



Experimental studies in Ultrasonic Pulse Velocity of roller compacted concrete pavement containing fly ash and M-sand

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Abstract

This paper presents the experimental investigation results of Ultrasonic Pulse Velocity (UPV) tests conducted on roller compacted concrete pavement (RCCP) material containing Class F fly ash of as mineral admixture. River sand, M-sand and combination of M-sand and River sand are used as fine aggregate in this experimental work. Three types of fly ash roller compacted concrete mixes are prepared using above three types of fine aggregates and they are designated as Series A (River sand), Series B (manufactured sand) and Series C (combination of River sand and M-sand). In each series the fly ash content in place of cement is varied from 0% to 60%. In each series and for different ages of curing (i.e 3, 7, 28 and 90 days) forty two cube specimens are cast and tested for compressive strength and UPV. The UPV results of fly ash containing roller compacted concrete pavement (FRCCP) show lower values at all ages from 3 days to 90 days in comparison with control mix concrete (0% fly ash) in all mixes. However, it is also observed that Series B and C mixes containing fly ash show better results in UPV values, compressive strength and Dynamic Elastic Modulus in comparison to Series A mixes with fly ash. Relationships between compressive strength of FRCCP and UPV and Dynamic Elastic Modulus are proposed for all series mixes. A new empirical equation is proposed to determine the Dynamic Elastic Modulus of FRCCP.

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Keywords: Compressive strength; Dynamic Elastic Modulus; Fly ash; Roller compacted concrete pavement; Ultrasonic Pulse Velocity

1. Introduction

The River sand obtained from river beds has been used primarily as fine aggregate in concrete production. Since the supply of River sand is inadequate and its incessant supply is not certain, use of manufactured sand (M-Sand) as a substitute to River sand has become inevitable. The International Center of Aggregates Research (ICAR) project work show 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 has become 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 as that 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

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Nomenclature

| | | | |
|--------|---|-----------|---|
| UPV | Ultrasonic Pulse Velocity | t | concrete age [days] |
| RCCP | roller compacted concrete pavement | V_p | velocity, km/s |
| FA | fly ash of Class F | V | pulse velocity (m/s) |
| M-sand | manufactured sand | L | length of travel (m) |
| FRCCP | fly ash roller compacted concrete pavement | T | effective time (s) |
| ICAR | International Center of Aggregates Research | g | acceleration due to gravity, m/s^2 |
| ACI | American Concrete Institute | ρ | Density of concrete in KN/m^3 |
| E_d | dynamic modulus of elasticity | f_c | cube compressive strength of RCC in MPa |
| V_L | longitudinal wave velocity m/s | $(E_d)_t$ | dynamic modulus of elasticity at the age of t days in MPa |
| V_S | shear wave velocity m/s | p_{fa} | % of replacement of cement by fly ash |
| E | dynamic modulus of elasticity (GPa) | | |
| μ | dynamic Poisson's ratio | | |

main advantage of RCC over conventional concrete pavement is the speed in construction and cost savings. RCC needs no formwork, dowels and no finishing [26].

In roller compacted concrete pavements addition of active mineral admixtures like fly ash has great scientific significance. Fly ash (FA) consists of SiO_2 and Al_2O_3 , and has high potential activity. The main useful and significant effects of FA can be three fold: Morphologic effect, pozzolanic effect, and Micro aggregate effect [49]. Research in India regarding the utilization of fly ash has shown that the quality of fly ash produced at National thermal power Corporation (NTPC) plants is extremely good with respect to fineness, low un-burnt carbon, high pozzolanic activity and conforms to the requirements of IS:3812 – 2003-Pulverized Fuel Ash for use as Pozzolana in cement, cement mortar and concrete. The fly ash generated at NTPC stations is ideal for use in the manufacture of concrete [50].

Assessing the quality of concrete used for paving applications has become essential for control operations during and after construction. Use of fly ash in roller compacted concrete pavement is gaining importance due to numerous advantages. Fly ash 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.

Ultrasonic Pulse Velocity (UPV) is a non 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 [42,43]. The UPV is a useful parameter for estimation of static modulus of elasticity, dynamic modulus of elasticity, static Poisson's ration and dynamic Poisson's ratio [16].

Yildirim and Sengul [4] conducted experimental investigation on the modulus of elasticity of concrete. A total of 60 mixtures are prepared, in which the effects of water/

cement ratio, maximum size of the aggregate, aggregate type, and fly ash content are investigated. Modulus of elasticity of the concretes was obtained besides compressive strength and ultrasound pulse velocities of the concrete. A model is also proposed to predict the dynamic modulus of concrete. The predicted model has close association with experimental test results. Wen and Li [17] conducted experimental study on Young's Modulus of concrete through P-Wave velocity measurements. Two empirical equations for obtaining static Young's Modulus and Dynamic Young' Modulus when dynamic Poisson ratio varies around 0.20. Qasrawi [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 Kolluru et al. [19] was proposed a technique for evaluating the elastic material constants of a concrete specimen using longitudinal resonance frequencies using Rayleigh-Ritz method. A simple, accurate and more reliable method is developed for determining dynamic elastic constants of concrete.

Yaman et al. [20] investigated the use of indirect UPVs in Concrete slabs and found similarity between direct and indirect UPVs. A significant conclusion is drawn that the indirect UPV is statistically similar to direct UPV. Choudhari et al. [21] proposed a methodology to determine the elastic modulus of concrete by Ultrasonic method. Conrad et al. [22] investigated stress-strain behavior and modulus of elasticity of young Roller Compacted concrete from the ages of 6 hours to 365 days. The Young's Modulus for the early ages and aged low cementitious RCC can be an exponential type function. Washer et al. [23] conducted extensive research on Ultrasonic testing of Reactive powder concrete. Demirboga et al. [34] found a relationship between ultrasonic velocity and compressive strength of concrete using different mineral admixtures such as fly ash (high volume), Blast Furnace Slag and combination of FA and BFS in replacement of Portland cement. Compressive strength, UPV values are determined at 3, 7, 28 and 120 days curing period. An exponential relationship between compressive strength and UPV was reported.

Atici [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. Two different methods like artificial neural network and multivariable regression analysis were adopted for estimation of concrete strength and concluded that the application of an artificial neural network had more potential in predicting the compressive strength of concrete than multivariable regression analysis. Trtnik et al. [36] proposed a numerical model for predicting the compressive strength of concrete based on Ultrasonic Pulse Velocity and some concrete mix characteristics. Panzera et al. [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. Turgut [38] proposed a relationship between concrete strength and UPV. Hannachi et al. [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.

From the above literature survey it is observed that, many researchers studied the relationship between compressive strength in relation with UPV, but the relationships between UPV and the Elastic and Mechanical properties of fly ash roller compacted concrete pavement mixes have not been investigated. Also the use of manufactured sand on the strength and elastic modulus of fly ash roller compacted concrete pavement has not yet been investigated. Hence an experimental investigation has been planned to predict the quality and behavior of RCC made with fly ash intended for lean concrete bases and cement concrete surface courses and similar applications. This research work was focused on the relationship between Elastic properties, Compressive strength properties and UPV.

2. Materials and mix proportioning method

2.1. Materials

Ordinary Portland Cement (OPC) of 53 grade is used in the present experimental investigation. Cement was tested as IS 4031-1999 [27]. Fly ash obtained from NarlaTata Rao Thermal Power Station (NTTPS) at Ibrahimpatnam, Vijayawada, Andhra Pradesh, India and was tested as per IS 1727:1967 [48]. Properties of cement and fly ash are shown in Table 1. River sand and manufactured sand (M-sand) are used as fine aggregate material. Three type of concrete mixtures are prepared using these fine aggregates and they designated as Series A (100% River sand), Series B (100% M-sand) and Series C (50% River sand and 50% M-sand). The manufactured sand was collected from V.N.S Ready Mix plant, Vijayawada, India. The specific gravities of River sand and M-sand are 2.68 and

Table 1
Properties of cement and fly ash.

| Cement and fly ash characteristics | | |
|---------------------------------------|--------|---------|
| Component (%) | Cement | Fly ash |
| <i>(a) Chemical analysis</i> | | |
| Loss Ignition | 1.8 | 0.73 |
| SiO ₂ | 20.4 | 62.84 |
| Fe ₂ O ₃ | 3.2 | 4.74 |
| Al ₂ O ₃ | 3.9 | 23.94 |
| CaO | 63 | 3.43 |
| MgO | 2.4 | 0.97 |
| Na ₂ O | - | 0.4 |
| K ₂ O | - | 0.71 |
| SO ₃ | 3 | 0.77 |
| <i>(b) Physical properties</i> | | |
| Fineness (Blaine), m ² /kg | 285 | 359 |
| % of passing 45 μm | 88.5 | 8 |
| Compressive strength, MPa | | |
| 3 Days | 29.00 | - |
| 7 Days | 40.00 | - |
| 28 Days | 58.00 | - |
| Specific gravity | 3.15 | 2.5 |

2.713 respectively. The particle size distribution of both the fine aggregates is shown in Fig. 2. The fine aggregates are conformed to IS: 383-1970 [28] requirements. Igneous rock material consisting of granite was used as coarse aggregate in the preparation of FRCCP. The grain size distribution is shown in Figs. 3 and 4 and other properties are listed in Table 3. The gradational requirements of combined aggregate are satisfied as per ACI 211.3R-02 [29] (Table A3.2). Potable drinking water is used in the preparation of all RCC mixtures. All ingredients used in the present investigation are shown in Fig. 1 (cement, fly ash, River sand, M-sand, Coarse Aggregate) (see Table 2).

2.2. Mix proportioning method

The basic mix proportions (control mix) are achieved based on soil compaction principles and ACI 211 3R-02 (2002) [29] guidelines. The target flexural strength for the preparation mix was 5.0 MPa [11,12,30–32,51–58]. The cement content of control mix is obtained as 295 kg/m³. The Series A, B and C, mixes are prepared using River sand, M-sand and combination of River sand and M-sand as fine aggregate materials. In all series cement was replaced with fly ash with % replacement levels of 0, 10, 20, 30, 40, 50 and 60 by weight of cement keeping coarse aggregate proportion as constant. The designation of mix proportions and quantity of material are presented in Table 3.

2.3. Preparation, casting and testing of specimens

2.3.1. Compressive strength

Compressive strength of roller compacted concrete specimens are obtained at 3, 7, 28 and 90 days of curing age as

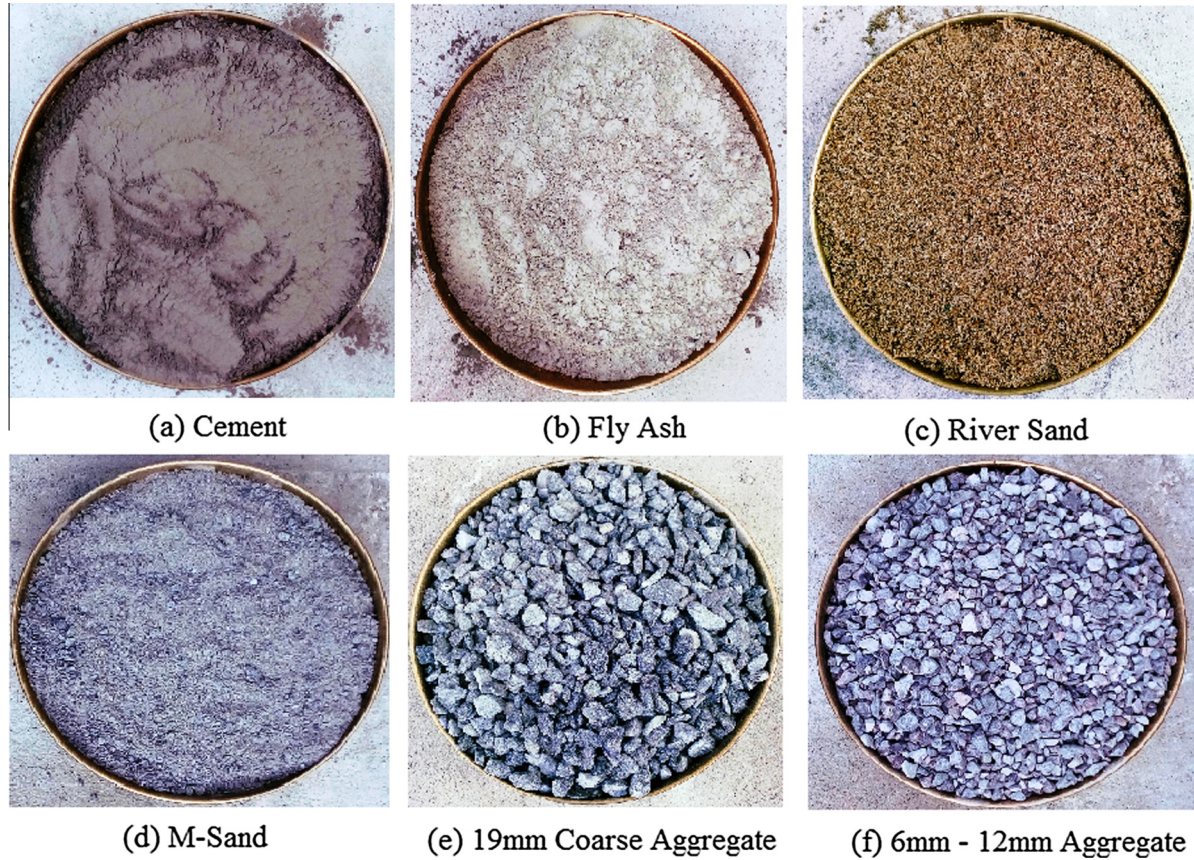


Fig. 1. Various ingredients used in the present experimental investigations of RCC mixes of Series A, B, C.

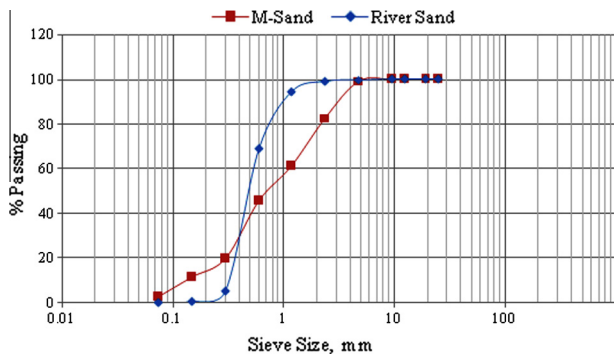


Fig. 2. Particle Size distribution curve for fine aggregate (River sand & M-sand).

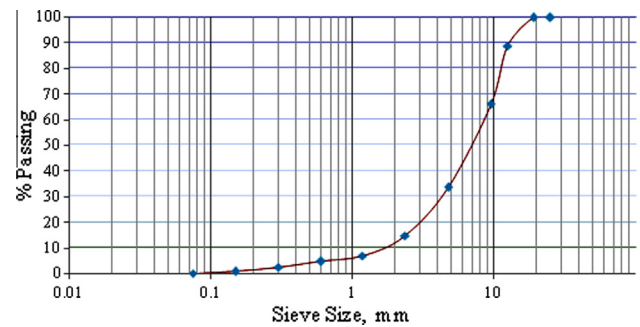


Fig. 3. Particle size distribution curve for coarse aggregate.

per IS 516-1959 [33]. The cube specimens after casting demoulded after 24 h and kept for curing for required number of days. The cube specimens are tested in compression testing machine of 3000 kN capacity by applying load at the rate of 4.5 kN/s until the resistance of the cube to the applied load breaks down (Fig. 5). The test results are presented in Table 4.

2.3.2. Ultrasonic pulse velocity test

For the assessment of compressive strength of concrete, UPV is not sufficient, since a large number of parameters

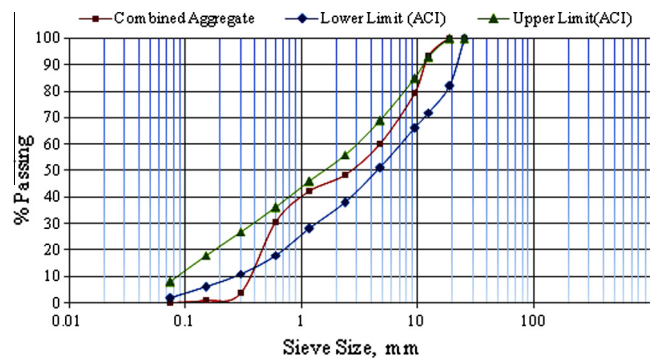


Fig. 4. Particle size distribution curve for combined aggregate.

Table 2
Properties of coarse aggregate.

| S.No. | Property | Test value |
|-------|--|---|
| 1 | Specific gravity | 2.88 |
| 2 | Sieve analysis test results | Particle size distribution curve shown in Figs. 2 and 3 |
| 3 | Aggregate impact value, % | 21.50 |
| 4 | Aggregate crushing value, % | 20.40 |
| 5 | Combined Flakiness & Elongation value, % | 21.90 |

Table 3
Quantities of materials per one m³ of RCC of 5 N/mm² flexural strength.

| Series | Type of fine aggregate | Mix designation | Mix proportion (Kg/m ³) | | | | | |
|--------|-------------------------------|-----------------|-------------------------------------|---------|------|------------|--------|--------|
| | | | Cement | Fly ash | CA | River Sand | M-Sand | Water |
| A | River Sand – 100% | F0 | 295 | 0 | 1209 | 801 | - | 114 |
| | | F10 | 265.5 | 29.5 | 1209 | 801 | - | 118 |
| | | F20 | 236 | 59 | 1209 | 801 | - | 123.9 |
| | | F30 | 206.5 | 88.5 | 1209 | 801 | - | 129.8 |
| | | F40 | 177 | 118 | 1209 | 801 | - | 141.6 |
| | | F50 | 147.5 | 147.5 | 1209 | 801 | - | 144.55 |
| | | F60 | 118 | 177 | 1209 | 801 | - | 147.5 |
| B | M-Sand – 100%% | F0 | 295 | 0 | 1209 | - | 801 | 114 |
| | | F10 | 265.5 | 29.5 | 1209 | - | 801 | 118 |
| | | F20 | 236 | 59 | 1209 | - | 801 | 123.9 |
| | | F30 | 206.5 | 88.5 | 1209 | - | 801 | 129.8 |
| | | F40 | 177 | 118 | 1209 | - | 801 | 141.6 |
| | | F50 | 147.5 | 147.5 | 1209 | - | 801 | 144.55 |
| | | F60 | 118 | 177 | 1209 | - | 801 | 147.5 |
| C | River Sand 50% and M-Sand 50% | F0 | 295 | 0 | 1209 | 400.5 | 400.5 | 114 |
| | | F10 | 265.5 | 29.5 | 1209 | 400.5 | 400.5 | 118 |
| | | F20 | 236 | 59 | 1209 | 400.5 | 400.5 | 123.9 |
| | | F30 | 206.5 | 88.5 | 1209 | 400.5 | 400.5 | 129.8 |
| | | F40 | 177 | 118 | 1209 | 400.5 | 400.5 | 141.6 |
| | | F50 | 147.5 | 147.5 | 1209 | 400.5 | 400.5 | 144.55 |
| | | F60 | 118 | 177 | 1209 | 400.5 | 400.5 | 147.5 |



Fig. 5. Compression test (before and after test).

Table 4
Compressive strength test results.

| Series | Type of fine aggregate | Mix designation | Compressive strength of FRCC, N/mm ² | | | |
|--------|-------------------------------|-----------------|---|--------|---------|---------|
| | | | 3 days | 7 days | 28 days | 90 days |
| A | River Sand – 100% | F0 | 19.11 | 26.50 | 43.20 | 49.50 |
| | | F10 | 17.11 | 23.88 | 38.44 | 45.11 |
| | | F20 | 16.40 | 23.10 | 35.00 | 41.00 |
| | | F30 | 14.11 | 20.44 | 28.88 | 36.11 |
| | | F40 | 12.88 | 18.20 | 24.00 | 32.50 |
| | | F50 | 9.88 | 13.55 | 20.11 | 29.44 |
| B | M-Sand – 100% | F0 | 18.67 | 22.22 | 33.74 | 45.20 |
| | | F10 | 16.80 | 20.00 | 30.88 | 41.41 |
| | | F20 | 14.70 | 17.88 | 28.50 | 38.50 |
| | | F30 | 12.80 | 15.70 | 24.40 | 36.00 |
| | | F40 | 10.60 | 13.60 | 21.30 | 33.78 |
| | | F50 | 8.80 | 11.70 | 18.90 | 30.20 |
| C | River Sand 50% and M-Sand 50% | F0 | 28.11 | 32.70 | 48.14 | 52.30 |
| | | F10 | 25.90 | 29.80 | 45.80 | 50.00 |
| | | F20 | 23.90 | 27.50 | 42.89 | 48.10 |
| | | F30 | 19.30 | 24.80 | 38.30 | 46.60 |
| | | F40 | 16.40 | 21.60 | 35.30 | 44.90 |
| | | F50 | 13.44 | 18.60 | 31.04 | 42.66 |
| | | F60 | 10.00 | 15.70 | 28.50 | 40.03 |

like quality of material 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, V is a function of the square root of the ratio of E and its density (d).

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

g = acceleration due to gravity, m/s^2 .

$$V = \frac{L}{T} \quad (2)$$

V = Pulse velocity (m/s).

L = Length of travel (m).

T = Effective time (s).

Once the velocity is determined, the concrete quality, uniformity, strength, density and condition can be attained. As per IS 13311(Part1): 1992 [15], Table 5 shows the use of velocity obtained from the test to classify the quality of concrete.

Table 5
Quality of concrete as a function of UPV.

| S.No | Pulse velocity cross probing (km/S) | Concrete quality grading |
|------|-------------------------------------|--------------------------|
| 1 | > 4.5 | Excellent |
| 2 | 3.5–4.5 | Good |
| 3 | 3.0–3.5 | Medium |
| 4 | < 3.0 | Doubtful |

The UPV testing (Fig. 6) on cube specimens of all twenty one mixtures is carried out as per IS: 13311(Part1): 1992 [15]. The UPV tester PUNDIT (Fig. 7) 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 for all specimens at respective ages of RCC mixes as shown in Fig. 7.

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

$$E_d = \frac{\rho(\text{UPV})^2(1 + \mu)(1 - 2\mu)}{1 - \mu} \quad (3)$$

where

E_d = Dynamic Modulus of elasticity in MPa.

ρ = Density of concrete in KN/m^3 .

UPV = Ultrasonic Pulse Velocity in Km/s.

μ = Poisson's ratio of concrete.

For calculation of E_d in this experimental work, $\rho = 2450 \text{ kN/m}^3$ and $\mu = 0.2$ have been assumed [40]. The test results are presented in Table 5.

3. Results and discussions

3.1. Effect of fly ash on Ultrasonic Pulse Velocity of RCC with time

The experimental progression of UPV of Control Mix and fly ash roller compacted concrete pavement (FRCCP) with the age is shown in Fig. 8(a)–(c) and Tables 6 and 7.

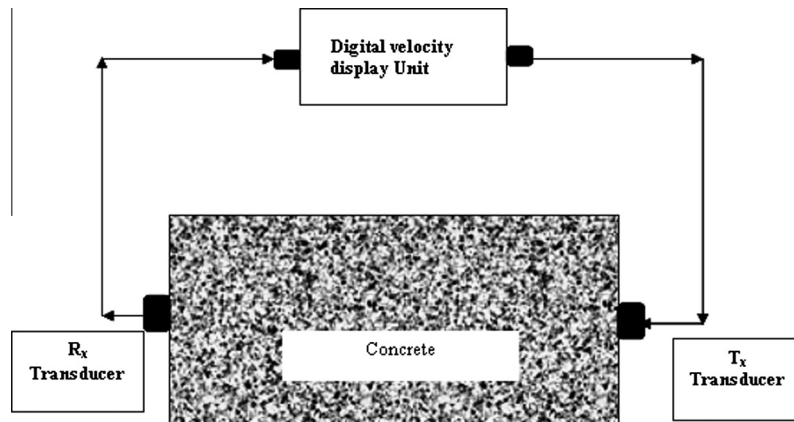


Fig. 6. Ultra Sonic Pulse Velocity measurement test set up.



(a) UPV Apparatus



(b) UPV Test on Cube Specimen

Fig. 7. Ultrasonic Pulse Velocity Test in Progress.

The Ultrasonic Pulse Velocity of FRCC mixes increases with increase in curing age of roller compacted concrete for all the mixes as expected. The UPV of FRCC mixes was found to be lower than the control mix (F0) for all replacement levels and at all ages of all mixes i.e Series A, B and C. The decrease in UPV with increase in fly ash content is due to the fact that, the contribution of fly ash to the strength of roller compacted concrete is lower than that of cement even at 90 days of curing and hence lower UPV values have been observed. This aspect has been conformed with the

findings of Teng et al. [45], where the pozzolanic activity of mineral admixture at low water cement ratio is lesser at early ages.

3.2. Effect of fly ash on quality of roller compacted concrete and UPV with age

Table 5 shows the range of UPV qualitative rating as per IS: 13311(Part 1): 1992 [15]. A value of above 4.5 km/s shows the concrete with excellent quality. For good

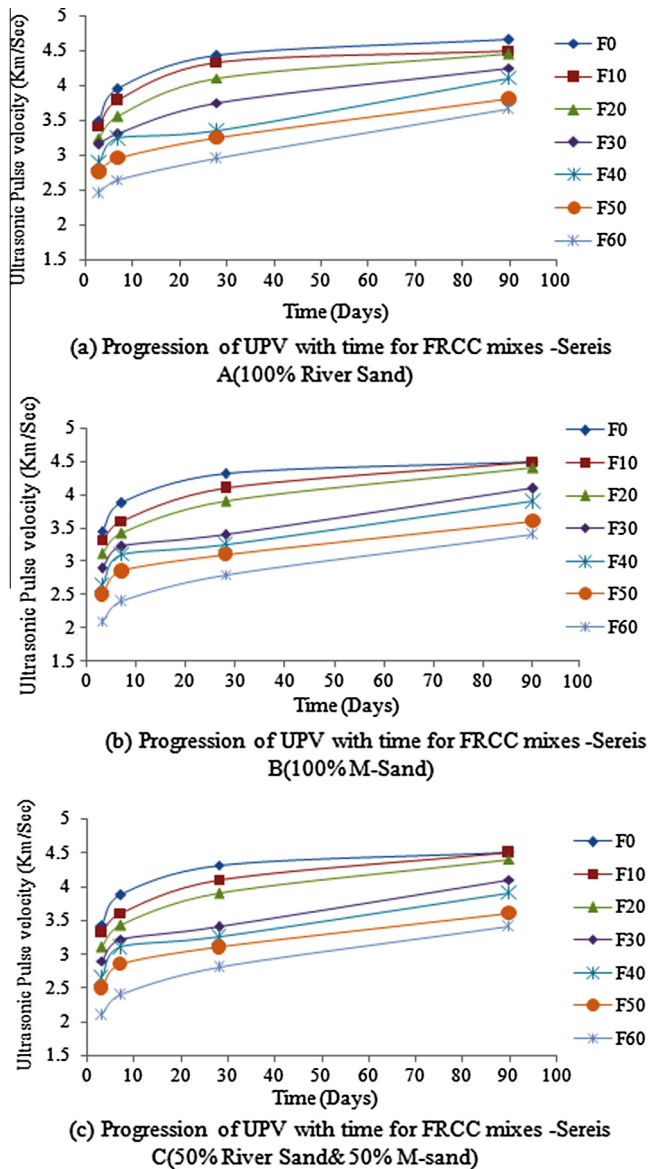


Fig. 8. Progression of UPV with time.

concrete the UPV shall be varying between 3.5 and 4.5 km/s; for medium quality concrete the UPV shall be between 3.0 and 3.5 km/s. The effect of fly ash on the quality of RCC mixtures with curing age for all mixes is shown in Table 7.

Based on UPV test results the quality of Series A mixes is studied. For three days cured specimens containing fly ash with 40%, 50% and 60% produced concrete with doubtful quality. At 7 days 50% and 60% fly ash content in mix produced doubtful quality. At 28 days, only 60% fly ash replacement level produced doubtful quality of concrete. However, at 90 days of curing all replacement levels produced concrete of good quality, which is even at 60% replacement level.

In Series B mixes containing fly ash with 30%, 40%, 50% and 60% produced concrete with doubtful quality. At 7

days 50% and 60% fly ash content mix produced doubtful quality. At 28 days, only 60% fly ash replacement level produced doubtful quality. However, at 90 days all mixes with replacement levels up to 60% produced concrete of good quality. Between Series A and Series B mixes, it was observed that the effect M-Sand on FRCCP is inferior to River sand Mixes (Series A). This is due to the fact that M-Sand produced harsh mixes than River sand mixes.

In Series C mixes, where the fine aggregate was comprised of 50% of River sand and 50% of M-sand produced good quality mixes at 28 days and excellent quality mixes at 90 days. This was due to the fact that the combination of fine aggregate produced proper packing of aggregate and hence denser mixes of Series C lead to increase in UPV.

3.3. Relationship between compressive strength and UPV of RCC Mixes

From the literature review, it was observed that there is no definite relationship existing between UPV and compressive strength of Roller Compacted Concrete. Hence a relationship between compressive strength of RCC mixtures with different replacement levels of fly ash and UPV has been developed. Fig. 9 shows the relationship between compressive strength of FRCCP mixtures (F0, F10, F20, F30, F40, F50 and F60) of Series A, Series B and Series C and UPV at all ages. Fig. 9 can be used to assess the compressive strength at any age of concrete. From the experimental results, exponential power relation between cube compressive strength and UPV of FRCCP mixtures is proposed as under for Series A, Series B and Series C mixes:

$$f_c = 1.526e^{0.761V_p} \quad R^2 = 0.895 \quad (4)$$

where

f_c = cube compressive strength of FRCC in MPa.

UPV = Ultrasonic Pulse Velocity in km/s.

Eq. (4), follows research findings of Omer et al. [41], Shariq et al. [13], Atici [35]. The empirical Eq. (4) is useful in predicting the compressive strength of Roller Compacted Concrete for different conditions in terms of UPV at any age and any dosage of fly ash where the fine aggregate was River sand for Series A, M-sand for Series B and 50% of River sand and 50% of M-sand for Series C mixes.

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 Eq. (4) shall be useful in predicting the quality of cement concrete for rural roads in India, when Class F fly ash is used as mineral admixture and M-sand in combination of River sand is used.

Table 6
Ultrasonic pulse velocity test results (at various ages of concrete).

| Series | Type of fine aggregate | Mix designation | UPV, Km/s | | | |
|--------|-------------------------------|-----------------|-----------|--------|---------|---------|
| | | | 3 days | 7 days | 28 days | 90 days |
| A | River Sand – 100% | F0 | 3.50 | 3.95 | 4.42 | 4.65 |
| | | F10 | 3.42 | 3.78 | 4.33 | 4.50 |
| | | F20 | 3.25 | 3.55 | 4.10 | 4.45 |
| | | F30 | 3.15 | 3.30 | 3.75 | 4.25 |
| | | F40 | 2.90 | 3.24 | 3.35 | 4.10 |
| | | F50 | 2.76 | 2.95 | 3.25 | 3.80 |
| | | F60 | 2.45 | 2.65 | 2.95 | 3.65 |
| B | M-Sand – 100%/% | F0 | 3.44 | 3.882 | 4.32 | 4.50 |
| | | F10 | 3.32 | 3.61 | 4.10 | 4.50 |
| | | F20 | 3.11 | 3.42 | 3.90 | 4.40 |
| | | F30 | 2.90 | 3.22 | 3.40 | 4.10 |
| | | F40 | 2.65 | 3.10 | 3.25 | 3.90 |
| | | F50 | 2.50 | 2.85 | 3.10 | 3.60 |
| | | F60 | 2.10 | 2.40 | 2.80 | 3.40 |
| C | River Sand 50% and M-Sand 50% | F0 | 3.88 | 4.12 | 4.55 | 4.90 |
| | | F10 | 3.52 | 4.05 | 4.40 | 4.60 |
| | | F20 | 3.42 | 3.95 | 4.40 | 4.60 |
| | | F30 | 3.25 | 3.75 | 4.10 | 4.20 |
| | | F40 | 3.05 | 3.50 | 3.85 | 4.00 |
| | | F50 | 2.85 | 3.25 | 3.50 | 3.80 |
| | | F60 | 2.45 | 3.10 | 3.40 | 3.60 |

Table 7
Effect of fly ash on quality of RCC mixtures with age.

| Series | Type of fine aggregate | Mix designation | UPV (km/s) | | | |
|--------|-------------------------------|-----------------|------------|--------|---------|---------|
| | | | 3 days | 7 days | 28 days | 90 days |
| A | River Sand – 100% | F0 | G | G | G | E |
| | | F10 | G | G | G | G |
| | | F20 | M | G | G | G |
| | | F30 | M | M | G | G |
| | | F40 | D | M | M | G |
| | | F50 | D | D | M | G |
| | | F60 | D | D | D | G |
| B | M-Sand – 100%/% | F0 | M | G | G | E |
| | | F10 | M | G | G | G |
| | | F20 | M | M | G | G |
| | | F30 | D | M | M | G |
| | | F40 | D | M | M | G |
| | | F50 | D | D | M | G |
| | | F60 | D | D | D | M |
| C | River Sand 50% and M-Sand 50% | F0 | G | G | E | E |
| | | F10 | G | G | G | E |
| | | F20 | M | G | G | E |
| | | F30 | M | G | G | G |
| | | F40 | M | G | G | G |
| | | F50 | D | M | G | G |
| | | F60 | D | M | M | G |

E = Excellent; G = Good; M = Medium; D = Doubtful.

3.4. Dynamic modulus of elasticity of FRCC mixes

Fig. 10(a)–(c) shows that the variation of dynamic modulus of elasticity of RCC mixtures with age of curing for

FRCC mixtures. The dynamic modulus of elasticity of RCC is higher for control mix concrete in comparison with the FRCC mixtures with fly ash contents of 10–60% at all ages of curing for Series A, Series B and Series C mixes.

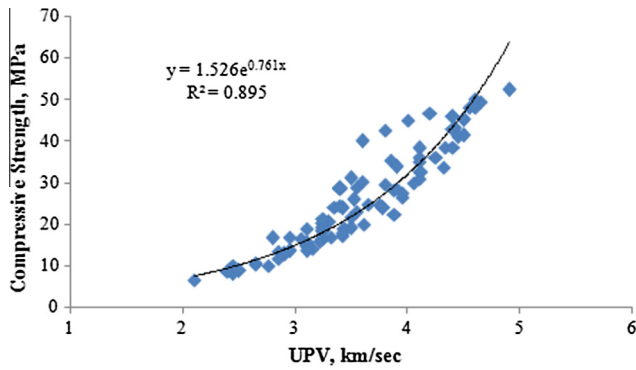


Fig. 9. Relation between UPV and compressive strength.

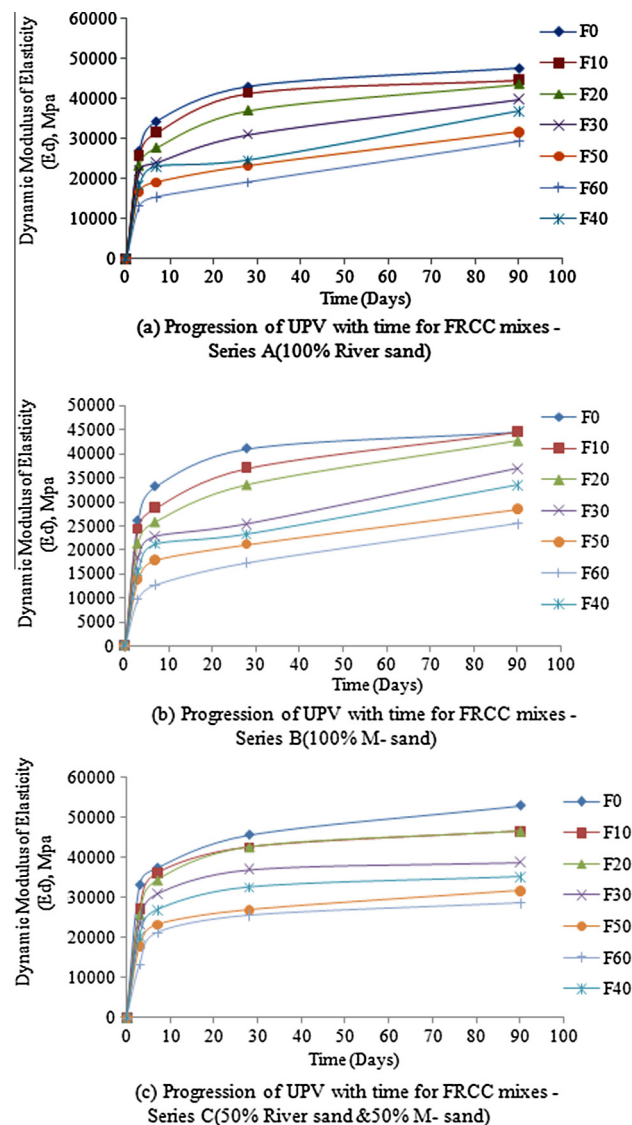


Fig. 10. Various of dynamic modulus with time.

attained by the FRCCP mixture of F10 and F20 at 90 days. The dynamic Modulus of the Control mix concrete (F0) could not be attained even at 90 days for cement replacement of 60%. For Series B mixes, the 28 days dynamic modulus of elasticity control mix (F0) (i.e. 41.1 GPa) has been attained by the FRCC mixtures of F10 and F20 at 90 days. The dynamic Modulus of the Control mix concrete (F0) could not be attained by mix contains 60% fly ash at 90 days. Also for Series C mixes, the 28 days dynamic modulus of elasticity of control mix (F0) (i.e. 45.6 GPa) has been attained by the FRCC mixtures of F10 and F20 at 90 days. The dynamic Modulus of the Control mix concrete (F0) could not be attained by the mixes with fly ash 60% even at 90 days.

Among various mixes of FRCCP of three series, at initial curing periods, the attainment of the dynamic modulus of elasticity is lower than the control mix concrete. However from 28 days to 90 days age the FRCCP mixes with 10% and 20% fly ash, the dynamic modulus of FRCCP is nearer to the control mix concrete for all three series mixes/mixtures. The dynamic modulus of elasticity increases with age of concrete from 28 days to 90 days and it is 11% more in Control mix (F0), where as it is found 08%, 18%, 28%, 50%, 37% and 53% higher for 10%, 20%, 30%, 40%, 50% and 60% fly ash mixes respectively for Series A. In Series B mixes, the dynamic modulus of elasticity development with age of concrete from 28 days to 90 days is 9% more in Control mix (F0), where as it is 20%, 27%, 45%, 44%, 35% and 47% higher for 10%, 20%, 30%, 40%, 50% and 60% fly ash RCC mixes respectively. Also for Series C mixes, the dynamic modulus of elasticity increases with age of concrete from 28 days to 90 days and it is 16% more for Control mix (F0), where as it is 09%, 09%, 05%, 08%, 18% and 12% higher for 10%, 20%, 30%, 40%, 50% and 60% fly ash mixes respectively.

For Series A mixes, at the age of 28 days, the dynamic modulus of elasticity for 10%, 20%, 30%, 40%, 50% and 60% fly ash is 96%, 86%, 72%, 57%, 54% and 45% lower when compared to control mix(F0).

Similarly, the dynamic modulus of elasticity for 10%, 20%, 30%, 40%, 50% and 60% fly ash is 90%, 82%, 62%, 57%, 51% and 42% lower than control mix concrete (F0) for Series B and 94%, 94%, 81%, 72%, 59% and 56% lower for Series C in comparison with the control mix(F0).

From the above points, it has been observed that, the variation of dynamic modulus of elasticity with age of concrete for FRCCP mixes (F10–F60) is lower than control mix (F0) concrete dynamic modulus of elasticity. Also the development of dynamic modulus of elasticity decreases as the percent replacement of cement with fly ash increases. The attainment of dynamic modulus of elasticity at early ages i.e. at 3 days and 7 days is low in comparison to other ages is due to the fact that, the setting delay induced by the fly ash at the early ages. Also during early hydration of fly ash the attainment of UPV is also low corresponding to the latter ages.

For Series A mixes, the 28 days dynamic modulus of elasticity of control mix (F0) (i.e. 43.0 GPa) has been

3.5. Relationship between dynamic modulus of elasticity and compressive strength of FRCCP

Fig. 11 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 that are shown in Fig. 11.

The relation can best be expressed as:

$$E_d = 3.176(f_c)^{0.684} \quad R^2 = 0.908 \quad (5)$$

The empirical Eq. (5) confirms the findings of Salman et al. [46]. Proposed empirical Eq. (5) 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.

3.6. Proposed Empirical equation for dynamic modulus of elasticity with age of RCC

From the experimental results obtained in this investigation on RCC mixtures using M-sand as fine aggregate in combination with River sand and fly ash as mineral admixture for partial replacement of cement, there is a relationship existing among dynamic modulus of concrete, UPV, age of concrete and fly ash content. Hence an empirical equation has been proposed for the prediction of dynamic modulus of elasticity of roller compacted concrete at any age of concrete and for percent replacement of fly ash of Class F. The best – fit multiple regression equation was proposed based on the test data:

$$(E_d)_t = 14.90(\text{UPV}) - 0.017(p_{fa}) + 0.0135(t) - 24.17 \quad (6)$$

Multiple correlation coefficient (R) = 0.995 and significance $F = 1.608e^{-81}$

where,

$(E_d)_t$ = dynamic modulus of elasticity at the age of t days in MPa.

UPV = Ultrasonic Pulse velocity in km/s.

p_{fa} = % of replacement of cement by fly ash.

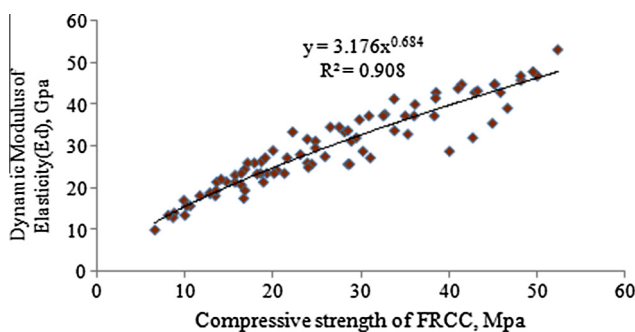


Fig. 11. Relationship between E_d and compressive strength of FRCC mixes.

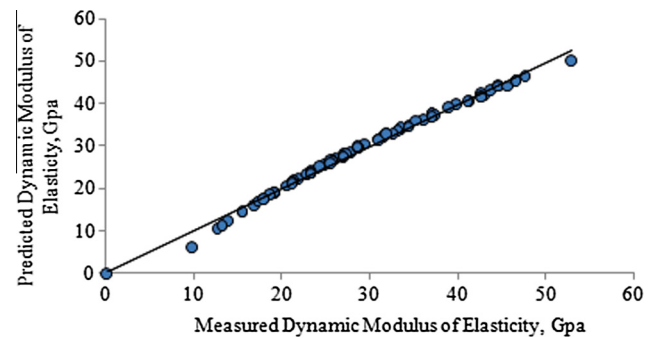


Fig. 12. Comparison of predicted and measured values of E_d of FRCC mixes using proposed model.

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 Fig. 12. Fig. 12 show that the measured and predicted values are in good relation. Eq. (6) has been proposed for evaluating dynamic modulus elasticity of roller compacted concrete for flexural strengths varying between 3.5 MPa to 5.0 MPa, Fly ash conforming to IS 1727 (1967) [48] and M-sand conforming to IS 383 specifications [28].

4. Conclusions

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

- (1) The Ultrasonic Pulse Velocity of RCC mixes with fly ash as partial replacement of cement increases with increase in curing at all replacement levels as expected in all three series of mixes.
- (2) In Series A, B and C mixtures where the cement was replaced partially with fly ash, the compressive strength, the UPV and the dynamic modulus of elasticity were decreased with increase in fly ash content. This is attributed to the lower strength contribution of fly ash to cement even at the age of 90 days.
- (3) In Series B mixtures where the fine aggregate is M-sand (100%), the UPV, strength values and dynamic modulus values are lower than the Series A mixture. It is due to the fact that M-sand produces harsh mixes and requires more water/cement ratio than normal concrete which contains River sand as fine aggregate.
- (4) In Series C mixtures where the fine aggregate is in combination of M-sand (50%) and River sand (50%) yielded higher strengths, UPV and dynamic modulus of elasticity at all replacement levels of fly ash. This is due to proper packing of aggregate which resulted in increasing the density of packing.
- (5) The quality of roller compacted concrete with fly ash at 3 days is found to be doubtful for Series A mixes at 40%, 50% and 60% replacement levels, for series B mixes at 30%, 40%, 50% and 60% replacement levels

and for series C mixes at 50% and 60% replacement levels. At 7 days of curing, Series A and B produced RCC of doubtful quality at 50% and 60% replacement level. However, in Series C mixes at 7 days age all mixes produced medium quality to good quality mixes, hence M-sand can be considered as partial replacement of River Sand. At 28 days age only Series A and Series B mixes have produced doubtful quality at the level of 60% replacement of fly ash.

- (6) An empirical equation has been proposed for time dependent dynamic modulus of elasticity of roller compacted concrete containing fly ash and it was found to be in good agreement with experimental test results.

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