# EVALUATION OF DYNAMIC ELASTIC MODULUS OF ROLLER COMPACTED CONCRETE CONTAINING GGBS AND M-SAND

By

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***ABSTRACT***

*Use of industrial by-products such as Ground Granulated Blast furnace Slag (GGBS) as one of the raw materials in Roller Compacted Concrete Pavement (RCCP) is appropriate to deal with the sustainability of concrete and industrial growth. The present experimental investigation assesses the potential of GGBS in roller compacted concrete for pavement applications. The fine aggregate used in the investigation was Manufactured sand (M-sand) in place of natural river sand. The Ultrasonic Pulse Velocities (UPV) was determined at various ages varying from 1 day to 90 days of curing. The GGBS is used as partial replacement of Cement at the range varying from 10% to 60% by weight. The UPV of GGBS Roller Compacted Concrete Pavement (GRCCP) was lower for all mixtures at 1 day when compared to control mix concrete. However as the age of concrete increases the Ultrasonic pulse velocities were appreciably improved for all the mixes. Empirical relationships between strength, UPV and Dynamic Elastic Modulus were proposed. A new model is proposed to determine the Dynamic Elastic Modulus of GRCC.*

*Keywords: Compressive Strength, Dynamic Elastic Modulus, GGBS, Roller Compacted Concrete, Ultrasonic Pulse Velocity.*

## INTRODUCTION

The River sand has been used mainly as fine aggregate in the construction industry. The infrastructural development that took place in the world leads to the demand for river sand. As the supply of suitable natural sand material near to the source of construction is becoming exhausted, the cost of the sand is increasing. Therefore, a replacement material for river sand is needed and the finer materials from crushing operations are more suitable as substitute materials. Since the supply of River sand is limited and its continuous supply is not guaranteed, use of Manufactured Sand (M-Sand) as an alternative to River sand has become inevitable. ICAR (The International Center of Aggregates Research) research project work was shown that concrete can successfully be made using unwashed M-sand without modifying the sand. With the use of manufactured sand in concrete there was increase in flexural strength, improved abrasion resistance, increased unit weight and lowered permeability [44].

In the recent past, there has been enormous increase in the usage of mineral admixtures in concrete such as Fly ash and Ground Granulated Blast Furnace Slag (GGBS) and it became one of the ingredients of concrete [1-12]. The American Concrete Institute (ACI) defines Roller Compacted Concrete (RCC) as the concrete compacted by roller compaction [24]. RCC is a stiff and extremely dry concrete and has a consistency of wet granular material or wet moist soil. The use of RCC as paving material was developed from the use of soil cement as base material. The first use of RCC pavement was in the construction of Runway at Yakima, WA in 1942 [25]. The main advantage of RCC over conventional concrete pavement is speed in construction and cost saving. RCC needs no formwork, dowels and no finishing [26].

The GGBS is a mineral admixture which is obtained from the pig-iron in blast furnaces as a by-product and it derives from the minerals contained in iron ore, flux ashes and foundry coke. It consists of mainly Calcium alumina-Silicates and is essential for producing hydraulic binder. It is used as partial replacement of cement in concrete for reducing the heat of hydration, improving mechanical properties and reduces the permeability of concrete [4, 13].

Ultrasonic Pulse Velocity (UPV) is the main destructive method of testing of concrete quality, homogeneity and compressive strength of existing structures. This method is also a useful tool in evaluating dynamic modulus of elasticity of concrete [14, 15]. The Dynamic modulus of Elasticity ($E_d$) is an essential and important factor when assessing the quality and performance of structural concrete. The UPV is an useful parameter for estimation of static modulus of elasticity, dynamic modulus of elasticity, static Poisson's ratio and dynamic Poisson's ratio [16].

### 1. Literature Review

Wen Shi –You, Li Xi – Bing [17] conducted an experimental study on Young's Modulus of concrete through P-Wave velocity measurements. They proposed two empirical equations for obtaining static Young's Modulus and Dynamic Young's Modulus when dynamic Poisson ratio varies around 0.20. Hisham Y. Qasrawi (2000) [18] proposed an empirical equation between UPV and Cube Compressive strength of Concrete and its $R_2$ value was found to be 0.9562. Subramanian V. Kolluru et al (2000) [19] proposed a technique for evaluating the elastic material constants of a concrete specimen using longitudinal resonance frequencies using Rayleigh- Ritz method. They developed a simple, accurate and more reliable method for determining dynamic elastic constants of concrete. The wave velocities are related to the material elastic constants by,

$$V_L = \sqrt{\frac{E(1-\mu)}{(1+\mu)+(1-2\mu)\rho}} \quad (1)$$

$$V_S = \sqrt{\frac{E}{2(1+\mu)\rho}} \quad (2)$$

where $V_L$ = longitudinal wave velocity m/s,

$V_S$ = Shear wave velocity m/s,

E = Dynamic Modulus of Elasticity (Gpa), and

$\mu$ = Dynamic Poisson's Ratio,

Ismail Ozgur Yaman et al. (2001) [20] investigated the use of indirect UPVs in Concrete slabs and found similarity between direct and indirect UPVs. Their significant conclusion is that the indirect UPV is statistically similar to direct UPV. N.K. Choudhari et al (2002) [21] proposed a methodology to determine the elastic modulus of concrete by Ultrasonic method. Their proposed equations are as follows:

$$\sigma = \frac{(t_S^2 \; -2t_L^2}{2(t_S^2 - t_L^2\,)} \quad (3)$$

$$E_c = E_d + \left(\frac{5.9}{1.5}\right), GPa \quad (4)$$

where σ = Poisson's Ratio,

$t_s$ and $t_L$ are the time of flight displayed on the pulse velocity instrument for longitudinal velocity and shear velocity respectively.

$E_c$ = Static Modulus of Elasticity of Concrete, and

$E_d$ = Dynamic Modulus of Elasticity of Concrete

M. Conrad et al (2003) [22] investigated stress-strain behavior and modulus of elasticity of young Roller Compacted concrete from the ages of 6 hours to 365 days. They found that the Young's Modulus for the early ages for aged low cementitious RCC can be by an exponential type function. This function can be written as:

$$E_c(t) = E_{c,\alpha} \exp\,(a.\,t^b) \quad (5)$$

$E_c$ (t) = Time dependent Modulus [GPa],

$E_c\,\alpha$ = Final modulus of elasticity [GPa],

t = Concrete age [days],

a, b are model parameters

Glenn Washer et al (2004) [23] conducted an extensive research on Ultrasonic Testing of Reactive powder concrete. Ultrasonic pulses were generated using high power ultrasonic instrument in three different geometric shapes (Cube, Cylinder and Prism). Average P-wave velocity and average S- Wave velocity were found. From the following expressions the elastic constants of concrete were found.

$$V_L = \sqrt{\frac{(\lambda+2\mu)}{\rho}} \quad (6)$$

$$V_S = \sqrt{\frac{\mu}{\rho}} \quad (7)$$

where

$V_L$ = Longitudinal Velocity,

$V_S$ = is the shear wave velocity, and

λ, $\mu$ are Lame` Constants.

Lame` Constants have direct relation to engineering constants like Young's Modulus of Elasticity (E), Shear Modulus (G) and Poisson's Ratio v, according to the relations :

$$E = \frac{\mu(3\lambda + 2\mu)}{(\lambda + \mu)} \quad (8)$$

$$\nu = \frac{\lambda}{2(\lambda + \mu)} \quad (9)$$

$$G = \mu \quad (10)$$

Ramazan Demirboga et al (2004) [34] found a relationship between ultrasonic velocity and compressive strength of concrete using different mineral admixtures such as High Volume Fly ash, Blast Furnace Slag and FA+BFS in replacement of Portland Cement. Compressive strength, UPV values are determined at 3,7,28 and 120 days of curing period. They reported that the relationship between compressive strength and UPV were exponential. They proposed the relationship in the following form:

$$f_c^! = 0.008 e_c^{0.02V} \quad (11)$$

where

$f_c^!$ = Compressive Strength= MPa

V= UPV in m/s

U. Atici (2011) [35] estimated the compressive strength of concrete containing various amounts of blast furnace slag and fly ash through non destructive tests like rebound hammer and ultrasonic pulse velocity tests at different curing ages of 3,7,28,90 and 180 days. They used two different methods of estimation of concrete strength by artificial neural network and multivariable regression analysis and concluded that the application of an artificial neural network had more potential in predicting the compressive strength of concrete than multivariable regression analysis.

Gregor Trtnk et al. (2009) [36] proposed a numerical model for predicting the compressive strength of concrete based on Ultrasonic Pulse Velocity and some concrete mix characteristics. T.H. Pazera et al. (2004) [37] published a paper on Ultrasonic Pulse Velocity evaluation of cementitious materials and emphasized the significance of UPV as an important non-destructive technique and provides reliable results on the basis of rapid measurements.

P. Turgut, (2004) [38] proposed a relationship between the concrete strength and UPV and the relation is as follows:

$$S = 1.146 e^{0.77V_p} \quad (12)$$

Where S= Strength of Reinforced concrete member in Mpa, and

$V_p$ = Velocity , Km/s

Samia Hannachi et al. ( 2012) [39] studied the use of UPV and Rebound Hammer tests on the compressive strength of concrete and proposed three equations for rebound hammer, UPV and combined methods for predicting the compressive strength of concrete.

### *2. Scope of the Research Work*

There were many studies carried out in relation with UPV, but the relationship between UPV and the Elastic and Mechanical properties of GGBS Roller Compacted Concrete has not been investigated. GGBS has become an essential mineral admixture for producing good pavement quality concrete and the same can be used in the design and construction of low volume rural roads. The findings of this experimental investigation will be useful in predicting the quality and behavior of RCC made with GGBS intended for lean concrete bases and cement concrete surface courses and similar applications. This research work was focused on the relationship between Elastic properties, strength properties and UPV.

## 3. Experimental Program

### *3.1 Raw Materials*

Ordinary Portland Cement (OPC) of 53 Grade was used in the present experimental investigation. Cement was tested as IS 4031[27]. Ground Granulated Blast furnace Slag (GGBS) used in this research project was collected from the Toshali Cements Pvt Ltd located at Visakhapatnam District, Andhra Pradesh, India. The GGBS was ground in a laboratory mill to a Blaine fineness of 4222 $cm^2/g$. The properties of cement and GGBS and (Figure 1) are given in Table 1 and Table 2 respectively. Local aggregate available in the area were used in the study, namely Manufactured sand (M-sand) as fine aggregate and coarse aggregate of Nominal Maximum size of 19mm were used (Figure 2). Some of the physical properties of aggregates are shown in Table 3. The particle size distribution curves of fine, coarse and combined aggregate was shown in Figure 2 and Figure 3 respectively. The fine aggregate and coarse aggregate were conforming to BIS:383-1970 [28]. Potable drinking water is used in the preparation of all RCC mixtures.

### *3.2 Mixture*

Seven mixtures prepared and the details of mix proportions were given in Table 4. The concretes produced are designated as G0, G10, G20, G30, G40, G50 and G60 on the basis of percent replacement of GGBS into it. All the mixes were designed for a specified flexural strength of 5.0 MPa. [11,12, 30, 31, 32, 48, 49, 50, 51]. The mix design was based on soil compaction

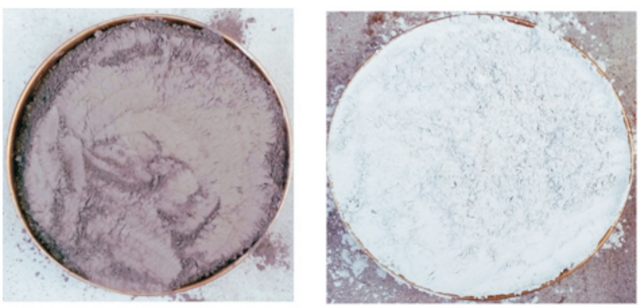

Figure 1. Cement and GGBS


Figure 2. Particle Size Distribution of Fine Aggregate (M-Sand)

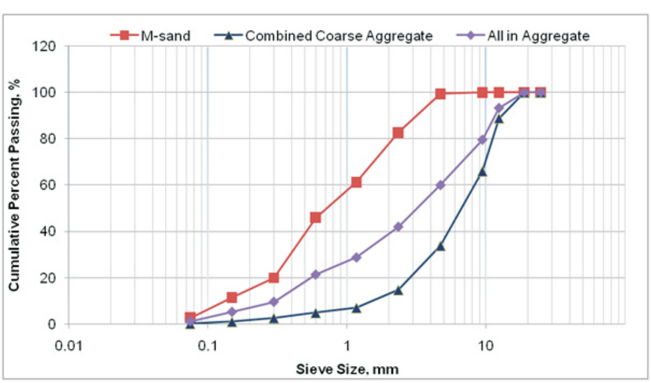


Figure 3. Particle Size Distribution of all in Aggregate

| Element | Weight Percentage |
|---|---|
| $SiO_2$ | 34.4 |
| $Fe_2O_3$ | 2.65 |
| $Al_2O_3$ | 15.6 |
| CaO | 33.1 |
| MgO | 8.9 |
| $Na_2O$ | 0.62 |
| $K_2O$ | 0.6 |
| $So_3$ | 2.46 |
| Loss Ignition | 1.01 |

Table 1. Chemical Composition of GGBS (toshali Cements Pvt Ltd located at Visakhapatnam District, Andhra Pradesh, India)

| Components | % Mass |
|---|---|
| $\frac{(CaO-0.7SO_3)}{(2.8SO_2+1.2Al_2O_3+0.65Fe_2O_3)}$ | 0.953 |
| $\frac{Al_2O_3}{Fe_2O_3}$ | 1.218 |
| Total loss on Ignition | 1.80 |

Table 2. Chemical Composition of Cement

| S.No. | Property | Test Value | |
|---|---|---|---|
| | | Fine Aggregate | Coarse Aggregate |
| 1 | Specific Gravity | 2.88 | 2.88 |
| 2 | Sieve Analysis Test results | Particle Size Distribution Curve shown in Figure 3. | |
| 3 | Water absorption | 0.1% | 0.5% |
| 4 | Aggregate Impact Value, % | - | 21.50 |
| 5 | Aggregate crushing value, % | - | 20.40 |
| 6 | Combined Flakiness & Elongation Value, % | - | 21.90 |

Table 3. Properties of Aggregate

principles and ACI 211.3R [29] guidelines. The cement content of control mix of RCC was 295 kg/m$^3$. In six RCC mixtures 10, 20, 30, 40, 50 and 60% by weight of cement were replaced with mineral admixture i.e. GGBS. The coarse aggregate of NMSA of 19mm was used in the RCC mixtures. The identification of mix proportions and quantity of material are given in Table 4.

### *3.3 Preparation, Casting and Testing of Specimens*

#### *3.3.1 Compressive Strength*

Compressive strength of roller compacted concrete specimens was measured at 1,3, 7, 14, 28 and 90 days of curing age as per IS 516 [33]. The specimens were casted and demoulded after 24 hours and kept for curing. Then they were tested in compression testing machine of 3000 KN capacity by applying load at the rate of 4.5 KN/sec until the resistance of the cube to the applied load breaks down (Figure 4). The test results are presented in Table 5.

*3.3.2 Ultrasonic Pulse Velocity Test*

To test the quality of the concrete and also to check the cracks and voids in the concrete, the most convenient and non-destructive method is Ultrasonic Pulse Velocity (UPV) method. Ultrasonic wave's frequencies are in the range of 20 kHz-150 kHz, which is higher than upper audible limit (20 kHz) and the main reason to take this frequency range is its path length is in the range of 1500mm to 500mm.

This method consists of one ultrasonic pulse generator, two transducers and CRO and a digital time display unit. The transducer is a device which can transform any physical quantity like temperature, pressure, sound, etc into electrical quantity voltage or current waves and vice versa. There are different types of transducers available like temperature transducer, pressure transducer, ultrasonic transducers etc. At one end of the concrete ultrasonic pulse generator and transducer and at the opposite end, second transducer is connected. Both the transducers are connected to the concrete using jelly or grease. The first transducer or transmitting end transducer receives the ultrasonic pulse and converts it into electrical waves and this signal is induced into concrete. These waves travel in three types through concrete. Some of the waves travel a long distance through concrete and reach the receiving transducer. These are called longitudinal waves. These longitudinal waves are important in the measurement of wave velocity. Some waves travel perpendicular to the longitudinal waves (wave propagation) and these are called transverse or shear waves. Surface waves or Rayleigh waves travel at the surface of the concrete at a depth of one wavelength. These waves travel in elliptical orbit.

| Concrete Mix | Mix Proportion (Kg/m$^3$) | | | | | |
|---|---|---|---|---|---|---|
| | Cement | GGBS | CA | M-Sand | w/c | VeBe, Sec |
| G0 | 295 | 0 | 1209 | 801 | 0.38 | 54 |
| G10 | 265 | 30 | 1209 | 801 | 0.39 | 41 |
| G20 | 235 | 60 | 1209 | 801 | 0.40 | 40 |
| G30 | 205 | 90 | 1209 | 801 | 0.42 | 35 |
| G40 | 175 | 120 | 1209 | 801 | 0.44 | 28 |
| G50 | 145 | 150 | 1209 | 801 | 0.49 | 24 |
| G60 | 115 | 180 | 1209 | 801 | 0.52 | 18 |

Table 4. Quantities of materials per one m$^3$ of RCCP of 5 N/mm$^2$ Flexural Strength


Figure 4. Compression Test on GRCCP Specimens

| Concrete Mix | Compressive Strength of GRCC, N/mm$^2$ | | | | | |
|---|---|---|---|---|---|---|
| | 24 hours | 3 days | 7 days | 14 days | 28 days | 90 days |
| Control Mix | 9.11 | 18.67 | 22.22 | 30.41 | 33.74 | 45.2 |
| G10 | 7.88 | 15.1 | 28.65 | 37.56 | 45.51 | 52.37 |
| G20 | 7.05 | 14.65 | 30.1 | 39.27 | 47.02 | 54.66 |
| G30 | 6.66 | 13.27 | 31.44 | 42.26 | 47.86 | 57.87 |
| G40 | 5.45 | 12.71 | 33.42 | 45.63 | 48.32 | 59.91 |
| G50 | 5.74 | 12.24 | 32.03 | 42.32 | 46.41 | 58.11 |
| G60 | 5.12 | 11.73 | 31.87 | 39.36 | 44.32 | 57.34 |

Table 5. Compressive Strength Test results of 150mm x 150mm cube

The first transducer and the second transducer output probes are connected to the Digital time display unit. The Digital time display unit displays the time taken by the ultrasonic pulse to travel through the concrete. The same result can be obtained using CRO display (cathode Ray Oscilloscope). The output of the first transducer is connected to the x-channel of the CRO and the output of the Receiver transducer is connected to y-channel of CRO. The time between these two pulses leading edges gives the time elapsing between $T_x$ and $R_x$ pulses (Figure 5). If the pulse velocity is high, it indicates the best quality of the concrete.

For the assessment of compressive strength of concrete, UPV is not sufficient, since a large number of parameters are like materials and its mixed proportions, environmental conditions. etc., are required. The Dynamic Young's Modulus velocity can be determined from the Ultrasonic Pulse Velocity test method [15].

The principle of this test was that the velocity of sound in a solid material like concrete, ehich V is a function of the square root of the ratio of E and its density (d).

$$V = f\left(\frac{gE}{d}\right)^{1/2} \qquad (13)$$

g= acceleration due to gravity, m/sec$^2$

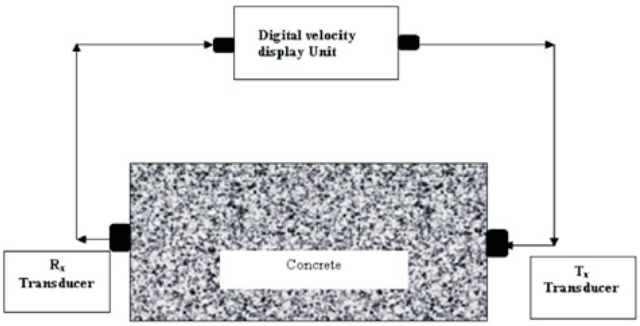


Figure 5. Ultrasonic Pulse Velocity Test Set up

The time the pulses take to travel through the concrete specimen recorded. Then the velocity is equal to

$$V = \frac{L}{T} \quad (14)$$

Pulse velocity (m/s)

Length of travel (m)

Effective time (s)

Once the velocity is determined, the concrete quality, uniformity, strength, density and condition can be attained. Table 6 is suggested by IS 13311(Part1): 1992 [15] and shows the use of velocity obtained from the test to classify the quality of concrete. The UPV testing (Figure 6) on cube specimens of all seven mixtures was carried out as per IS: 13311(Part1): 1992[15]. The UPV tester PUNDIT (Figure 8) equipment consists of ultrasonic tester, two transducers, i.e. one receiver head of 54 kHz and one transmitter. Tests were conducted on each cube specimen on three facets namely Facet 1( $F_1$)i.e. casting direction, Facet ($F_2$) and Facet 3($F_3$) for all specimens at respective ages of RCC mixes as shown in Figure 7.

The following formula is used for calculating the dynamic modulus of elasticity of Roller compacted concrete [1]

$$E_d = \frac{\rho(UPV)^2(1+\mu)(1-2\mu)}{(1-\mu)} \quad (15)$$

$E_d$ = Dynamic Modulus of elasticity in MPa

r= Density of concrete in $KN/m^3$

UPV=Ultrasonic Pulse Velocity in Km/s

$\mu$=Poisson's Ratio of concrete

For the purpose of calculations in this experimental work, = 2450 KN/m3 and $\mu$= 0.2 have been assumed [40]. The test results are presented in Table 7 and Table 3.

| S.No | Pulse Velocity Cross Probing, Km/Sec | Concrete Quality Grading |
|---|---|---|
| 1 | > 4.5 | Excellent |
| 2 | 3.5 – 4.5 | Good |
| 3 | 3.0 – 3.5 | Medium |
| 4 | < 3.0 | Doubtful |

Table 6. Quality of concrete as a function of UP

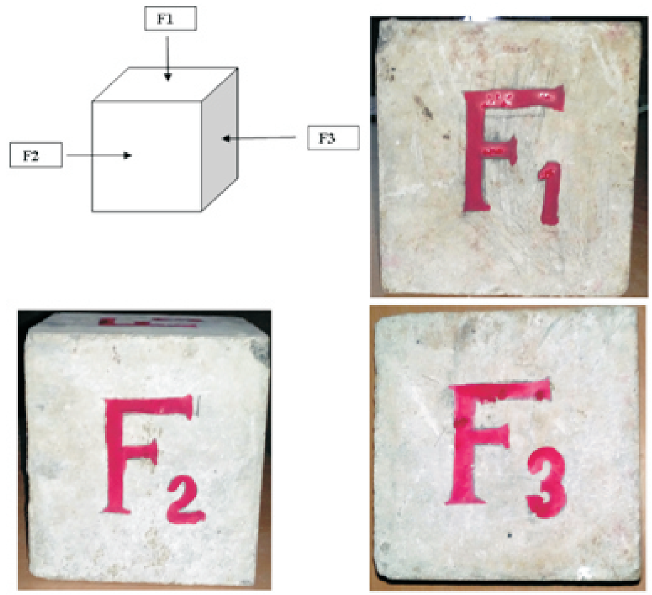


Figure 6. Cube Specimen Facet $F_1$, $F_2$ and $F_3$

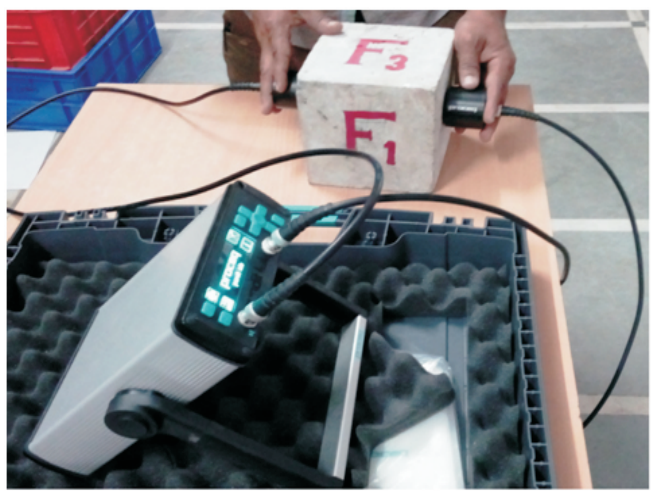

Figure 7. UPV Measurement on $F_1$, $F_2$ and $F_3$ of a Cube Specimen

## 4. Results and Discussion

Following are the observations made from various test results and have been discussed under the following sub headings.

Figure 8. Ultrasonic Pulse Velocity Test apparatus

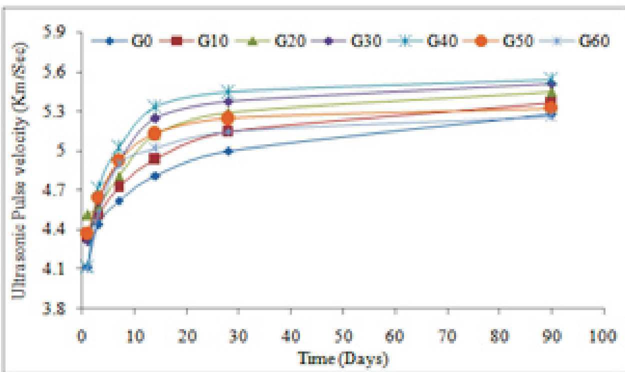


Figure 9. Progression of UPV with time for GRCC Mixes

### *4.1 Effect of GGBS on Ultrasonic Pulse Velocity of RCC with Time*

The experimental progression of UPV of Control Mix and GGBS Roller Compacted Concrete (GRCC) with the age was shown in Figure 9 and Table 8 for RCC Mixes from G0 to G60 (Total seven mixtures). The Ultrasonic Pulse Velocity of GRCC mixes increases with increase in curing age of roller compacted concrete for all the mixes as expected. Also the UPV of GRCC mixes was found to be higher than the control mix (G0) for all replacement levels up to 40% replacement at all ages for all mixes. The increase in UPV from 24 hours to 3 days is at a slower rate, but beyond 3 days to 90 days the UPV increases rapidly. This is due to the fact that the hydration rate is slow at initial ages with GGBS and faster at later ages.

### *4.2 Effect of GGBS on Quality of Roller Compacted Concrete and UPV with Age*

Table 6 give the range of UPV qualitative rating as per IS: 13311(Part 1): 1992 [12]. A value of above 4.5 Km/s shows the concrete with excellent quality. For good concrete, the UPV shall be varying between 3.5- 4.5 Km/s; for medium quality concrete, the UPV shall be between 3.0 – 3.5 Km/s. The effect of GGBS on the quality of RCC mixtures with curing age for all mixes was shown in Table 9.

The quality assessment of RCC of control mix with age shows that the quality of RCC is found to be good at early ages of 1 and 3 days. However, as the time increases from 3 days to 90 days, the quality of concrete changes from good to excellent for control mix (G0). Similar trend has been observed for mixtures G10 to G60, when cement was partially replaced with GGBS from 10 % to 60 %.

Amongst the GRCC mixtures from G0 to G60, G40 mix shows good to excellent quality and higher UPV values in comparison with other mixes. Hence 40% GGBS replacement has been considered as an optimum replacement level in GRC mixtures. Table 9 shows the effect of GGBS on quality of RCC Mixtures with age.

### *4.3 Relationship between Compressive Strength and UPV of RCC Mixes*

From the literature review, it was concluded that there is no definite relationship was existing between UPV and compressive strength of Roller Compacted Concrete. Hence a relationship between compressive strength of RCC mixtures with different replacement levels of GGBS and UPV has been developed. Figure10 and Figure 10 (e,f,g) shows the relationship between compressive strength of GRCC mixtures (G0, G10,G20, G30,G40, G50 and G60) and UPV at all ages. Figure 10 (a-g) can be used to assess the compressive strength of control mix (G0) and GRCC (G10, G20, G30,G40, G50 and G60) at any age of concrete. From the experimental results, exponential relationship between cube compressive strength and UPV of control mix (G0) and GRCC mixtures containing 10%, 20%, 30%, 40%, 50% and 60 % GGBS respectively has been proposed as under:

$f_c = 0.043e^{1.335(UPV)}$, $R^2 = 0.954$ for Control Mix (G0) (16)

$f_c = 0.004e^{1.792(UPV)}$, $R^2 = 0.889$ for 10% GGBS (G10) (17)

$f_c = 0.002e^{1.905(UPV)}$, $R^2 = 0.855$ for 20%GGBS (G20) (18)

$f_c = 0.003e^{1.780(UPV)}$, $R^2 = 0.961$ for 30% GGBs (G30) (19)

$f_c = 0.004e^{1.720(UPV)}$, $R^2 = 0.975$ for 40%GGBS (G40) (20)

| Concrete Mix | UPV, Km/s | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 24 hours | | | | 3 Days | | | | 7 Days | | | |
| | $F_1$ | $F_2$ | $F_3$ | Avg | $F_1$ | $F_2$ | $F_3$ | Avg | $F_1$ | $F_2$ | $F_3$ | Avg |
| G0 | 4.03 | 4.11 | 4.22 | 4.12 | 4.32 | 4.48 | 4.52 | 4.44 | 4.513 | 4.627 | 4.723 | 4.621 |
| G10 | 4.26 | 4.38 | 4.41 | 4.35 | 4.38 | 4.56 | 4.59 | 4.51 | 4.687 | 4.739 | 4.737 | 4.721 |
| G20 | 4.27 | 4.58 | 4.68 | 4.51 | 4.42 | 4.64 | 4.68 | 4.58 | 4.792 | 4.817 | 4.824 | 4.811 |
| G30 | 4.02 | 4.5 | 4.41 | 4.31 | 4.51 | 4.66 | 4.69 | 4.62 | 4.904 | 4.932 | 4.939 | 4.925 |
| G40 | 3.82 | 4.3 | 4.24 | 4.12 | 4.57 | 4.75 | 4.81 | 4.71 | 5.005 | 5.028 | 5.036 | 5.023 |
| G50 | 4.27 | 4.39 | 4.45 | 4.37 | 4.53 | 4.68 | 4.71 | 4.64 | 4.909 | 4.932 | 4.937 | 4.926 |
| G60 | 3.79 | 4.32 | 4.22 | 4.11 | 4.39 | 4.55 | 4.59 | 4.51 | 4.879 | 4.891 | 4.894 | 4.888 |

Table 7. Ultrasonic Pulse Velocity Test results (1, 3, 7 Days)

| Concrete Mix | UPV, Km/s | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 14 Days | | | | 28 Days | | | | 90 Days | | | |
| | $F_1$ | $F_2$ | $F_3$ | Avg | $F_1$ | $F_2$ | $F_3$ | Avg | $F_1$ | $F_2$ | $F_3$ | Avg |
| G0 | 4.792 | 4.819 | 4.825 | 4.812 | 4.987 | 5.003 | 5.007 | 4.999 | 5.264 | 5.282 | 5.285 | 5.277 |
| G10 | 4.921 | 4.938 | 4.946 | 4.935 | 5.132 | 5.149 | 5.151 | 5.144 | 5.351 | 5.369 | 5.372 | 5.364 |
| G20 | 5.104 | 5.129 | 5.136 | 5.123 | 5.278 | 5.29 | 5.293 | 5.287 | 5.431 | 5.449 | 5.452 | 5.444 |
| G30 | 5.233 | 5.248 | 5.254 | 5.245 | 5.363 | 5.379 | 5.383 | 5.375 | 5.501 | 5.516 | 5.519 | 5.512 |
| G40 | 5.312 | 5.339 | 5.345 | 5.332 | 5.431 | 5.448 | 5.453 | 5.444 | 5.529 | 5.546 | 5.548 | 5.541 |
| G50 | 5.116 | 5.132 | 5.136 | 5.128 | 5.234 | 5.251 | 5.253 | 5.246 | 5.305 | 5.325 | 5.333 | 5.321 |
| G60 | 5.001 | 5.019 | 5.022 | 5.014 | 5.135 | 5.151 | 5.155 | 5.147 | 5.241 | 5.259 | 5.262 | 5.254 |

Table 8. Ultrasonic Pulse Velocity Test results (14,28,90 Days)

| Time ( Days) | Quality of RCC Mixes for all replacement levels (from 0% to 60%) | | | | | | |
|---|---|---|---|---|---|---|---|
| | G0 | G10 | G20 | G30 | G40 | G50 | G60 |
| 1 | G | G | E | G | G | G | G |
| 3 | G | E | E | E | E | E | E |
| 7 | E | E | E | E | E | E | E |
| 14 | E | E | E | E | E | E | E |
| 28 | E | E | E | E | E | E | E |
| 90 | E | E | E | E | E | E | E |

E= Excellent; G= Good

Table 9. Effect of GGBS on quality of RCC Mixtures with age

$f_c = 0.002e^{2.4073(UPV)}$, $R^2 = 0.9725$ for 50% GGBS (G50) (21)

$f_c = 0.008e^{2.1462(UPV)}$, $R^2 = 0.9909$ for 60% GGBS (G60) (22)

Where $f_c$ = Cube Compressive strength of RCC in Mpa, and

UPV= Ultrasonic Pulse Velocity in Km/s

Equations (16 to 22), follows research findings of Shamarke Abdi Omer [41], Mohd Shariq et al., [13], U. Atici (2011) [35], where the researchers gave a relationship between UPV and Compressive Strength as:

$$f_c^{|} = a e^{b V_c} \quad (23)$$

Where $d_c$ is the Compressive Strength and $V_c$ is UPV

Mohd Shariq et al., [13] also proposed an exponential relationship for the cube specimens in the form of exponential equations are:

$f_c = 0.333e^{1.065Vp}$, For plain concrete (24)

$f_c = 0.23e^{1.16Vp}$, For 20% GGBFS (25)

$f_c = 0.114e^{1.13Vp}$, For 40% GGBFS (26)

$f_c = 0.195e^{1.119Vp}$, For 60% GGBFS (27)

U. Atici (2011) [35] proposed an exponential relationship between Compressive Strength and UPV in the form of:

$y = 0.0316e^{0.0013(UPV)}$ Where $R_2 = 0.85$ (28)

Equations (16)-(22) were useful in predicting the Compressive strength of Roller Compacted Concrete for different conditions in terms of UPV at any age and any dosage of GGBS where the fine aggregate was M-sand. It also gives the quality of Roller Compacted concrete used in the construction of Pavements. In India, the cement concrete pavements of rigid pavement category have been in use for different traffic and soil conditions. For Low volume rural roads, the characteristic compressive strength of minimum 30 MPa shall be used [47], however the other compressive strengths also varying from 30 MPa to 40 MPa for laying rural low volume traffic roads. So, the equations from (16) to (22) shall be useful in predicting the quality of cement concrete for rural roads in India.

### *4.4 Dynamic Modulus of Elasticity of GRCC Mixes*

Figure 11 show that the variation of dynamic modulus of elasticity of RCC mixtures with age of curing for control mix (G0) and GRCC mixtures (G10 to G60). Figure 11 shows that the dynamic modulus of elasticity of RCC is lower for control mix concrete in comparison with the GRCC mixtures with GGBS contents of 10 % to 60% at the all ages of curing. The 28 days dynamic modulus of elasticity control mix (G0) ( i.e. 55.10 GPa) has been attained by the RCC mixture of G20, G30, G40, G50, and G60 at 14 days of curing. Similarly the same value has been attained by the RCC mix of G40 at 7 days, this is due to the fact that the hydration of GGBS has been started from the age of 7 days to 28 days at faster rate. Also the effectiveness of GGBS has been improved from three days. This trend has been confirmed with other investigators, [Teng. S et al., 2013], where the GGBS effectiveness was significant at low water –cement ratio. In the present experimental investigations, the RCC mixes used were of low water–cement ratios. This trend has also seen in the attainment of UPV from 7 days to 28 days of curing. Amongst the various RCC mixtures, at early age of concrete, the dynamic modulus of elasticity decreased with increase in the percent of GGBS. After 28 days, dynamic modulus of elasticity GRCC is observed to be higher for 40% GGBS content that other replacements i.e. 10,20,30,50 and 60% respectively.

The dynamic modulus of elasticity development with age of concrete from 7 days to 28 days is 17% for Control mix (G0), where as it is 19%, 21%,19%, 17%, 13% and 16% for 10%, 20%, 30%, 40%, 50% and 60% respectively for all GRCC mixtures. However, from 28 days to 90 days the dynamic modulus development was 11%, 9%, 6%, 5%, 4%, 3% and 4% for G0,G10,G20,G30,G40,G50 and G60 respectively. At the age of 28 days, the variation of dynamic modulus of elasticity for 10%, 20%, 30%, 40%, 50% and 60% GGBS replacement is 106%, 112%,116%,

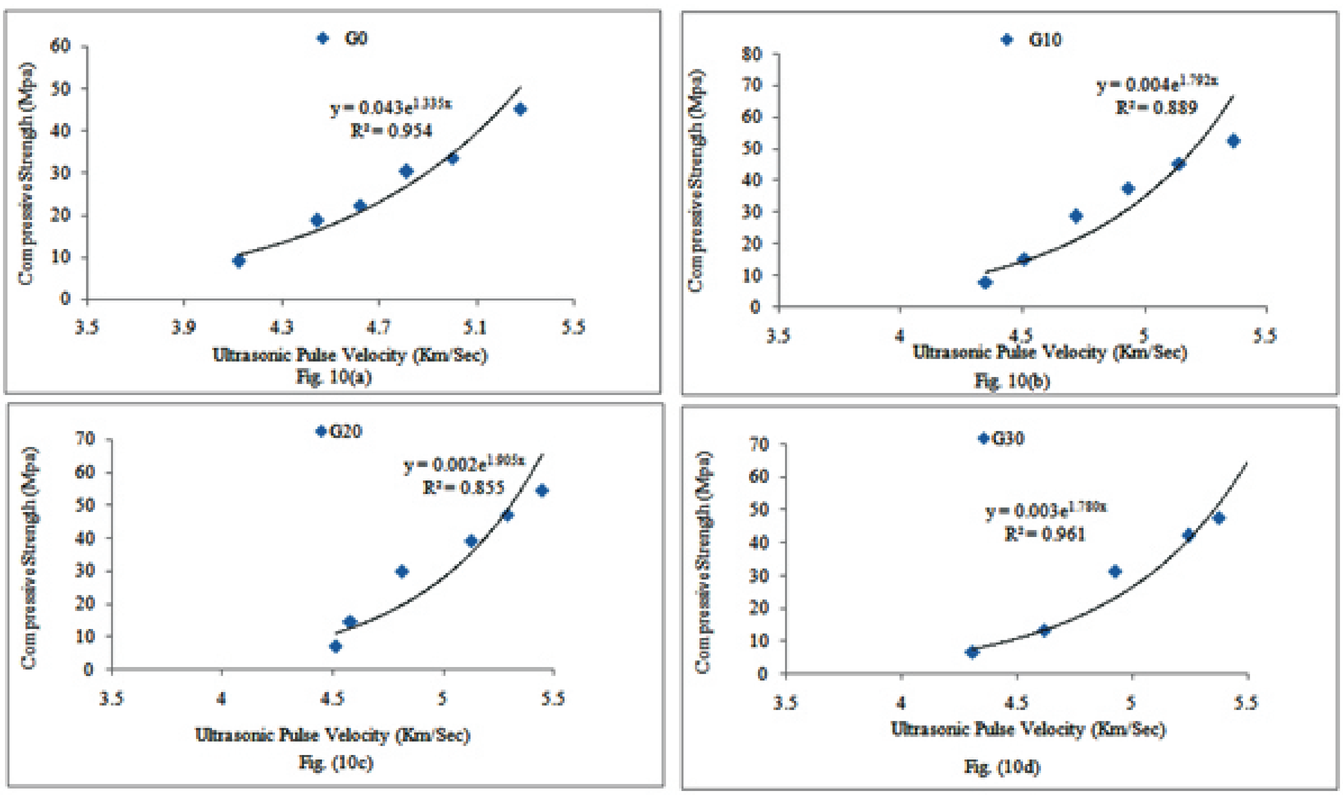


Figure 10 (a,b,c,d). Relationship between compressive strength of GRCC and UPV

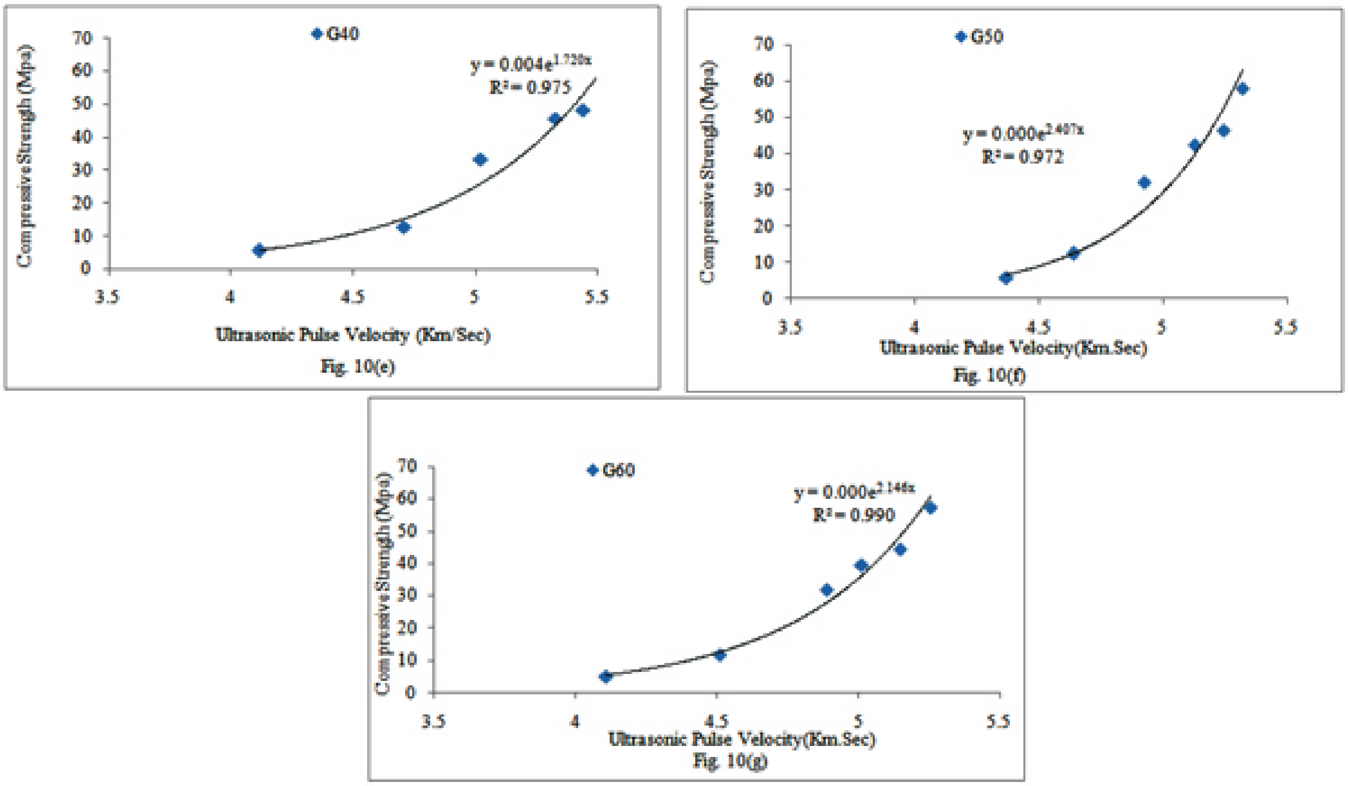


Figure 10 (e,f,g). Relationship between compressive strength of GRCC and UPV

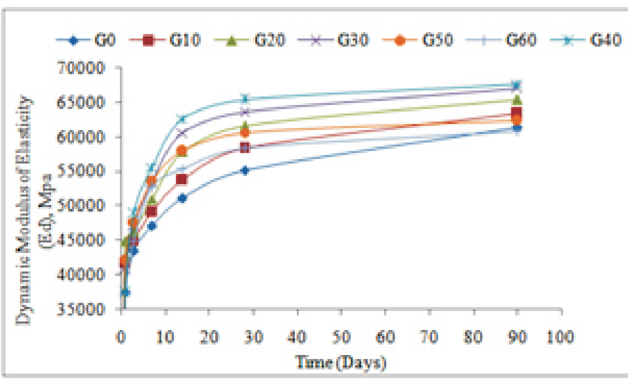


Figure 11. Progression of Dynamic Modulus of Elasticity of GRCC with Age

119%, 110% and 106% respectively in comparison with the control mix (G0). At the age of 90 days, there is slight variation observed as 103%,106%, 109%, 110%, 102% and 99% in 10%, 20%, 30%, 40%, 50% and 60% respectively.

From the above points, it has been observed that, the variation of dynamic modulus of elasticity with age of concrete for GRCC mixes (G10 to G60) is higher than control mix (G0) concrete dynamic modulus of elasticity.

Also the development of dynamic modulus of elasticity increases as the percent replacement of cement with GGBS increases. The attainment of dynamic modulus of elasticity at early ages i.e. at 24 hours is low in comparison with other ages is due to the fact the the setting delay induced by the GGBS at the early ages. Also during early hydration of GGBS, the attainment of UPV is also low corresponding to the latter ages. The cement replacement of 40% by GGBS was found to be the optimum for Roller Compacted Concrete.

### *4.5 Relationship between Dynamic Modulus of Elasticity and Compressive Strength of GRCC*

Figure 12 shows that the relationship between the dynamic modulus of elasticity and the compressive strength of cube which increases with increase in the Roller Compacted Concrete strength. The best fit equation was found with the observed test results is shown in Figure 12.

The relation can best express as:

$$E_d = 26.52(f_c)^{0.211} \quad R_2 = 0.89 \qquad (29)$$

Equation (29) confirms the findings of M.M. Salman et al., [46] and their proposed equation was in the form of

$E_{d1} = 7.3\ f_c^{\ 0.533}$, For normal strength concrete (30)

$E_{d2} = 29.0\ (f_c\ )^{0.139}$, For high strength concrete (31)

The proposed equations shall be useful in the design of Low volume rural roads in India, where the minimum recommended Elastic Modulus is 30,000 MPa and Poisson's ratio of 0.15, and these proposed values are low in comparison with the experimental values and hence there shall be change in the design thickness of the pavements and hence economy in the consumption of cement if roller compacted concrete pavements is adopted for rural roads in India.

### *4.6 Proposed Model for Dynamic Modulus of Elasticity with Age of RCC*

From the experimental results obtained in investigations on RCC mixtures using M-sand as fine aggregate and GGBS as mineral admixture for partial replacement of Cement, there is a relationship the exist among dynamic modulus of concrete, age of concrete and GGBS content. Hence a model has been proposed for the prediction of dynamic modulus of elasticity of Roller Compacted Concrete at any age of concrete and percent replacement of GGBS. The best – fit multiple regressions equation was proposed based on the test data:

$$(E_d)_t = 91.71(t)^{0.05} + 0.0011(p_g) - 51.23 \qquad (32)$$

where,

$(E_d)_t$ = dynamic modulus of elasticity at the age of t days in M Pa, and

$p_g$ = % of replacement of cement by GGBS.

The prediction of dynamic modulus of elasticity from the above expression was compared with the experimental data obtained from the test results and it is graphically shown in Figure 13. From Figure 13, it shows that the measured and predicted values are in good relation.

### Conclusions

From the experimental work conducted on the Roller Compacted Concrete with GGBS as mineral admixture, following conclusions were drawn:

1. The ultrasonic pulse velocities are higher at the age of 28 days and beyond 28 days for mixes with 40% GGBS content.
2. At the one day hydration, the quality of RCC with GGBS is found to be good for all mixes. However, from the ages of 3 to 90 days the quality was improved from good to excellent due to the contribution of GGBS on strength.
3. Use of UPV measurements is adequate to evaluate the compressive strength and dynamic modulus of elasticity of roller compacted concrete from day 1to day 90 for known replacement level of GGBS. Also a model was proposed for time dependent dynamic modulus of elasticity of Roller Compacted Concrete containing GGBS.

### Future Scope

This work shall be extended to study the effect of other mineral admixtures like Fly Ash, Rice Husk Ash, Meta Kaolin,

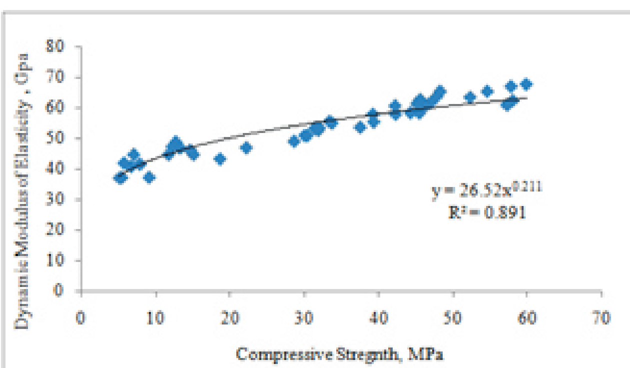


Figure 12. The Relationship Between the Dynamic Modulus of Elasticity with Compressive Strength of GRCC

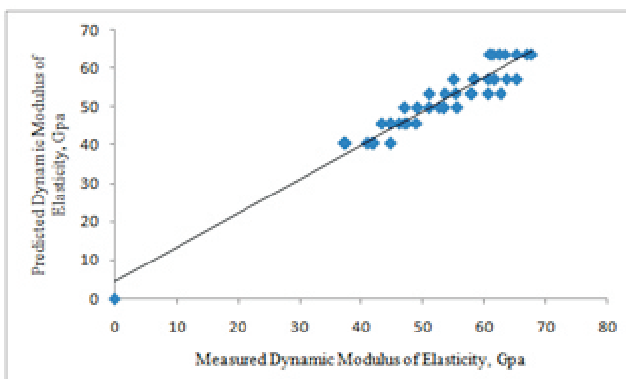


Figure 13. Comparison of Predicted and Measured Values of Dynamic Modulus of Roller Compacted Concrete with GGBS using Proposed Model

Silica Fume, etc., and the effect of the fine aggregate replacement with bottom ash, Copper Slag on the Dynamic Properties of Roller Compacted Concrete Pavements.

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