber contents to HVFA RCC pavement, nano silica partially mitigated the loss in strength. Therefore, 1% nano silica was found to be the optimum dosage. This is mainly due to the fact as a higher dosage of nano silica is added, the consistency of HVFA RCC pavement decreases because nano silica absorbs more mixing water due to its larger surface area. The lower consistency reduces the compaction quality and pastes distribution of the fresh RCC mixture. This, in turn, leads to the voids between the aggregates not properly filled, and consequently reduces the strength. The increment in strength with nano silica addition is attributed to the following reasons; nano fills the pore structures of HVFA RCC up to nano size making the hardened RCC mix denser, high pozzolanic reaction of nano silica making it react consume surplus Portlandites produced during hydration process of cement and produces more C-S-H gel which is responsible for strength development and densification of the interfacial transition zone between crumb rubber and cement paste (Mohammed, Awang et al. 2016).

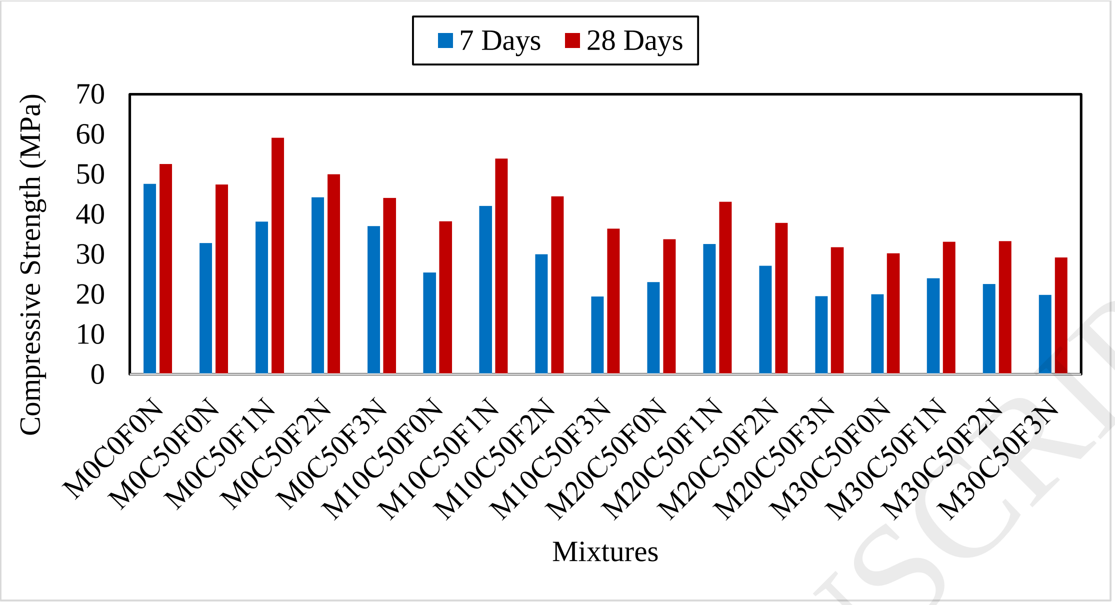

Fig 4. Compressive strength of HVFA RCC pavement mixtures

It can be observed from Fig 5a, tensile failure mode occurred on RCC pavement without any crumb rubber. The sample develops a single horizontal crack which developed catastrophically without any sign. The crack is parallel to the direction of load and this shows the rigid nature of conventional RCC pavement. On the other hand, as shown in Fig 5b, the failure mode of HVFA RCC pavement containing crumb rubber occurred after multiple cracks were formed on the surface of the specimen. This is the resulting gradual and delay in crack propagation, reduction in brittleness nature of the RCC. This occurs due to the higher elastic and deformation, elastic and fiber nature of crumb rubber which makes it absorb more strain energy and increase ductile behavior of HVFA RCC pavement.

a) Without crumb rubber

b) With crumb rubber

Fig 5. Failure mode of HVFA RCC pavement

3.3 Rebound Hammer

The rebound hammer test was used to measure the surface hardness of HVFA RCC pavement mixtures in terms of rebound number (RN) which was then translated to compressive strength. The average 28 days RN for HVFA RCC pavement mixtures is presented in Fig 5. The incorporation of HVFA as a partial replacement to cement decreases the surface hardness of RCC pavement. This can be observed by comparing the RN values of M0C0F0N with that of M0C50F0N. This is caused by the slower hydration (pozzolanic) reaction of fly ash at an early age which lowers the amount of C-S-H gel produced and increases. This resulted to increased porosity as the C-S-H gel is the main compound responsible for the pore filling effect and the calcium hydroxide eventually leached out thereby creating voids in the hardened RCC, and leads to a reduction in compressive strength and consequently lower RN (Neville 2011).

The RN for HVFA RCC mixtures decreases with increase in percentage replacement of fine aggregate with crumb rubber. This is due to the increased porosity of hardened HVFA RCC caused by the air entrained by the crumb rubber during mixing, which consequently reduces its surface hardness. Another reason is the resulting energy absorption capacity of crumb rubber making it absorb some of the echo impacted by the Schmidt hammer without transmitting it back for receiving the value (Mohammed, Azmi et al. 2011). The addition of nano silica up to 2% by weight of cementitious materials increases the surface hardness (RN) for HVFA RCC mixtures as shown in Fig 5. This is due to densifying the ITZ between crumb rubber particles and hardened cement paste which cause increasing in the surface hardness of RCC pavement and consequently increasing the RN readings (Mohammed, Awang et al. 2016). Another reason is due to the ability of nano silica to ignite the hydration (pozzolanic) reaction of fly ash at early age, which resulted from increased nucleation site effects by nano silica which helps in precipitating the hydration products from cement and silicon dioxide from fly ash, thereby accelerating rate of calcium hydrate silicate production which fills up the voids and densified the microstructure of HVFA RCC pavement matrix (Norhasri, Hamidah et al. 2017).

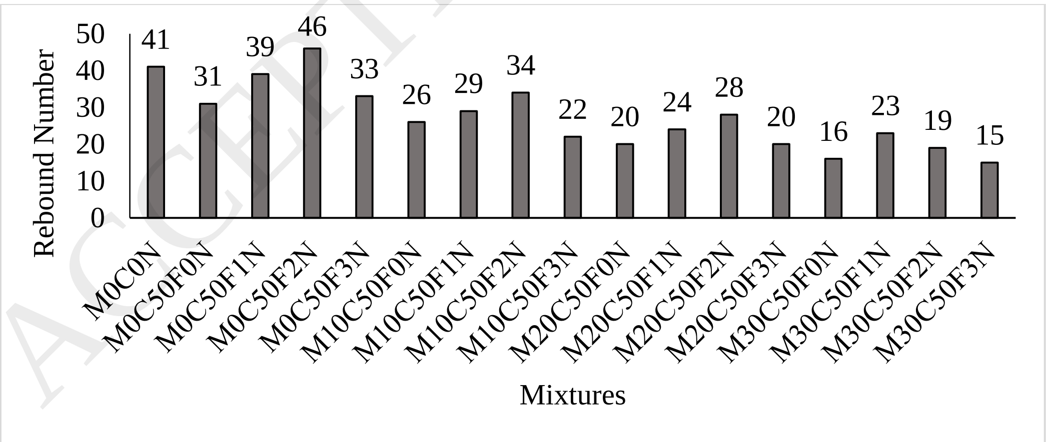

Fig 6. Rebound Number for HVFA RCC pavement

3.3.1 The relationship between compressive strength and Rebound Number of HVFA RCC pavement

The RN of concrete is used to evaluate its compressive strength with the help of correlation curves given on the Schmidt hammer, the difficulties and uncertainties experienced in using the calibration lead to the development of the correlations between compressive strength and RN (Tsioulou, Lampropoulos et al. 2017). Tsioulou, Lampropoulos et al. (2017) proposed linear, power and exponential relationships between compressive strength and RN of ultra-high performance fiber reinforced concrete. While Mohammed, Azmi et al. (2011), proposed an exponential relationship between compressive strength and RN of rubbercrete. Therefore in this study, linear, exponential and power relationships were developed for estimating the compressive strength of HVFA RCC pavement. As shown in Fig 6, the power relation has the best correlation degree and therefore is most suitable for the relationship between compressive strength and RN of HVFA RCC pavement.

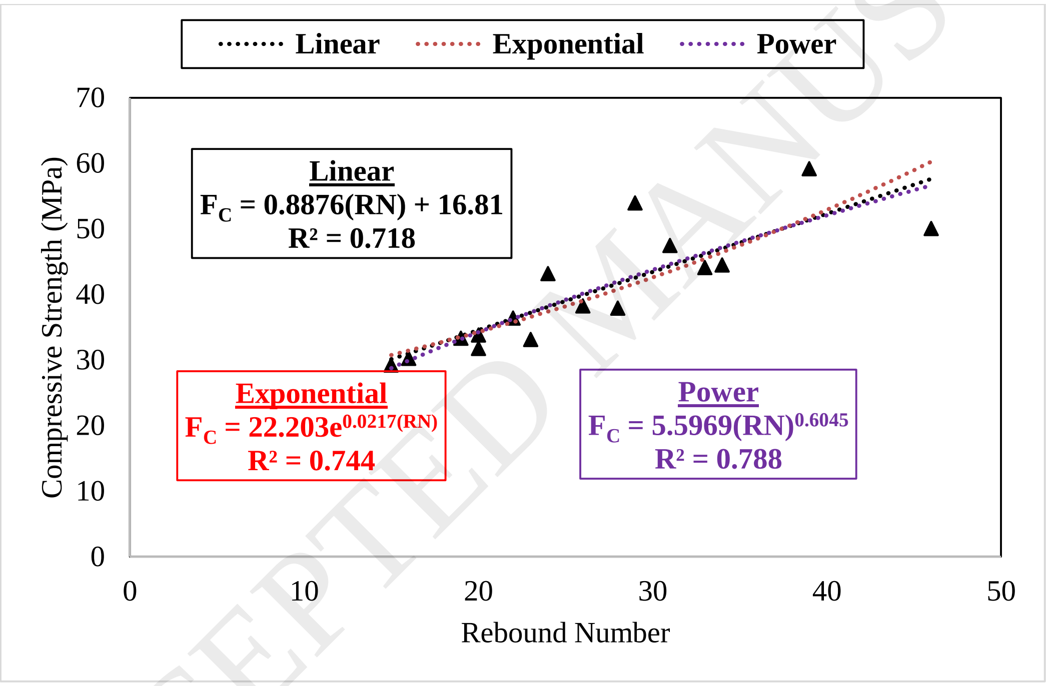

Fig 6. Relationship between compressive strength and RN of HVFA RCC pavement

3.4 Ultrasonic pulse velocity

The results of the 28 days UPV for HVFA RCC pavement mixtures is presented in Fig 7. By comparing the UPV value of M0C0F0N with that of M0C50F0N, It can be seen that the use of HVFA as a partial replacement to cement decreases the UPV values of RCC pavement. This is caused by the lower contribution of hydration (pozzolanic) reaction of fly ash at an early age. This resulted to the slower generation of C-S-H gel which is the main hydration product for pore filling effect and strength development. This leads to increase in porosity of the hardened matrix, thereby resulting in more discontinuities, decrease in strength and consequently lower UPV values (Rao, Sravana et al. 2016). The UPV values decrease with increase in partial replacement of fine aggregate with crumb rubber. In comparison with the control mixture (M0C50F0N), the UPV values of M10C50F0N, M20C50F0N, and M30C50F0N were lower by 3.90%, 13.54%, and 35.05% respectively. The decrease in UPV is caused by the air entrapped on the surface of the crumb rubber particles (due to its hydrophobic nature) during mixing which consequently leads to the more porous hardened rubbercrete mixture. This increases the discontinuities in the hardened HVFA RCC mixtures, thereby increasing the travel time of the ultrasonic pulse thus decreasing the UPV values (Mohammed, Azmi et al. 2011).

The UPV values OF HVFA RCC pavement increases with the addition of up to 2% nano silica as seen in Fig 7. This can be attributed to the same reasons mentioned in section 3.2 and section 3.3 for compressive strength and rebound number respectively.

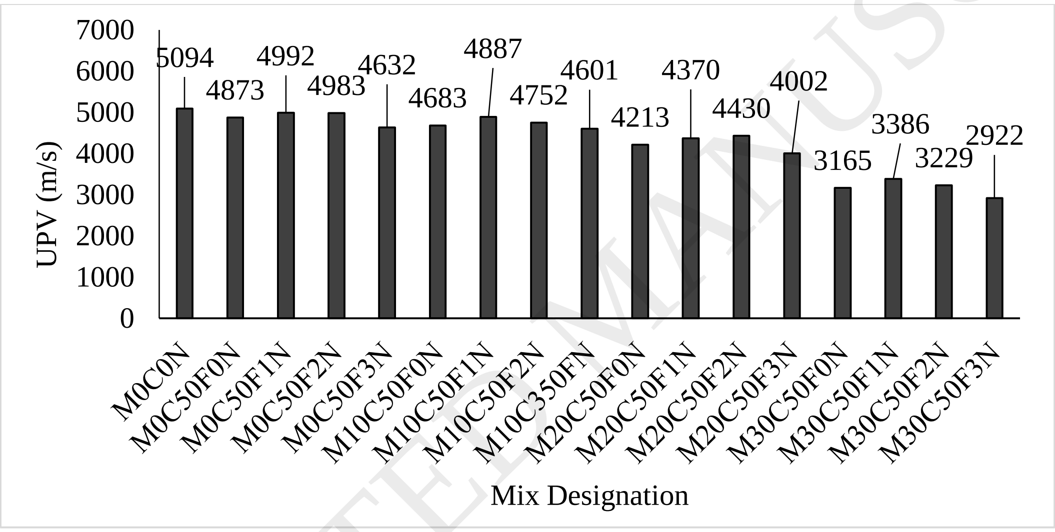

Fig 7. UPV for HVFA RCC pavement mixtures

The quality of HVFA RCC pavement in dry conditions can be classified based on Table 4 i.e. UPV classification of concrete in dry condition. By comparing the UPV values in Fig 7 with Table 4, HVFA RCC pavement containing up to 10% crumb rubber as a partial replacement to fine aggregate and 0% to 3% nano silica as an additive to cementitious materials has excellent quality. HVFA RCC pavement with up to 20% crumb rubber as a partial replacement to fine aggregate and 0% to 3% nano silica as an additive to cementitious materials are classified as having good quality. Finally, all HVFA RCC pavement mixtures with 30% crumb rubber as a partial replacement to fine aggregate and 0% to 3% nano silica as an additive to cementitious materials have a questionable quality.

Table 4: Ultrasonic pulse velocity classifications of concrete (Malhotra 1976, IS 13311-1 1992)

S/N	UPV range of values (m/s)	Concrete Classification
1	V > 4575	Excellent
2	4575 > V > 3660	Good
3	3660 > V > 3050	Questionable
4	3050 > V > 2135	Poor
5	V < 2135	Very poor

3.4.1 Relationship between compressive strength and UPV of HVFA RCC pavement

There is no standard correlation between UPV and compressive strength of concrete. Therefore, for each concrete mix, the relationship between compressive strength and UPV needs to be established, but the heterogeneous nature of concrete will leads to scattering correlation between them (Bogas, Gomes et al. 2013). Mohammed, Azmi et al. (2011) proposed an exponential relationship between compressive strength and UPV of rubbercrete. Rao, Sravana et al. (2016), proposed an exponential relationship between compressive strength and UPV of fly ash RCC pavement. Therefore in this study, exponential and power equations were used to establish the relationship between compressive strength and UPV of HVFA RCC pavement. From Fig 8, it can be seen that all the relationship between compressive strength and UPV has a reasonable correlation coefficient (R^2>0.65). The exponential relationship has the best degree of correlation, and therefore it is the most suitable for estimating the compressive strength of HVFA RCC pavement

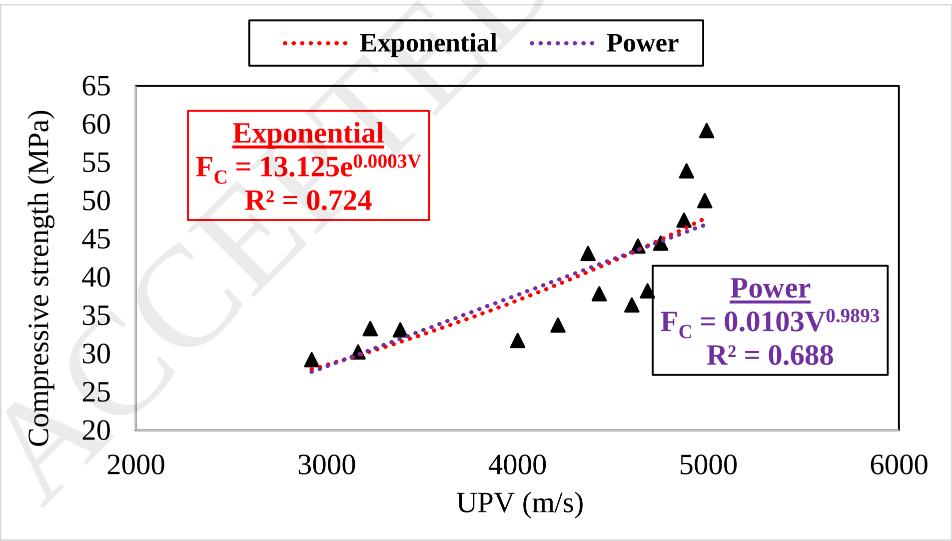

Fig 8: Relationship between compressive strength and UPV for HVFA RCC

3.5 Dynamic modulus of elasticity

The results of dynamic modulus of elasticity (DMOE) for all the HVFA RCC pavement mixtures is presented in Fig 9. The DMOE of RCC pavement decreases when HVFA was used to partially replace cement. The DMOE of mixture M0C50F0N was lower than that of M0C0F0N by 9.4%. This is caused by the slower pozzolanic reactivity of fly ash which resulted to increased porosity in the hardened matrix, thereby decreasing the UPV and unit weight, and consequently lower DMOE (Rao, Sravana et al. 2016). The DMOE of HVFA RCC pavement decreases as the percentage of the crumb rubber replacement to fine aggregates increases. The DMOE of for M10C50F0N, M20C50F0N, and M30C50F0N were less than for M0C50F0N by 13.11, 29.23% and 61.12% respectively. The decrease in DMOE with partial replacement of fine aggregate by crumb rubber is attributed to crumb rubber increases the porosity of HVFA RCC pavement, this resulted to increasing the path length through which ultrasonic wave travels, thereby decreasing the UPV, and consequently DMOE (Gupta, Chaudhary et al. 2016).

The addition of nano silica up to 2% by weight of cementitious materials increases the DMOE of HVFA RCC pavement with or without crumb rubber as shown in Fig 9. For example, the DMOE of M10C50F1N and M10C50F2N increases by 10.53% and 5.30% respectively. Similarly, the DMOE of M30C50F1N and M30C50F2N increases by 14.88 and 4.18% respectively. This increase is due to the pozzolanic reaction of nano silica with $Ca(OH)_2$ from cement hydration, this produces more calcium-silicate-hydrates (C-S-H) gel which densified the HVFA RCC pavement microstructure (Mohammed, Awang et al. 2016). This leads to increase in density and decrease the path length through which ultrasonic wave travel, thereby increasing UPV, and consequently DMOE.

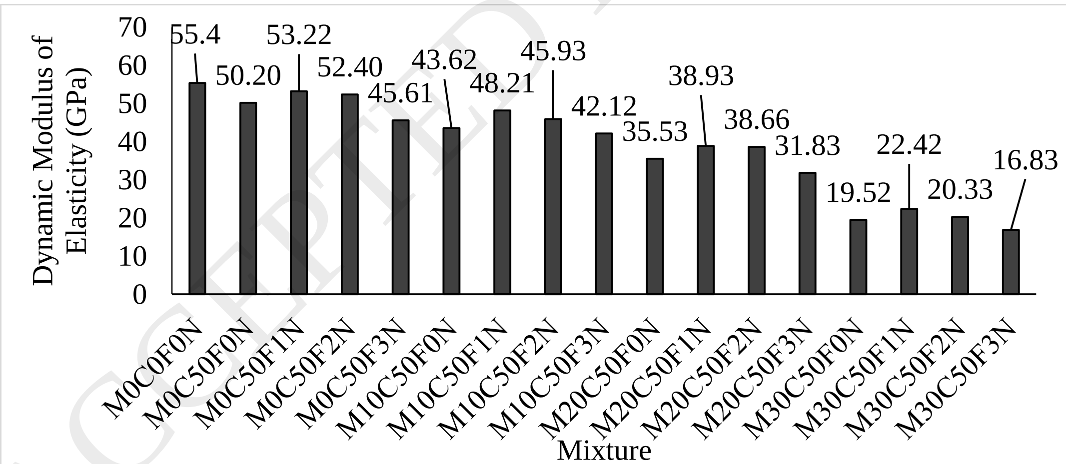

Fig 9. Dynamic modulus of elasticity for HVFA RCC pavement

3.5.1 Relationship between compressive strength and dynamic modulus of elasticity of HVFA RCC pavement

Different standards such as ACI 381, ACI 363 and the Euro code 2 developed standard relationships between static MOE and compressive strength of concrete. However, with respect to DMOE, no standard relationship was found. In this study, the logarithmic relationship was developed between DMOE and compressive strength of HVFA RCC pavement containing crumb rubber and nano-silica. As shown in Fig 10, the developed relationship has a good degree of correlations ($R^2 \geq 0.8$), and the DMOE of HVFA RCC pavement is directly proportional to compressive strength, meaning the higher the compressive strength the higher its DMOE will be.

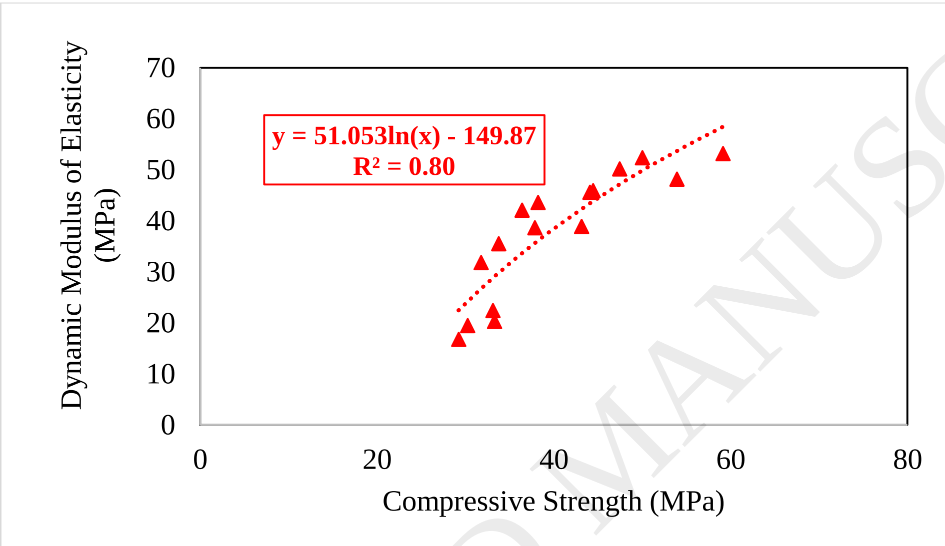

Fig 10. Relationship between DMOE and compressive strength of HVFA RCC pavement

3.6 Formulation of combined SonReb models for HVFA RCC pavement

SonReb models are multivariable regression developed using a combination sonic (UPV) and rebound number as the variables and they usually produce more accurate predicting the compressive strength and quality of concrete with less error and higher reliability. SonReb formulation is based on empirical methods using multivariable regression (Tsioulou, Lampropoulos et al. 2017). Different models have been developed for predicting concrete compressive strength by combining two variables i.e. ultrasonic pulse velocity and rebound hammer (SonReb method). The double power multivariable regression analysis is the most commonly used method as recommended by RILEM-43 CND (RILEM 43 - CND 1993). Although bilinear and double exponential models are also used (Breysse 2012). However, this is applicable to conventional concrete.

In this study, four model types were used for computing the SonReb formulations of HVFA RCC pavement and the best fitted is recommended. They are the double power, bilinear, double exponential, and quadratic models. For the double power model, the coefficients were calculated according to the method recommended by Proceq (Proceq 2013) using the Linest function in MS Excel, the exponential model was developed using the Logest function in MS Excel, while the coefficients of the other model types were determined using normal regression analysis by Microsoft Excel.

The developed combined SonReb models using double power, bilinear, double exponential, and quadratic models are presented in Eqns 2, 3, 4 and 5 respectively.

$$F_C = 0.548258 * V^{0.342022} * N^{0.440586} \tag{2}$$

$$F_C = 0.004877V + 0.566143N + 4.58532 \tag{3}$$

$$F_C = 15.77154 * 1.000136^{V} * 1.012785^{N} \tag{4}$$

$$F_C = 112.0361 - 0.04479V - 0.61831N + 3.87 \times 10^{-6} V^2 - 0.04841N^2 + 0.000858 * V * N \tag{5}$$

where F_C is the compressive strength in MPa; V is the UPV in m/s; N is the rebound number; a, b, c, and d are regression coefficients.

The model's analysis of variance (ANOVA) is shown in Table 5. The significance of each model can be explained using the 5% confidence interval. Therefore all the models have a very high significance as their P-Significance values are very low, with the double power model having the highest level of significance. In addition, the higher Fisher-Statistical values (F-Values) can also be used to verify the significance of each model. The goodness of fit (degree of correlation) for each model with respect to the experimental data can also be verified using the R^2 values. An R^2 value of 1 implies perfect correlation. Therefore, all the models can be said to have a good degree of correlations as their R^2 values are greater than 0.75. This is to say the predicted models are in agreement with the experimental data. Furthermore, the quadratic model is the found to be the best in terms of goodness of fit. In terms of error, all the models have a lower standard error as it less than 5. However, the quadratic models have higher standard errors compared to the exponential and power SonReb models. Therefore, the double exponential model can best be used to formulate the SonReb models due to its high degree of correlation, lower standard error, and higher statistical significance. These models which are in contrary to that of normal concrete recommended by RILEM-43 CND.

Table 5: ANOVA summary for combined SonReb models

Model Type	R^2	Adjusted R^2	Standard Error	F – Values	P – Significance
Double power	0.812	0.783	0.0998	28.021	0.0000193
Bilinear	0.772	0.737	4.576	21.970	0.0000677
Exponential	0.817	-	0.098	29.103	-
Quadratic	0.872	0.807	3.900	13.679	0.000335

The adequacy and degree of the developed models were checked graphically by plotting the predicted strength based on the developed models versus the actual strength from experimental work as shown in Fig 11. It can be seen that for all model types, the predicted compressive strengths were in agreement with the actual compressive strength. This can be verified as the data points fitted along the straight trend lines. The exponential model type was found to have the best fit followed by the quadratic model, while the power model has the least fitness compared to other model types. Therefore all the developed models can be used to predict the compressive strength of HVFA RCC pavement using a combination of UPV and RN as the variables.

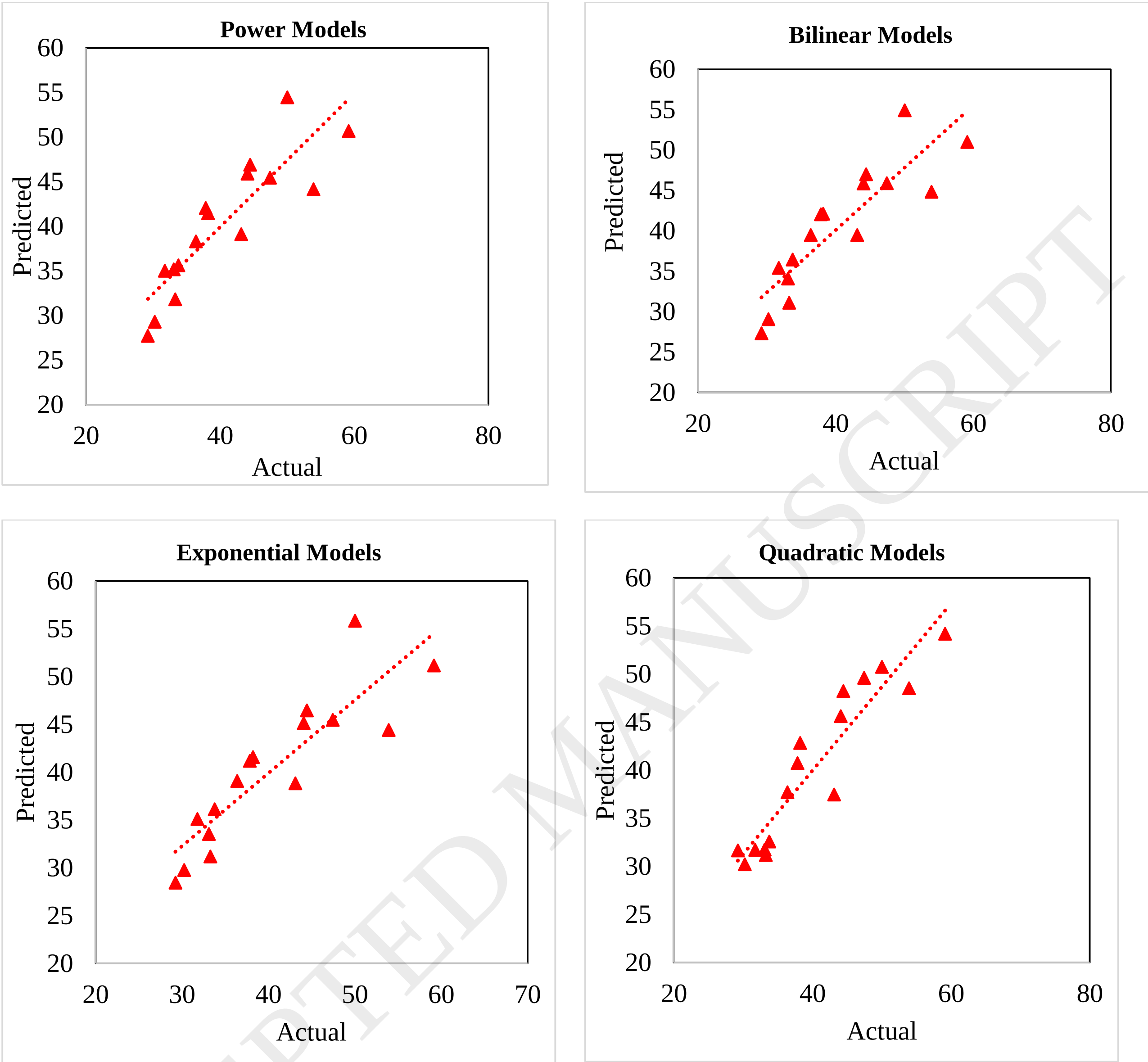

Fig 11. Predicted versus actual compressive strength of HVFA RCC pavement based on SonReb models

4. Conclusions

The following conclusions were drawn based on the experimental work carried out and results analysis.

- The use of high volume fly ash (HVFA) as a partial replacement to cement in RCC pavement results to decreased unit weight, compressive strength, surface hardness (RN), UPV and dynamic modulus of elasticity.

- The incorporation of crumb rubber as a partial replacement to fine aggregate in HVFA RCC pavement leads to decrease in unit weight, compressive strength, and surface hardness (RN), UPV and dynamic modulus of elasticity.
- Nano silica increases the unit weight, compressive strength, surface hardness (RN), UPV, and dynamic modulus of elasticity of HVFA RCC pavement.
- Nano silica was successful in improving the early strength development in HVFA RCC pavement by igniting pozzolanic reactivity of fly ash at an early age.
- Nano silica was successful in mitigating the loss of compressive strength in HVFA RCC pavement when 10% crumb rubber was incorporated as a partial replacement to fine aggregate. For higher crumb rubber contents, nano silica partially mitigated the loss of compressive strength.
- A high degree of correlation exists between compressive strength – UPV, compressive strength – RN, and compressive strength – dynamic modulus of elasticity of HVFA RCC pavement.
- The exponential combined SonReb model is the most suitable for predicting the compressive strength of HVFA RCC pavement using UPV and RN as the independent variable.
- The combined SonReb model (multi-variable model) has the better predicting ability, higher correlation compared to the single variable models.

Conflict of Interest

The authors declare that they have no conflict of interest

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