Engineering Journal issn: 0125-8281

Article

Correlation Between Compressive Strength and Ultrasonic Pulse Velocity (UPV) of Fly ash Cenosphere Concrete

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Abstract. The utilization of Fly Ash Cenosphere (FAC) as a substitute for sand in concrete presents a practical solution to address environmental concerns stemming from the disposal of fly ash. However, it's essential to recognize that the strength properties of FAC concrete differ from those of conventional M sand concrete. To effectively manage design and quality control in construction projects, it becomes necessary to explore the applicability of non-destructive testing methods for estimating the in-situ mechanical characteristics of FAC concrete. In this context, the current research study seeks to establish a connection between compressive strength and ultrasonic pulse velocity (UPV) as a means of predicting the compressive strength of FAC concrete using UPV testing. The study also investigates the influence of FAC replacement levels and curing duration. The experimental program involves a concrete mix proportion of 1:1.95:1.96 with a constant water-cement (w/c) ratio of 0.5. FAC replaces M sand in varying percentages from 10% to 50%, in increments of 10%, while the control mix maintains 100% M sand content. Concrete samples are cast, cured at ambient temperatures, and subsequently tested at curing ages of 7 days, 14 days, and 28 days. The consistent findings demonstrate that FAC concrete consistently exhibits lower UPV values and compressive strength compared to the control concrete across various replacement levels, curing durations, and mix compositions. Additionally, empirical relationships were established between compressive strength and UPV, displaying a strong exponential nature and a high correlation, ranging from 0.91 to 0.99. The effectiveness of these developed empirical equations for predicting compressive strength is validated through a comparison with actual test results.

Keywords: Fly ash cenosphere, compressive strength, non-destructive technique, ultrasonic pulse velocity (UPV).

ENGINEERING JOURNAL Volume 28 Issue 4
Received 27 January 2024
Accepted 14 April 2024
Published 30 April 2024
Online at https://engj.org/
DOI:10.4186/ej.2024.28.4.41

DOI:10.4186/ej.2024.28.4.41

1. Introduction

The construction sector shoulders a substantial responsibility for the excessive extraction of natural sand from riverbeds in response to the escalating demand for housing and infrastructure [1]. Concrete, a pivotal constituent in building structures, predominantly comprises cement, fine aggregate, water, and admixtures [2]. The incorporation of Fly Ash Cenosphere (FAC), a by-product derived from thermal power plants, as a fine aggregate in concrete represents a sustainable and eco-friendly stride toward fostering sustainable construction practices [3]. Numerous researchers have probed into the characteristics and feasibility of integrating FAC as a substitute for natural sand in concrete, yielding encouraging outcomes, particularly in replacement percentages ranging from 20% to 50%. Compressive strength stands out as a pivotal property among concrete materials, serving as a vital determinant. Various physical and durability attributes, such as elastic modulus, impermeability, and resistance to environmental weathering, are believed to hinge upon strength and are consequently inferred from strength test results [4]. Multiple techniques are available for assessing the mechanical properties of concrete, broadly classified into destructive and non-destructive categories. Destructive methods, although accurate, entail high costs, extended timeframes, and necessitate sophisticated equipment. Non-destructive techniques offer an economical and straightforward alternative to evaluate material properties. In non-destructive approaches, material characteristics are correlated with measurable experimental parameters [5, 6].

The Ultrasonic Pulse Velocity (UPV) technique emerges as a prominent non-destructive method employed to assess the mechanical properties of various materials, including concrete, mortar, rock, masonry, bricks, and cement paste backfill [6, 7]. The versatility, repeatability, and simplicity of the UPV test render it highly effective for material condition assessments. This method involves the measurement of the velocity of ultrasonic pulses propagating through the given material specimens [8]. A multitude of studies have explored the utility of UPV testing in the realm of concrete evaluation. Wang and Wang [9] conducted research on the application of Ultrasonic Pulse Velocity (UPV) in self-consolidating waste glass concrete. They observed that the concrete's strength increased with age but decreased with higher water-to-binder ratios. Al-Nu'man et al. [10] developed a formula for compressive strength prediction in a single-grade concrete using UPV measurements. Shariati et al. [11] employed UPV and the Schmidt rebound hammer as non-destructive tests for assessing the compressive strength of reinforced concrete. More recently, Fatahi and Jafari [12] explored the prediction of compressive strength in lightweight aggregate concrete. Additionally, Lee and Lee [10] investigated the effects of the water-to-cement (W/C) ratio, curing conditions, and aggregate on early-stage direct transmission UPV. Previous literature has extensively employed UPV testing for characterizing mortar properties. Fly ash cenosphere (FAC) concrete, an environmentally friendly material, holds promise for applications in construction. While prior studies have examined various physical and mechanical aspects of Fly Ash Cenosphere (FAC) concrete, none have provided insights into predicting its compressive strength before construction. Therefore, the present study concentrates on establishing non-destructive UPV test-based predictive equations through empirical investigations. Experimental assessments were conducted on concrete specimens with varying levels of M sand replacement by FAC, specifically at replacement percentages of 10%, 20%, 30%, 40%, and 50%. Evaluations were performed at curing durations of 7 days, 14 days, and 28 days. The outcomes from these tests were plotted, leading to the formulation of empirical equations for predicting compressive strength utilizing UPV test data. To verify the reliability of the proposed empirical equations, they were rigorously validated against experimental test data.

2. Materials and Methodology

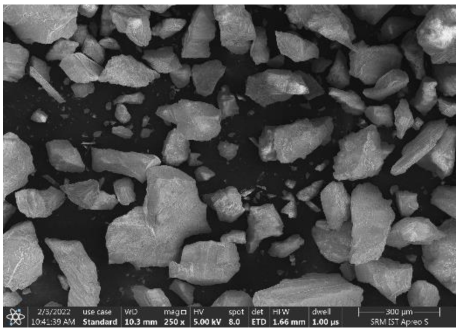
The materials employed in this study consisted of Ordinary Portland cement (OPC 53 grade) in accordance with IS 12269:1987 [13], Manufactured sand (M sand) in compliance with IS 383:2016 [14], and FAC. The M sand was procured from a supplier in the local area, while the Fly ash Cenosphere (FAC) was sourced from Thermal Plants. The physical properties of M sand and FAC were examined in accordance with the guidelines provided in IS 2386 (Part-III) [15]. The results of these tests are presented in Table 1.

Table 1. Physical Properties of M Sand and FAC.

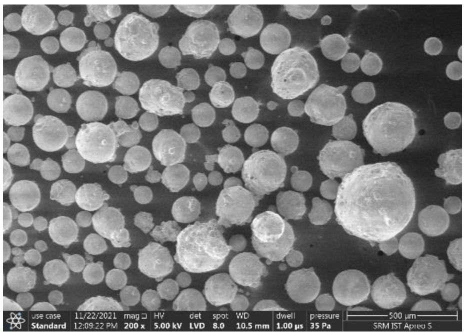
Description	Specific Gravity	Fineness Modulus	Water Absorption (%)	Bulk Density (kg/m^3)
M Sand	2.70	3.32	1.80	1650.00
FAC	0.73	1.97	8.00	485.00

Both M sand and FAC are classified under zone II of IS 383. The grading curve of the FAC was modified to resemble that of M sand, ensuring that the only variable under consideration is the type of fine aggregate used. Fig. 1 displays a scanning electron microscopic (SEM) image of M sand and FAC.

The FAC material has a high degree of porosity and has a smooth surface texture in comparison to M sand. In this investigation, five different volumetric mixes were employed, each with varying ratios of fine aggregate. FAC was utilized as a replacement for M sand at varying proportions of 10%, 20%, 30%, 40%, and 50%. The control mixture consists of fine aggregate composed entirely of M sand. The mix proportions of the various blends are provided in Table 2.



(a)



(b)

Fig. 1. SEM Image (a) M sand (b) FAC.

Table 2. Mix Details.

Mix	Cement (kg/m^3)	M sand (kg/m^3)	FAC (kg/m^3)	Coarse Aggregate (kg/m^3)	Water (kg/m^3)
CC		838.72	0		
M1		754.84	23.11		
M2	430.00	370.98	46.21	845.05	215.00
M3		587.10	69.32		
M4		503.23	92.42		
M5		419.36	115.53		

The assessment of workability was conducted following the guidelines outlined in the IS: 1199-1959 [16]. A consistent water-to-cement ratio (w/c) was maintained across all concrete mixtures. The process of combining the substances was conducted in compliance with the guidelines outlined in IS 10262:2019 [17]. For each mix, three specimens were cast. Determination of specimen's density was in accordance with average of three specimens. To determine the compressive strength, the 100mm x 100 mmx 100mm cube samples were cast as per IS 516: 2018 [18]. The concrete samples were tested at 7, 14 and 28 days of curing age using 1000 kN Universal Testing machine. The UPV test involves testing of the same cube specimens before testing in destructive condition as per IS 1331-1992 (Part 1) [19]. Prior to undergoing Ultrasonic Velocity Profiling (UPV) testing, the terminal surfaces of the specimens were meticulously rendered smooth. Subsequently, a thin layer of grease was meticulously applied as a coupling gel. This procedure was undertaken to guarantee optimal contact between the transducer and the surface of the test sample. The UPV was measured using a transducer with a precision of 0.1, connected to UPV testing device. To mitigate instrumental errors, the UPV testing apparatus was precisely calibrated using a reference bar prior to commencing the test. The determination of UPV was accomplished utilizing the direct transmission technique, involving the placement of transducers on opposing surfaces of the concrete sample. The velocity of the ultrasonic pulses is given as:

$$UPV = x/t, \tag{1}$$

where UPV is the velocity of ultrasonic pulse in m/s, x is the distance travelled in m, and t is the travel time in s.

3. Result and Discussions

This section explains the fresh concrete properties such as workability and density. The compressive strength and UPV is correlated in brief.

3.1. Workability and Density

The adjustment of concrete mix flow was rigorously controlled to achieve a range of 20 to 70 mm in accordance with IS 456:2000 [20]specifications for structural applications. To ensure a consistent water-to-cement (w/c) ratio, water was not added subjectively. The variability in workability was precisely measured through the slump test. The graph depicted in Fig. 2 illustrates the variation in slump values required to attain the target workability. As depicted in the figure, the control mix exhibited a slump of 75 mm. However, in the case of mixes designated as M1, M2, M3, M4, and M5, the corresponding slump values were 69, 59, 52, 45, and 31 mm, respectively. These values represent reductions in workability of 8%, 21%, 31%, 40%, and 59% compared to the control mix. The decline in workability observed in the FAC mixes can be attributed to the substantial water-absorption characteristics of FAC in contrast to M sand. FAC particles possess a high degree of porosity when compared to M sand, leading to the absorption of available water within the concrete mix. Consequently, more water is necessitated to maintain the specified workability. Additionally, the smoother surface texture of FAC particles, in contrast to M sand particles, significantly enhances inter-particle friction, resulting in a notable reduction in workability. However when compared with M sand, FAC has smaller particle size with larger specific surface area. When specific surface area increases, water absorption increases. The FAC has a particle configuration which is hollow shell in nature. The water is adsorbed by the particle on initial phase and react with cement at its secondary phase [21, 22].

DOI:10.4186/ej.2024.28.4.41

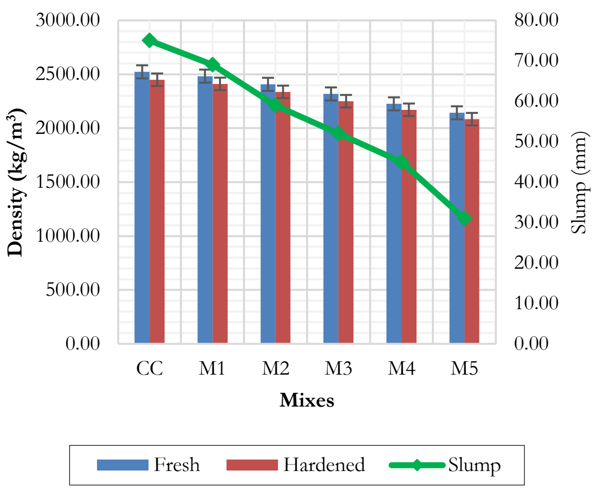


Fig. 2. Density and slump of FAC mixes.

Observations from Fig. 2 indicate a consistent trend wherein concrete compositions incorporating FAC exhibit notably lower dry densities when compared to the control mix. Among the series of mixes, the lowest dry density was observed in the case of M5, which contained 50 % FAC as its fine aggregate. This phenomenon can be primarily attributed to the elevated FAC content within the mixes. The reduction in the density of FAC mixes can be attributed to two key factors:

(a) A lower bulk density of FAC when contrasted with M sand.
(b) An increase in water absorption within the concrete to attain the required consistency.

Notably, FAC particles possess a porous nature, whereas M sand particles are solid, as depicted in Fig. 1. This distinction is further highlighted by the fact that the bulk density of FAC is approximately 20% lower than that of M sand, as documented in Table 1. Consequently, when FAC is integrated into the concrete mixture, it contributes to a reduction in density due to the formation of a greater number of pores, rendering the structure porous and lighter in weight when compared to conventional concrete [23].

3.2. Compressive Strength and UPV

3.2.1. Influence of varying proportion of FAC

The study on FAC contents on the ultrasonic pulse velocity (UPV) and compressive strength of concrete involved the assessment with varying levels of FAC replacement is shown in Fig. 3. For the sake of simplicity in the analysis, the 28-day curing was selected as the reference basis for evaluation on UPV and compressive strength measurements of concrete. Notably, as depicted in Fig. 3, an increase in FAC content correlates with a reduction in compressive strength. For instance, the concrete mixes denoted as M1, M2, M3, M4, and M5 exhibit compressive strengths of 36.70 MPa, 34.13 MPa, 32.70 MPa, 28.47 MPa, and 24.10 MPa, respectively which are lower when compared to the compressive strength of the control concrete samples, designated as CC (38.30 MPa). However, among the FAC concrete mixes, FAC up to 30% demonstrate comparable results with the control concrete, with a marginal reduction from 4.12% to 14.62%.

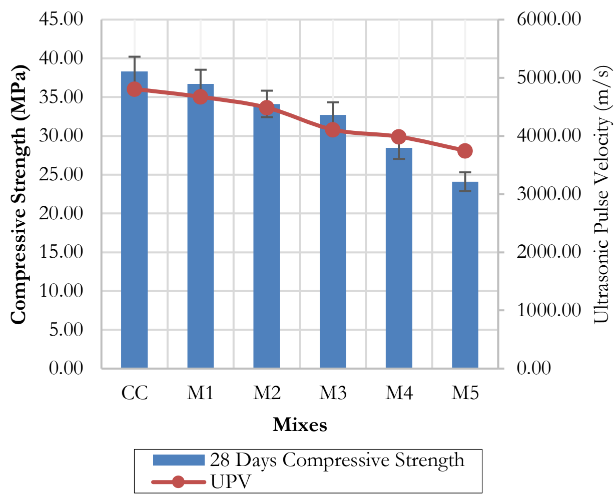


Fig. 3. UPV and Compressive strength in concrete specimens with varying levels of FAC replacement.

Due to the intrinsic porosity nature of the FAC particle, increase in FAC increases water absorption which results in more porosity. When the porosity of the concrete is more, the compressive strength of the concrete decreases due to inter transition zone crack between the cement paste. These observed trends align with findings reported in existing literatures by [24, 25]. However, in this study it has shown a more pronounced reduction in strength, likely attributable to the higher FAC content and increased water-to-cement (w/c) ratio in mixes compared to those studied in the existing literature. Also, the UPV values for FAC concrete are lower than those for control concrete, consistently decreasing with increasing FAC content. The 28-day cured FAC concrete samples exhibit UPV values ranging from 4672 to 3748 m/s, which are lower than the UPV value of the CC (Control Concrete) samples at 4808 m/s, as depicted in Fig. 3. The reduction in UPV values ranges from 2.83% to 22.05% for M1, M2, M3, M4, and M5 concrete specimens. The decline in UPV values is attributed to the lower dry density of FAC concrete, resulting in pore formation within the matrix filling up with air upon curing and drying period. The attenuation of pulse strength occurs when it traverses the air-filled voids in the concrete matrix, leading to an elongated path length and, consequently, the lower pulse velocity values observed.

3.2.2. Influence of curing period

The compressive strength test results, depicted in Fig. 4, exhibit a notable trend with respect to curing age. As observed, there is a progressive increase in the compressive strength of the specimens as the curing age extends. This phenomenon can be attributed to the prolonged curing period facilitating the formation of a greater quantity of hydration products, which, in turn, enhances the inter-particle bonding within the concrete matrix. However, it is significant that the rate of strength development and the magnitude of improvement differ among the specimens. This variation can be attributed to the differing compositions of the various concrete mixtures under investigation.

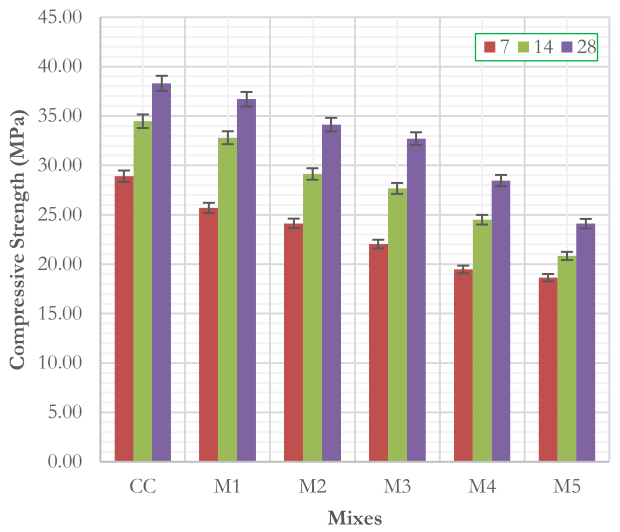


Fig. 4. Compressive strength at various curing age.

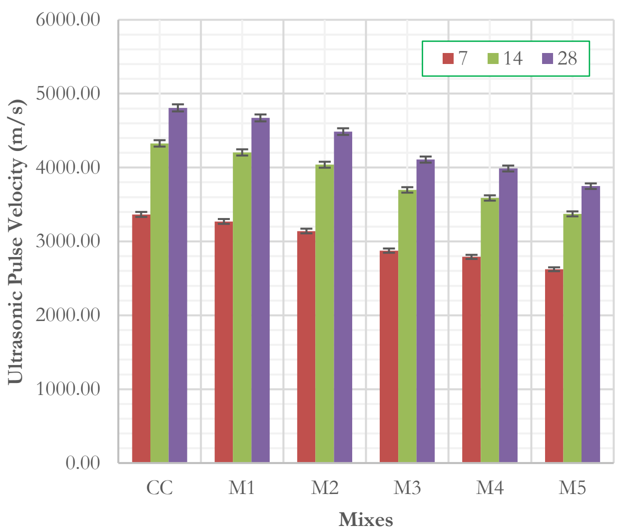


Fig. 5. Ultrasonic Pulse Velocity at various curing age.

The UPV (Ultrasonic Pulse Velocity) results, as illustrated in Fig. 5, demonstrate a consistent pattern across different curing periods. Equivalent to the behavior observed in compressive strength, the UPV values for all specimens exhibit an incremental trend as the curing period extends, regardless of the type of aggregate. The average increase in UPV values at 28 days of curing ranges from 0.35% for the control mix when compared to the UPV at 7 days. Similarly, in the case of FAC mixes the enhancement in UPV ranges 2.82% to 22.04% when compared to CC at 28 days. This phenomenon can be attributed to the constant hydration process over an extended curing period, resulting in the filling of pores within the concrete matrix with hydration products, i.e., Calcium-Silicate-Hydrate (C-S-H). Consequently, the concrete specimens become more compact and denser. Because of this densification, the velocity of ultrasonic pulses increases because less time is required for the pulses to traverse the solid concrete matrix. These findings align with prior research in the field, validating the observed effects of curing age on UPV values and the corresponding densification of concrete due to constant hydration [26].

3.2.3. Correlation between UPV and compressive strength

The arrived findings indicate a notable influence of FAC content, duration of curing on the Ultrasonic Pulse Velocity (UPV) and compressive strength of the concrete. The experimental analysis was conducted at varying concrete ages of 7, 14, and 28 days. To elucidate the correlation between these parameters, all collected data points were consolidated and visualized, as depicted in Fig. 6.

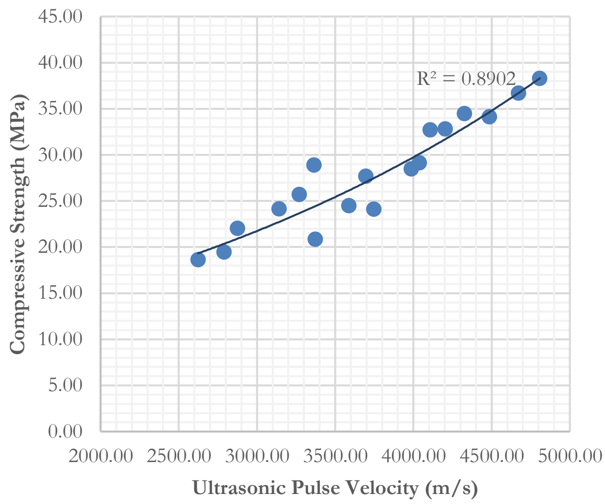


Fig. 6. Compressive Strength versus UPV.

The plotted test results demonstrate a discernible exponential relationship between the compressive strength of FAC concrete and UPV, as follows:

$$f_c = a^{eV} \quad (2)$$

where f_c is the compressive strength of concrete in MPa, e is exponential constant, and V is the Ultrasonic Pulse Velocity of the concrete in m/s. The general empirical equation of the arrived FAC concrete obtained to predict compressive strength from UPV values is,

$$f_c = 0.26^{e0.003V} \quad (3)$$

The coefficient of determination (R^2) for the FAC mix proportions reached an approximate value of 0.89. Figure 6 signifies that the variations observed in compressive strength concerning Ultrasonic Pulse Velocity (UPV) are effectively explained by an exponential relationship. Prior research conducted by Del Rio et al., [27] Nash et al., [28]and Shariq et al., [25] also supports the notion of an exponential correlation between UPV and compressive strength in concrete. To be more specific the graph illustrating the relationship between compressive strength and UPV in FAC concrete samples, segregated by different curing ages, is presented in Fig. 7.

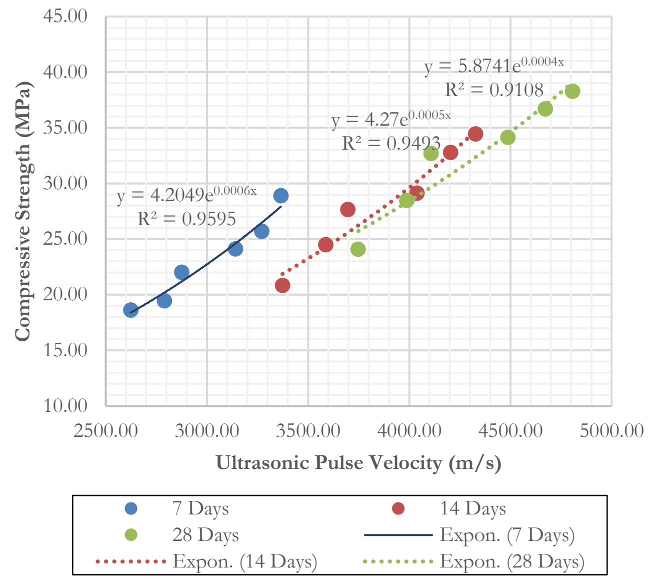


Fig. 7. Relationship between compressive strength and UPV in FAC on different curing ages.

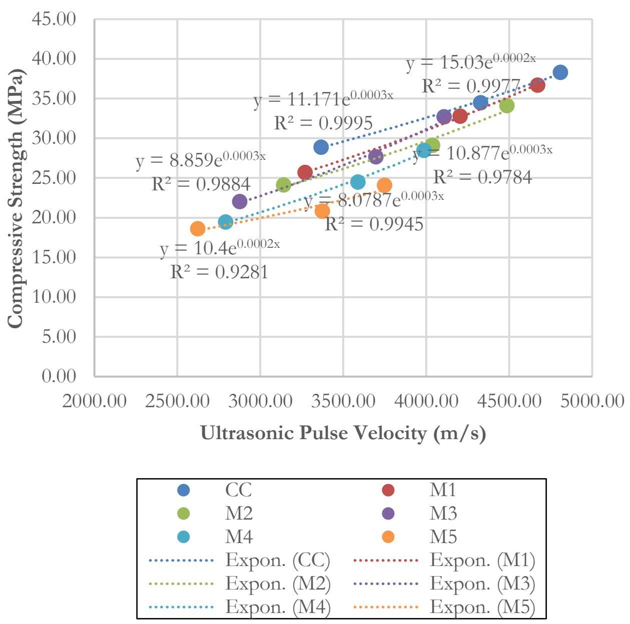


Fig. 8. Relationship between compressive strength and UPV in FAC on different mixes.

From Fig. 7 and Fig. 8, the coefficient of determination (R^2) exhibits variability, ranging from 0.90 to 0.96 for different curing periods and from 0.93 to 0.99 for distinct FAC replacement levels in the concrete specimens. To check the feasibility of FAC, the experimental results of FAC mixes were correlated with the predicted compressive strength based on Eq. (2). Figure 9 provides a comparison between the predicted compressive strength and the experimentally derived compressive strength values of FAC mixes.

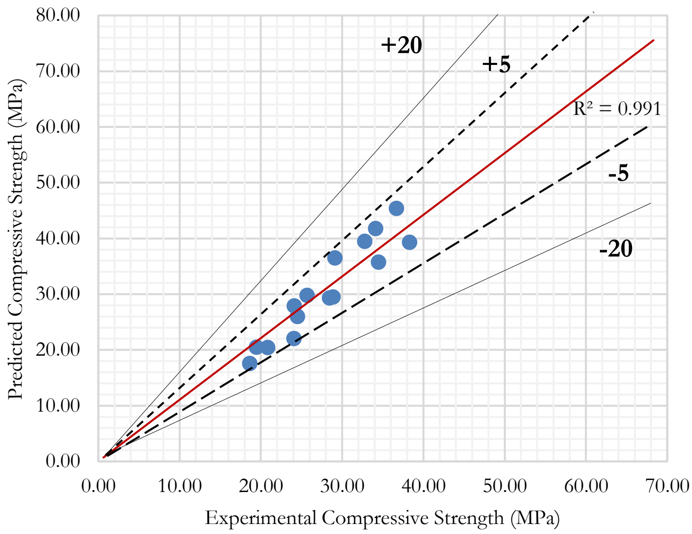


Fig. 9. Comparison between the predicted and experimental compressive strength.

From Fig. 9, most of the data points closely align with the 45-degree similarity line, indicating a strong concordance between the predicted and experimental results. However, a few data points fall slightly below the similarity line but remain within the acceptable deviation range of ± 10%. Furthermore, the predictions for compressive strength at 7 days, 14 days, and 28 days closely track the similarity line, underscoring the consistency between the predicted values and the experimental outcomes. This observation lends strong support to the efficacy of the proposed exponential equations as a reliable method for forecasting the compressive strength of FAC concrete specimens.

4. Conclusion

This study delves into the viability of employing the non-destructive Ultrasonic Pulse Velocity (UPV) technique as a means of assessing the strength-related properties of Fly ash cenosphere Concrete. A series of concrete specimens encompassing varying levels of FAC content within the range of 10% to 50%. Subsequently, these specimens undergo testing at distinct curing durations of 7, 14, and 28 days. The findings of this investigation yield the following significant conclusions:

The influence of FAC inclusion on UPV reflects that on compressive strength, with both parameters exhibiting a decline as the replacement level of FAC increases from 10% to 50%. Nevertheless, at lower substitution percentages, specifically up to 30%, the UPV and compressive strength results remain near those of the control concrete.

As the curing duration extends from 7 to 28 days, both compressive strength and UPV notices an improvement in their values. However, the rate and magnitude of this increase are contingent upon the composition of the concrete mix.

An empirical exponential relationship is established between UPV and compressive strength within the FAC concrete. Remarkably, plotting UPV against compressive strength at varying curing ages independently agrees these exponential relationships, exhibiting strong correlation coefficients ranging from 0.90 to 0.96 for different curing periods and from 0.93 to 0.99 for different levels of FAC replacement in the concrete specimens.

The estimable agreement between the predicted values and the experimental test results substantiates the efficacy of the proposed empirical equations in accurately assessing the compressive strength of FAC concrete samples.

This study underscores the feasibility of utilizing the UPV technique as a rapid and effective means for estimating the crucial characteristics of FAC concrete. In the pursuit of further advancing the application of FAC concrete, future research endeavors are encouraged to explore the impact of additional controlling factors such as particle size distribution, curing regimens, FAC mineralogical composition, admixtures, and other relevant parameters on the UPV-strength relationships in FAC concrete.

Credit author statement

Kowsalya M: Writing – Original Draft, Visualization, Methodology, Reviewing & Editing ; **Sindhu Nachiar S:** Conceptualization, Supervision, Reviewing & Editing; **Anandh S:** Supervision, Reviewing & Editing, Formal Analysis.

Acknowledgement

We would like to acknowledge Concrete Laboratory, Department of Civil Engineering, SRM Institute of Science and Technology for conducting the experimental works.

Conflict of Interest

The authors declare no conflict of interest.

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DOI:10.4186/ej.2024.28.4.41

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