Research on Engineering Structures & Materials
journal homepage: http://www.jresm.org

Research Article

Leverage of high-volume fly ash along with glass fiber for sustainable concrete

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Article Info

Article history:

Received 5 Oct 2021
Revised 13 Apr 2022
Accepted 12 May 2022

Keywords:

Sustainable;
Fine-grain fly ash;
Glass fiber;
Durability;
Ultrasonic pulse velocity;
Electrical resistivity

Abstract

The production of fly ash is mounting steadily every year all over the globe, but the rate of recovery is insufficient compared to its production. The disposal of fly ash is becoming more and more difficult in India. Reusing fly ash for some valuable uses is one of the most convenient solutions to this problem. As a result, the present study has focused on the use of high volume fine grain fly ash as a partial alternative material for cement and sand with a low volume fraction of glass fiber. Glass fiber reinforced concrete mixtures consisting of up to 40% replacement of cement and sand by fly ash were produced for making sustainable concrete. The experimental work was carried out by preparing diverse mixes with a 0.40 water-cement ratio and analyzing the fresh as well as hardened properties of mixes. The experimental results reveal that the separate and combined replacement of cement and sand by fly ash together with glass fiber, enhance the durability and strength of concrete. When combining 20% of cement and 40% of sand replaced by fly ash together with glass fiber, better result was observed than all other mixes. The compressive strength, electrical resistivity (ER), and ultrasonic pulse velocity (UPV) increased by 36.33%, 65.82%, and 7.25% over control mix (C0-0). This discovery is very useful for making dense, durable and sustainable concrete by using proposed mixes.

1. Introduction

Concrete is the utmost versatile and widespread construction material throughout the world, in which cement and sand (fine aggregate) are, basic components. The main role of cement in concrete is as a binding material while sand is used as a filler material. The sources of lime curtail due to the huge production of cement as the demand for infrastructure increases gradually. But during the production of cement, CO_2 is released into the atmosphere which creates environmental issues. Besides cement, the demand for natural sand also increases day by day due to the huge developmental work. The growth of society demands the generation of a wide range of waste items and industrial by-products. These materials end up in the environment, producing major issues. [1]. Today's need is to utilize these industrial-by-products for reducing the adverse effects on the environment. Researchers have thoroughly investigated the use of industrial by-products as supplementary cementitious materials in concrete, as well as their influence on strength and durability criteria. But the combined replacement for cement and fine aggregate by fly ash and their influence on strength and durability characteristics are lacking in the literatures. The recent efforts of researchers, concrete technologists and construction industries are to produce high strength, high performance and sustainable concrete at the lowest possible cost. Hence the present research was taken up to study the feasibility of and for purpose of comparison of locally available industrial by-products like fly ash as a partial alternative material for cement and fine aggregate along with glass fiber for making durable and sustainable concrete.

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DOI: http://dx.doi.org/10.17515/resm2022.349st1005

For generating one ton of cement, almost one ton of CO_2 is released [2], which is harmful to our society. Therefore, to reduce cement utilization, cement producers should use supplementary cementitious materials such as fly ash up to 25% to 35% in Portland Pozzolana Cement (PPC). On the other hand, due to government restriction on sand mining from a river bed, projects are delayed which increase the total cost of construction, thus the contractor always requires partial or full replacement material for sand. Presently, India is having about 167 major coal-based thermal power stations with an installed capacity of 177,070 Mega Watt (MW) which produced over 196.44 million tons (MT) of fly ash, out of which 131.86 MT is utilized [3]. According to the notification after 3rd November 2009 by the Ministry of Environment and Forest (MoEF), the utilization of fly ash should be 100% after four years from the date of commission i.e. at 2013, but at present consumption of fly ash is 67%, that means still 33% fly ash is unused creating environmental problems. The Indian government's Ministry of Energy estimates that around 600 million tons of fly ash will be produced annually between 2031 and 2032 [4]. Management of fly ash will pose a serious issue in the upcoming year if not handled properly, and it will require a huge land area for dumping. To fulfil this requirement, present paper discusses the use of high volume fine grain fly ash as a partial alternative material for cement as well as fine aggregate with the addition of a low quantity of glass fiber for making durable and sustainable concrete.

Numerous researchers disclosed that fly ash is used as a supplementary cementitious material due to its major advantages. One of the most important results of fly ash in a concrete is to improve its workability, as the fly ash particles are comparatively spherical than cement particles. Researcher's concluded that, Fly ash has a ball bearing effect due to its spherical shape hence, the flowability of fly ash concrete increases [5]. By substituting 30% of the cement with fly ash, 7% less water was required than the control mix of an equal slump [6]. By using 50% ultra-fine fly ash the rheological properties such as yield stress and plastic viscosity were increased by 76% and 169% respectively [7]. An improvement in rheological parameters and workability is due to increase in fly ash amount in the mix [8]. Researchers found that with increasing fly ash percentage in concrete as cement replacement (50% to 60%) the strength decreases [9-14]. The reduction in strength with the addition of high volume fly ash could be largely associated with the slow pozzolanic reaction of fly ash. However author also reported that in concrete with 50% fly ash as cement replacement including 0.5%, 0.75% and 1% steel fibres, the 28 days compressive strength increased by 7.3%, 7.46% and 9.2% respectively [15]. The laboratory experiment using 35%, 45% and 55% of class F fly ash as a replacement of fine aggregate, conclude that depending upon the fly ash content the compressive strength, splitting tensile strength, flexural strength and modulus of elasticity increased by 25 to 41%, 12 to 21%, 14 to 17% and 18 to 23% correspondingly at 28 days. Also, the enhancement in strength was continuous at 91 and 365 days [16]. By using fly ash as a partial alternative for fine aggregate (20% -30%) it is possible to preserve the supposed technological properties of cementitious composites and to greatly limit the costs of these undesirable residues for the environment [17]. By adding fly ash to the desalinated ocean sand mortar, the performance and mechanical properties of modified cement were extensively improved [18]. The researchers mention that, the inclusion of different fibers gives an excellent concrete performance, whereas fly ash in the mix can make up for the loss of workability owing to the incorporation of fibers and boost the strength [19-20].

Also, the investigators find that, the addition of finest particles such as the fly ash in mixture improves the durability of concrete. With the addition of 50% fly ash through cement replacement, the ER value of concrete samples increased after 28 and 365 days of curing period [21]. When 50% of cement was substituted with fly ash the ER of concrete samples increased by about 4.8 times over plain concrete [22]. Replacing 20% of cement with a varying fineness of class C fly ash reduced the alkali-silica reaction by more than 50% at 14 days [23]. To know the outcomes of fly ash on carbonation depth (CD), the author concluded that, with the increasing replacement of cement with fly ash up to 50%, the carbonation depth also increases [24]. The heterogeneities in the microstructure of the hydrated portland cement paste, particularly the existence of large crystalline products and large pores in the transition zone were highly decreased by the inclusion of fine particles of fly ash [25]. As per Neville, the replacement of cement up to 20% by fly ash improves strength and workability [26]. According to IS 10262: 2019, the dosages of fly ash by mass of entire cementitious materials is recommended in between 15-30% [27]. For reducing the production of cement and due to scarcity of sand, present research focused on using up to 40% fly ash as a cement replacement and up to 40% fly ash as a sand replacement separately and in combined along with glass fiber. This innovation is also very useful for reducing the CO_2 emission which is produced during cement production as well as reducing the use of natural sand in concrete whose resources are depleting day by day.

2. Experimental Program

The present paper discusses the study of physical properties of procured materials by conducting various tests on OPC, fly ash, fine aggregate and crushed stone aggregate (20 mm & 10 mm). Also, the authentic outcome of individual and combined percentage replacement of cement and fine aggregate by fly ash along with glass fiber on fresh and hardened concrete properties such as workability, rheology, ultrasonic pulse velocity (UPV), bulk electrical resistivity (ER), carbonation depth and compressive strength tested at the ages of 7, 28, 56 and 119 days. The rate of gain of compressive strength of normal concrete is faster over the first 28 days of casting and then gradually decreases. However, in fly ash concrete mixes, large pozzolanic activation activities occur among the first 56-90 days [28]. Researchers also stated that, the concrete strength increased up to 6.2 to 16% over a period that varies between 28 and 56 days when fine aggregates are replaced by fly ash [29]. In order to determine the effect of high-volume fly ash on proposed mixes over a long term curing period, the samples were tested up to 119 days in the current study.

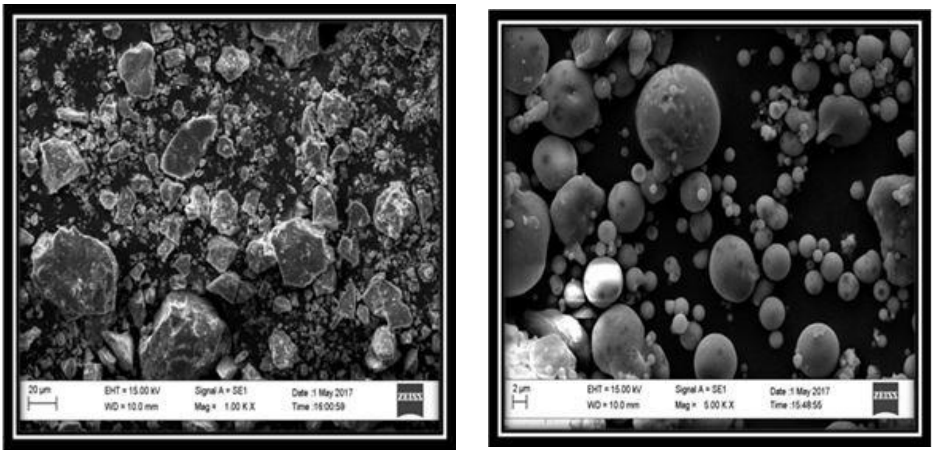
2.1. Materials used

2.1.1 Cement

The 53 grade Birla A-1 gold Ordinary Portland Cement (OPC) was purchased from locally available cement supplier was used in the present study. The initial and final setting time was found to be 118 minute and 220 minutes respectively. The specific gravity and soundness was observed as 3.15 and 2 mm respectively, while 3, 7 and 28 days compressive strength was observed as 31.5 N/mm^2, 38.5 N/mm^2 and 55 N/mm^2 respectively. All the results on cement were used as per the results of OPC conforming to the IS 12269-1987 [30]. The scanning electron microscope (SEM) test was performed on cement and revealed that the cement particles exhibit an irregular shape as shown in Figure 1 (a). The energy dispersion X-ray test (EDX) carried out on cement particles and its results are also organized in Table 1.

2.1.2 Fly Ash

According to IS 1727:1967 [31], the substantial properties of fly ash such as specific gravity and fineness were found as 2.15 and 12% (retained on 45-micron sieve) respectively. The SEM and EDX tests were conducted circular shape of the fly ash particles is observed as shown in Figure 1 (b) and their elemental content is shown in Table 1. The circular particle shape of fly ash helps for upgrading the workability of fresh concrete mix. The particle size distribution curve of fly ash and cement is shown in Figure 2.



(a) SEM image of cement particles　(b) SEM image of fly ash particles

Fig. 1 SEM image of cement and fly ash particles

Table 1. Elemental content of ordinary portland cement (OPC) and fly ash (%)

Chemical's elemental contents (%)	Si	Ca	Al	Fe	Mg	K	Na
OPC	16.68	67.82	4.74	3.67	1.88	2.42	0.39
Fly Ash	62.84	1.21	24.53	5.14	0.37	2.37	0.22

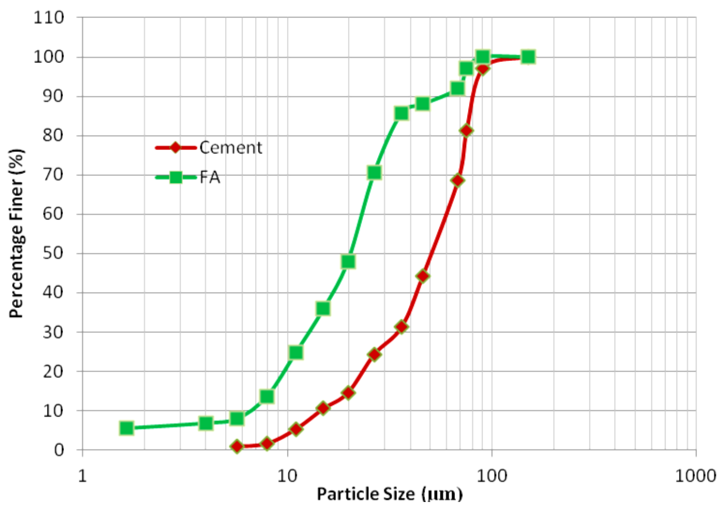


Fig. 2 Particle size distribution curves of fly ash and cement

2.1.3 Crushed Stone Aggregate

The crushed stone aggregates (20 mm and 10 mm) are collected separately from the local supplier. While collecting, it was ensured that the crushed stone aggregates were free from impurities, dust and clay particle etc. According to BIS 2386-1963 [32], the various substantial properties of aggregates were tested and are given in Table 2. As per BIS 383-1970 [33], to achieve the final grading of crushed stone aggregates, the aggregates of 20 mm and 10 mm are combined to 60% and 40% respectively. The mixing proportions were decided for achieving a crushed stone aggregate grading closer to the average of the desired grading guidelines.

2.1.4 Fine Aggregate

Nearby accessible Kharun river sand was procured from a local supplier and to protect it from dust it was stored in clean cement bags. According to IS 2386-1963, the various substantial properties of fine aggregate were tested and the results are arranged in Table 2 as an average of three samples.

2.1.5 Glass Fiber

In the present investigation, the discrete; alkali resistance (AR) glass fiber was used. The physical properties of the glass fiber, such as length were 12 millimeters, diameter 14 micrometers, tensile strength 1700 megapascals and elastic modulus 72 gigapascals, according to the available datasheet from the dealer. The nominal doses of glass fiber i.e. 0.6 kg/m^3 were decided based on trials to maintain the strength and workability at lower cost criteria. The investigator stated that as the volume fraction of the glass fiber increases, the compressive strength reduces caused by the difficulty of fully dispersing the fiber, and inability of good compact of mixes [34]. They also mention that additions of a minute quantity of fiber in the mix improve the compressive and splitting tensile strength than higher dose of fiber. In present study, while mixing the glass fiber in cement, care was taken that glass fiber should be mixed uniformly without the formation of balls.

2.1.6 Plasticizer

To improve the durability of concrete, polycarboxylic ether-based water-reducing solutions were used, the dosage was kept constant at 1% of the cementitious material.

Table 2. Physical properties of crushed stone aggregates and fine aggregate

Properties	Test Result		
	20 mm crushed stone aggregate	10 mm crushed stone aggregate	Fine aggregate
Specific gravity	2.68	2.65	2.56
Water absorption (%)	0.4	0.60	0.60
Bulk density (Loose in kg/m^3)	1480.34	1520.36	1648.7
Bulk density (Rodded in kg/ m^3)	1710	1730.14	1779
Bulk density (Vibrated in kg/ m^3)	1780.52	1811	1880
Percentage void (Loose)	45	43	35.50
Percentage void (Rodded)	36	35	30.50
Percentage void (Vibrated)	33.50	32	26.50
Impact Value (%)	9.71	6.57	---
Crushing Value (%)	22.57	17	---

2.2. Concrete Mix Proportions and Sample Preparation

To understand the effect of fly ash as a partial replacement material for cement and fine aggregate together with glass fiber, the mix design was prepared using 0.40 W/C ratios and mix percentages are specified in Table 3. In the present study, 20% and 40% cement was replaced by fly ash on a weight basis while 20% and 40% fine aggregate was replaced by fly ash on a volume basis.

Total 10 mixes were designed for 0.40 W/C including control mix, mix with glass fiber and mixes with a fly ash as a partial substitute material for cement and fine aggregate together with glass fiber. The control concrete mix is represented as Cx-y and concrete with glass fiber is represent as Fx-y. Here 'x' represents a percentage replacement for cement and 'y' represents a percentage replacement for fine aggregate. The specific gravity of cement was higher than the specific gravity of fly ash. The volume of fly ash was more than the volume of replaced cement. Hence, to counterbalance the total volume, the quantity of fine aggregate was reduced keeping the crushed stone aggregate same. The glass fiber content remained constant for all mixtures. According to IS 10262: 2019, when the cement was replaced by fly ash, the cementitious material increased by 10%. The crushed stone and fine aggregate used in this study were in a saturated surface dry condition.

Table 3. Concrete mix proportions for a 1m^3 concrete (0.40 W/C)

MIX	Cement (kg)	Fly ash (kg)	Crushed stone aggregate (kg)	Fine aggregate (kg)	Water (kg)	Glass Fiber (kg)	Admixture (kg)
C_{0-0}	418.5	0	1102	732	167.40	0.0	4.18
F_{0-0}	418.5	0	1102	732	167.40	0.6	4.18
F_{20-0}	368.4	92	1102	685	167.40	0.6	4.18
F_{40-0}	276.5	184	1102	671	167.40	0.6	4.18
F_{0-20}	418.5	150	1102	557	167.40	0.6	4.18
F_{0-40}	418.5	293	1102	383	167.40	0.6	4.18
F_{20-20}	368.4	230	1102	522	167.40	0.6	4.18
F_{40-20}	276.5	319	1102	510	167.40	0.6	4.18
F_{20-40}	368.4	366	1102	360	167.40	0.6	4.18
F_{40-40}	276.5	453	1102	351	167.40	0.6	4.18

All the ingredients of concrete for different mixes were uniformly mixed in a laboratory mixer. Weigh batching was conducted for the required quantities of all the materials. For proper mixing of glass fibers, the filaments of fibers were separated by hand and mixed with cement only. While mixing the fibers, proper care was taken that no balling of fibers should be created inside the mix. For proper mixing of the materials, firstly crushed stone and fine aggregates were mixed in a mixer for about two to three minutes. Water and superplasticizer were weighed and properly mixed in one container. A measured amount of cement was then poured into the mixer along with 50% of water, for proper mixing of materials the mixer was rotated for another two to three minutes. The 25% of water with superplasticizer was again poured inside the mix and rotated for two to four minutes in the mixer to get a homogeneous mix. The concrete mixed materials inside the mixer were taken out in a mixing tray. The remaining 25% of water was added to the rotating mixer for removing the cement and other concrete ingredients sticking to the inside of the mixer. At last, all the concrete materials in the mixing tray were properly mixed. Within 10 minutes of final mixing, the workability of mixture was measured via slump cone test followed by rheology test. The cube moulds of size 100 mm X 100 mm X 100 mm were filled in three different layers and slightly vibrated on the vibration table to eliminate the air bubbles and voids inside the concrete. All the samples were finished with a steel trowel after casting. Using wet gunny bags all the filled moulds were properly covered and de-moulded after 24 hours. After de-moulding of concrete cubes, they were submerged in a water curing tank for a period of 7, 28, 56 and 119 days.

2.3. Test on Fresh Concrete

To check the outcome of proposed mixes on the fresh properties of concrete, rheology and slump cone tests were performed. Especially attention was given to the behavior of workability and rheology of fresh concrete mixes. By using a rheometer as shown in Figure 3, yield stress and viscosity were measured for all 10 mixes and the results are tabulated in Table 4. Under stress conditions, to study the flow of material or deformation is termed as rheology, which generally consists of yield stress and viscosity. To begin the flow of a material, the minimum stress required is known as yield stress while viscosity is the resistance to the flow of the material. Rheological parameters help to illustrate the workability, placeability, compactability, finishability, flowability and pumpability of freshly mixed cementitious materials. The rheometer consists of two probes with 90 mm length on both sides of the centre of the shaft. Firstly, the freshly mixed concrete was poured into a container as shown in Figure 3 (a) and then inside the shaft of the container, the rheometer was placed as shown in Figure 3 (b). Then an input profile was chosen and stored in the smartphone which is supplied with a rheometer. By turning on the blue-tooth of the smartphone (used as a remote control) all the input commands of the rheometer are provided. With corresponding time, the rheometer recorded the torque at different locations, and for further analysis; the graphical measurements in the smartphone were transferred to the computer. The rheology is mainly used for such materials whose flow properties are difficult. Rheology expresses the workability in terms of numeric value which is more accurate and reliable than the slump cone test.

(a) Concrete mix in rheometer container   (b) Rotating rheometer in concrete mix

Fig. 3 Working of rheometer test apparatus

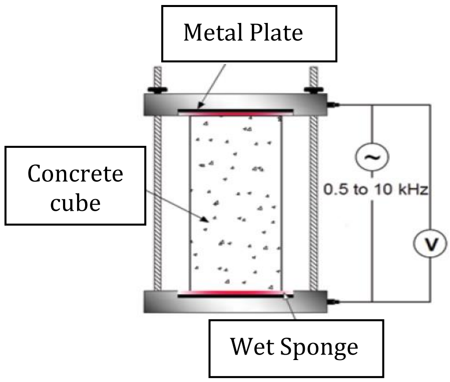
2.4. Test on Harden Concrete

For all 10 concrete mixes, the 100 mm x 100 mm x 100 mm cubes were tested for the required tests. The 160 cubes were tested for bulk electrical resistivity (ER) test and ultrasonic pulse velocity test (UPV) and same 160 cubes were tested for compressive strength by using a compressive testing machine at the age of 7, 28, 56 and 119 days. For the carbonation test, separate 40 cubes were tested at 28 days of curing period only. For each mix on each curing period, 4 cubes were tested for each test. Total 200 cubes were cast and tested for all 10 concrete mixes at different curing periods for different tests. To measure the ER of concrete cubes, a two-probe laboratory method was used. In this method, the soaked cubes were shifted between two similar metal plates of ER meter with a damp sponge placed on the bottom and the top face of the cube to provide contact between the concrete surface and electrode plates as shown in Figure 4 (a). By applying a small, irregular current at the proposed frequency, the voltage between the two ends of the concrete sample was measured. The electrical resistivity monitor displayed the impedance value (Z), through this impedance value, the resistivity of concrete was determined according to Eq. (1). The Simplified illustration of ER is shown in Figure 4 (b). This method gives a better suggestion of concrete electrical resistance as current is flown through the bulk of concrete.

$$\rho = \frac{A}{L} Z \tag{1}$$

Wherein, "ρ" is the resistivity of a concrete mix (Ωcm), "A" is the cross-sectional area of the specimen (cm^2), "L" is the length of the sample (cm) and "Z" is the impendence (Ω). By using Eq. (1) the result of ER are calculated and shown in Figure 8.

(a) ER equipment with concrete cube



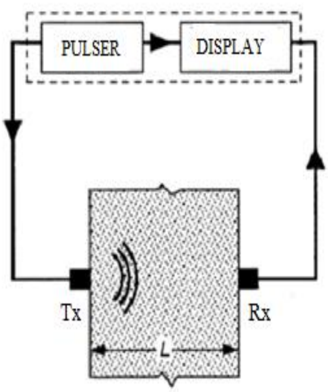
(b) Illustration of ER (Component)

Fig. 4 Arrangement of Electrical Resistivity Meter.

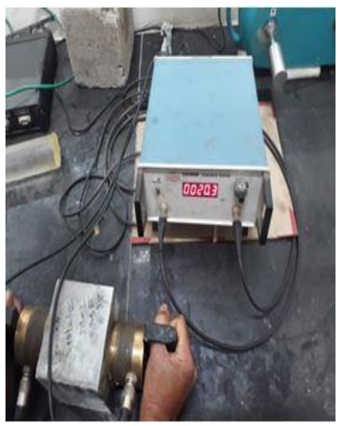
UPV test gives an idea about the strength, density and porosity of concrete. The UPV consists of computing the time travel of the pulse of longitudinal ultrasonic wave transient throughout the concrete sample. As per IS 13311 (Part-1) 1992 the results of UPV are calculated and shown in Figure 8. The UPV tester consists of two transducers and a monitor screen. To level and smoothen the rough surface area of the concrete cube, grease or petroleum jelly was applied on two opposite faces of the cubes. After that, the transmitting and receiving transducers were touched on both the sides of cubes to measure the time travel. In the transmitting transducer (T_X) the ultra-pulses of natural frequency within the range 20 kHz to 150 kHz were produced, which travel through concrete and then detected by receiving transducer (R_X) as shown in Figure 5 (a). The travel time period among the beginning of a pulse created at the passing transducer and the beginning of its arrival at the collecting transducer was measured and displayed on a monitor as shown in Figure 5 (b). With the help of the displayed value of travel time (T), the pulse velocity was determined by using Eq. (2).

$$V = \frac{\mathrm{L}}{\mathrm{T}} \tag{2}$$

To determine the carbonation resistance of the proposed concrete, 4 sample cubes measuring 100 mm x 100 mm x 100 mm were formed from each mix, a total of 40 cubes were formed for 10 different mixes and cured for 28 days. After curing, all cubes were taken out from the curing tank and allowed to dry at normal temperature. The air-dried cubes were placed in a carbonation chamber for 28 days. The "one week-time exposure of concrete specimen inside the carbonation chamber is to some extent equal to 12 months exposition beneath natural environment" [35]. According to this, in the present study, 28 days of cubes in the carbonation chamber gives an equivalent result after 4 years of concrete. The dose of temperature was kept at 35^{0}C, carbon dioxide (CO_2) at a rate of 5% and humidity at 70% as shown in Figure 6 (a). After 28 days of accelerated carbonation, the cubes were removed from the carbonation chamber and broken into two parts. To measure the depth of carbonation, a phenolphthalein indicator was applied on the broken surface of concrete cubes. On application of phenolphthalein indicator, pink colour was observed in an uncarbonated portion and in the carbonated portion, no change was seen as shown in Figure 6 (b). By using a measuring scale, the depth of carbonation was measured as shown in Figure 6 (c) and the results are shown in Figure 10. From the carbonation test, it can be concluded that fly ash as a partial sand replacement is very effective to reduce the carbonation depth of concrete. Wherein, "V" represents the ultra-pulse velocity, "L" represents the sample length and "T" represents the time travel.



(a)



(b)

Fig. 5 Arrangement of Ultrasonic Pulse Velocity Test

(a) (b) (c)

Fig. 6 Working of rheometer test apparatus

3. Result and Discussions

3.1. Workability and Rheology

By using a 0.40 water-cement ratio, all the mixes were prepared and the influence of fly ash together with the glass fibers on the workability and rheology parameters of the concrete was measured concerning the slump, yield stress and viscosity as shown in Table 4. According to the current investigation, it is seen that, glass fiber in the mix decreased the workability of concrete in contrast to the control mix. Also, the inclusion of glass fiber without any replacement in the mix signified that the yield stress and viscosity increased by 14.62% and 12.40% respectively than control concrete. The decrease in workability and increase in the yield stress and viscosity is due to the presence of glass fiber in mix which hinders the flow-ability of freshly mixed concrete [36]. It is also observed that as an alternative of cement increases by fly ash together with glass fiber, the workability of concrete also increases and is found to be 18.36% for higher replacement (40%) than control concrete. Similarly, the rheological parameters like yield stress and viscosity decreased 36.98% and 29.85% respectively than control concrete. The increase in workability and drop in yield stress and viscosity accounts due to the addition of fine grain fly ash which is spherical in shape and acts as a ball bearing effect which reduced internal friction and increases the flowability of fresh concrete [37]. In combined replacement, when 40% cement and 20% sand were replaced by fly ash together with glass fiber the slump was observed up to 14.28% more and yield stress and viscosity was observed as 31.69% and 29.43% respectively lower than all control mix.

Table 4 Result of slump and rheology test

Mix	Slump (mm)	Yield Stress (τ_0)	Viscosity (μ)
C_{0-0}	49	356.54	19.16
F_{0-0}	46	408.67	21.50
F_{20-0}	53	281.65	16.18
F_{40-0}	58	224.67	13.44
F_{0-20}	49	373.28	19.44
F_{0-40}	42	426.34	21.96
F_{20-20}	51	310.62	16.87
F_{40-20}	56	243.54	13.52
F_{20-40}	43	446.32	22.36
F_{40-40}	37	591.54	26.53

3.2. Compressive Strength

The compressive strength was calculated for 10 concrete mixes over 40 cubes for a 0.40 W/C ratio. Figure 7 shows the result of the compressive strength of various mixtures with diverse curing periods. The result shows that by adding 600 g/m^3 glass fiber to the mix, the compressive strength at 7, 28, 56 and 119 days of curing period increased by 4.88%, 5.08%, 5.53% and 5, 63% respectively over normal concrete. Plain concrete possesses low tensile strength and low tensile strain capacities i.e. brittle materials due to which cracks are inherently present in concrete even before loading. On the other hand, glass fiber has high tensile strength and high modulus of elasticity which are discontinuous and most commonly arbitrarily dispersed throughout the mix. Glass fiber in the cementitious matrix provides a bridge for stress to transfer across the cracks, which results in a decrease in the propagation of cracks in the fresh mix and increased the strength of concrete [38].

From the present analysis, it is examined that when 20% of cement was substituted by fly ash, slight strength reduced at 7 days but after 7 days the strength developed at an elevated rate than control concrete (C_{0-0}) and concrete with glass fiber (F_{0-0}). The 28 days strength improved by 11.65% while 119 days strength increased by 17.50% over control concrete. As the curing period increases, strength also increases due to slow and continuous pozzolonic reaction of fly ash mixes. The strength of concrete continuously increases, which could be attributed to the late gain of strength from the fly ash in the system [39-40]. The key finding of the present investigation is that even at 40% cement replacement by fly ash together with glass fiber, 56 days strength of mix (F_{40-0}) is almost equal to 28 days strength of control mix (C_{0-0}). From the test result, it may be concluded that it is possible to achieve 28 days strength of control mix at 56 days for the same W/C ratios even at 40% cement replacement by fly ash together with low doses of glass fiber, which reduced nearly 153 kg/m^3 of cement and consume a higher amount of fly ash and makes the concrete more sustainable by using the proposed method. The reduction in strength observed for 20% cement replacement at an early age (7 days) is because of slow pozzolanic reaction of a fly as compared to that of cement at the initial stage. At a later age, the increase in strength of concrete is due to the reaction in between hydrated calcium hydroxide in concrete and silica present in fly ash resulting in improved pore allocation in the mix. Finer fly ash offered a better particle packing effect, the unhydrated fine fly ash act as micro filler in the concrete which also improves the compressive strength of concrete [41].

The test results reveal that with an increasing percentage of fine aggregate replacement by fly ash, the compressive strength increased even at 7 days of curing period. When 40% of fine aggregate was replaced by fly ash (F_{0-40}) the compressive strength increased by 29% over the control mix at curing period of 28 days. The significant finding is that the compressive strength for 20% sand replacement by fly ash was nearly 2% higher than the compressive strength for 20% cement replacement by fly ash at 28 days. The increment in strength for fine aggregate replacement is due to the formation of extra CSH gel which reduced the pores inside the mixture [42]. The increase in strength due to fine particles is dominant which offered a better particle packing effect than sand particles hence, in sand replacement mixes better compressive strength observed over control and cement replacement mixes. For combined replacement, when 20% of cement and 40% of sand are replaced by fly ash together with glass fiber (F_{20-40}) best result is obtained than all other mixes. The increase in strength was observed as 36.33% more at the age of 28 days when compared to control concrete (C_{0-0}) as shown in Figure 7. The strength improvement in combined replacement (F_{20-40}) is because of the formation of extra calcium silicate hydrates (C-S-H) gel in fly ash based concrete and better particle packing arrangement, as it increases the microstructure by reducing the voids inside the concrete.

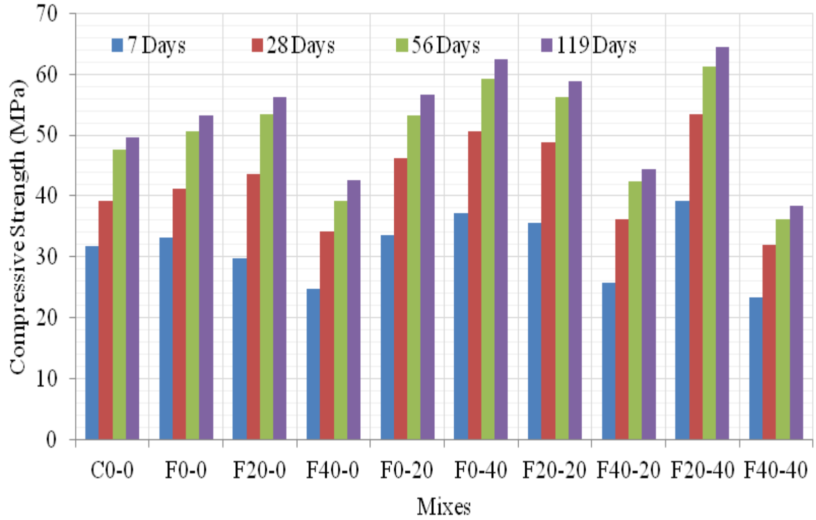


Fig. 7 Effect of separate and combine replacement of cement and sand by fly ash along with glass fiber on compressive strength over control concrete at different curing period

3.3. Bulk Electrical Resistivity

Electrical resistivity (ER) is generally dependent on the concrete microstructure like pore size and interconnection shape. It is observed that when 0.6 kg/m^3 of glass fiber is added to the mix the ER value increased nearly 11.75% than the control mix when the sample tested at 28 days. The discrete and randomly distributed glass fibres in the mix act as a crack arrester and hence reduce the permeability of concrete, resulting in increased electrical resistivity. The ER values for 7, 28, 59 and 119 days of curing periods are shown in Figure 8. From the test result it is seen that when separate 20% and 40% cement is replaced by fly ash together with glass fiber, the ER values increased by 28.50% and 49.20% respectively for a 0.40 water-cement ratio at 28 days of curing period. Fly ash as cement replacement material improved the particle packing which improve the microstructure of concrete, hence the ER values increased as cement replacement by fly ash increased.

In sand replacement mixes the ER values are more improved than cement replacement mixes. For 20% and 40% sand replacement, the ER values increased by 28.57% and 49.20% respectively at 28 days. The enhancement in ER result is due to extra finer contents which improve the packing density. When combine 20% cement and 20% sand ($F_{20\text{-}20}$) were replaced by fly ash, ER values increased up to 52.78% than the control mix ($C_{0\text{-}0}$). While for 40% cement and 40% sand replacement ($F_{40\text{-}40}$) the ER increased by 54% than control mix. In combine replacement, ER increased due to high amount of fly ash in concrete producing additional C-S-H gel which fills the voids inside the concrete. As well as finer fly ash fill the capillary pores which will be filled by water in control concrete. Hence combined replacement of cement and fine aggregate by fly ash together with glass fiber shows better results than other mixes.

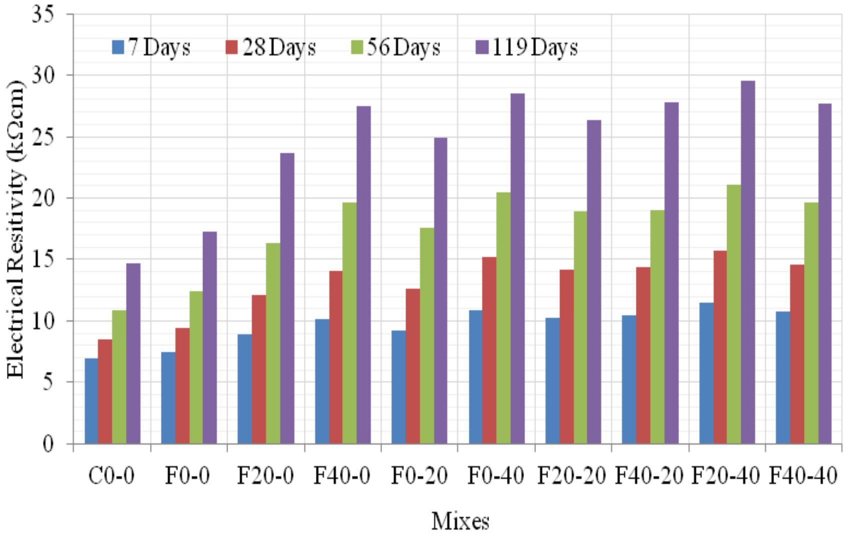


Fig. 8 Effect of separate and combine replacement of cement and sand by fly ash along with glass fiber on electrical resistivity over control concrete at different curing period

3.4. Ultrasonic Pulse Velocity

From a durability point of view, ultrasonic pulse velocity (UPV) is a very useful method that gives the idea about particle packing, homogeneity and quality of a structure. In the present investigation, the UPV values of various mixes reflect minor changes but higher changes in electrical resistivity (ER) were observed for the same mixes. The inclusion of 0.6 kg/m^3 of glass fiber in concrete improve the UPV values by 0.98% and 1.35% at 28 and 119 days respectively over the control mix. From the experimental investigation it is seen that as the percentage of cement replacement by fly ash increases, the UPV values also increased over the control mix. For 40% cement replacement along with glass fiber (F_{40-0}), the UPV increased up to 3.86% at the curing period of 119 days. The UPV values for different curing periods are shown in Figure 9. Fly ash produced more CSH gel which fills the voids inside the concrete. Also, finer fly ash improves the particle packing than cement particles due to which UPV increases as cement replacement by fly ash increases. While 40% sand was replaced by fly ash together with glass fiber the UPV values increased 3.35% to 6.94% at the curing period of 7 to 119 days respectively over the control mix.

Meanwhile, sand is replaced by fly ash together with glass fiber, the UPV values increased, which maybe because of the availability of additional finer fly ash in the mix which form additional CSH gel and reduce the voids inside the mix [43]. Also, coarser material (Sand) was replaced with finer material which improved the microstructure of concrete by increasing packing density. In view of the finer fly ash in concrete, the mix becomes denser than control concrete hence, UPV values increase as the proportion of sand replacement by fly ash increases. In combined mixes when cement and fine aggregate was replaced by fly ash together with glass fiber, the UPV values improved than control concrete (C_{0-0}) and concrete with glass fiber (F_{0-0}) as shown in Figure 9. For mix F_{20-20} and F_{40-40}, the UPV values increased by 5.57% and 8.68% respectively at the age of 119 days than the control mix.

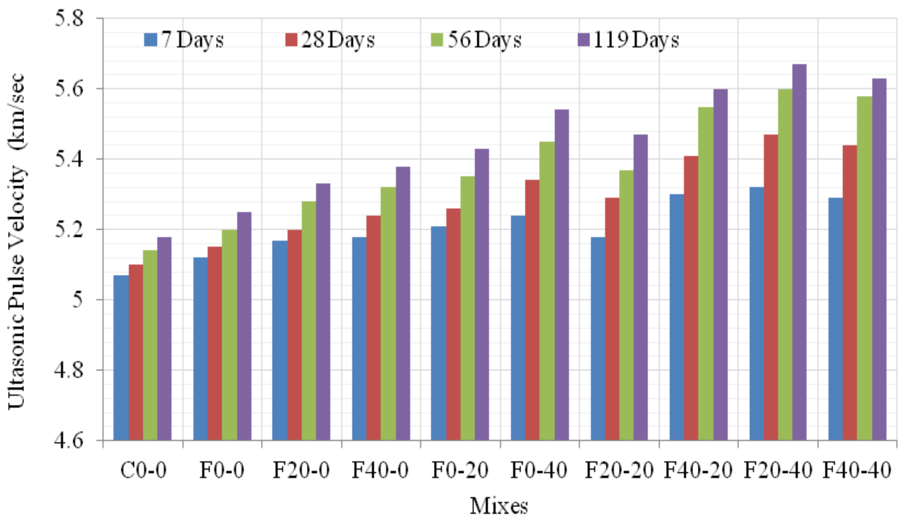


Fig. 9 Effect of separate and combine replacement of cement and sand by fly ash together with glass fiber on U.P.V. over control concrete at different curing period.

3.5. Carbonation Test

From carbonation test, it is seen that the addition of glass fiber in the mix reduced the carbonation depth by 12% over control concrete when samples were placed in a carbonation chamber for 28 days. The anti-cracking effect of glass fiber reduced the large number of microcracks in concrete which prevent the entry of CO_2 inside the concrete. Therefore, the addition of glass fiber in concrete reduced the depth of carbonation. From the experimental result it is also observed that as the cement replacement by fly ash increased, the carbonation depth also increased over control mix (C_{0-0}) and glass fiber mix (F_{0-0}). When 20% and 40% cement is replaced by fly ash together with glass fiber (F_{20-0} and F_{40-0}) the carbonation depth increased 2 times and 4.5 times more than the control mix. The expansion in carbonation depth is owing to the reduction of calcium hydroxide which reduced pH value and increased the depth of carbonation [44-45].

For sand replacement mixes, a positive result is observed on carbonation. The test result shows that as the percentage of fine aggregate replacement by fly ash increases, the depth of carbonation decreases than control mixes as shown in Figure 10. The reduction in carbonation depth was observed as 0.75 to 1.25 times more when 20% sand was replaced by fly ash together with glass fiber, while for 40% of sand replacement the reduction was up to 2 times more over control concrete (C_{0-0}). The carbonation depth reduced due to the total amount of carbona table constituents remains almost the same and the porosity decreases in sand replacement mix resulting in a reduction in carbonation depth observed than cement replacement mixes.

When combined cement and sand were replaced by fly ash together with glass fiber, the carbonation depth was slightly increased over control concrete (C_{0-0}) as shown in Figure 10. In combined replacement, the rate of increasing carbonation depth observed is lower than when only cement is replaced by fly ash mixes. For mix F_{20-20} the carbonation depth increased by 1.5 to 2 times more when compared to control concrete. For mix F_{20-40} the carbonation depth slightly increased over control mix.

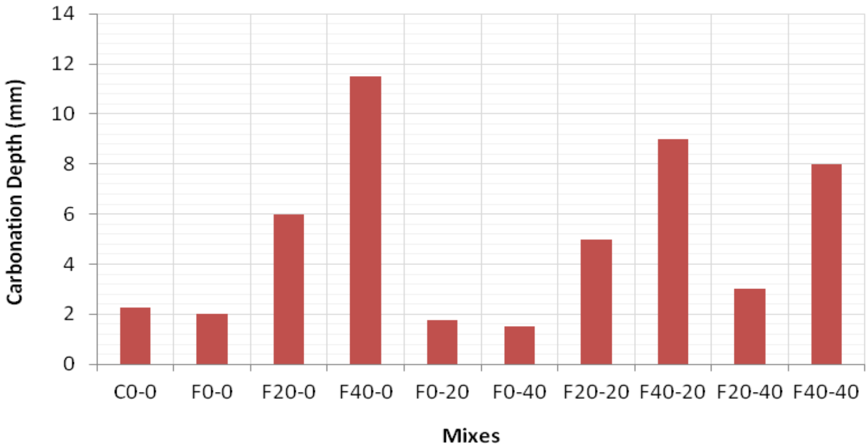


Fig. 10 Effect of separate and combine replacement of cement and sand by fly ash together with glass fiber on carbonation depth over control concrete at different curing period.

4. Conclusion

The prime purpose of the present research is an attempt to produce sustainable concrete by using available industrial by-products. The present research was taken up with the view to encourage the higher consumption of fly ash and minimize the use of cement and sand in concrete. Contactors are concerned about low early age strength because of the addition of fly ash as partial replacement materials for cement as well as a scarcity of sand in concrete. To address these concerns of contractors, glass fiber is used to compensate for the loss of early age strength in concrete when partial cement is replaced by fly ash. While partial replacements of sand by fly ash fulfil the requirements of sand for the construction industry, it also achieves higher strength and durability. The study was also taken up to curtail the use of cement and conserve locally available natural sand by utilizing the maximum quantity of fly ash available in the local region so that landfill area requirement for dumping the fly ash will be reduced. Supporting the test results, the subsequent conclusions were drawn to know the performance of proposed mixes by conducting different tests on fresh and hardened properties of concrete.

- Based on the present investigation it is observed that adding 0.6 kg/m^3 of glass fiber of whole volume of concrete, the slump height reduced by 6.12% and the yield stress and viscosity increased by 14.62% and 12.21% respectively than control mix. But loss of slump height due to inclusion of glass fiber is compensated by addition of fly ash in concrete. The carbonation depth reduced by 11.11%, while compressive strength, ER values and UPV values increased by 5.13%, 11.70% and 0.98% respectively at the age of 28 days than control mix.

- From the test result it is observed that when 20% of cement is substituted by fly ash in conjunction with fiber, the 28 days compressive strength, ER value and UPV improved by 11.65%, 38.90% and 2.40% respectively over control concrete. As the proportion of cement replacement by fly ash increased along with glass fiber, the workability and durability parameters increased while compressive strength decreased for higher replacement. For 40% cement replacement (F_{40-0}) the workability, ER, UPV and carbonation depth increased by 18.36%, 49.20% and 2.74% and 4.5 times respectively than control mix at 28 days of curing period.

- The important finding from the proposed mixes is that, even at 40% cement replacement by fly ash together with glass fiber, the 56 days strength of mix (F_{40-0}) is almost equal to 28 days strength of control mix (C_{0-0}). Based on the test results, it could be concluded that, it is feasible to attain 28-day compressive strength of control concrete at 56 days for the same W/C ratios even at 40% cement replacement by fly ash together with low doses of glass fiber and save nearly 153 kg/m^3 of cement for preparing 1m^3 of concrete.

- As the percentage replacement of sand by fly ash increased in conjunction with low volume of glass fiber, the carbonation depth reduces, on the other hand the compressive strength, ER and UPV values increased than control mixes and cement replacement mixes. For mix F_{0-40} the carbonation depth reduced by 2 times more than control mix. The Compressive strength, ER and UPV values increased by 25.61%, 65.31% and 6.94% respectively up to the age of 119 days over control mix.

- In combine replacement of cement as well as fine aggregate by fly ash along with glass fiber, the mixes F_{20-20} and F_{20-40} shows better result of compressive strength and durability parameters than all other mixes. For mix F_{20-40} the compressive strength increased by 36.33%, ER values increased by 65.82%, UPV values increased by 7.25% and nearly equal result obtained on carbonation depth when compared to control mix at 28 days of curing period. Using proposed method, it is possible to consume higher amount of fly ash and make the concrete more sustainable and durable.

- From the current research, it could be concluded that the addition of fly ash as cement replacement together with a small dose of glass fiber improves the durability of concrete in terms of ER and UPV. Also, sand replacement by fly ash together with glass fiber further improves the durability of concrete in terms of ER, UPV and CD. Fly ash in concrete improved the microstructure and proper bonding of fiber with a matrix which increased the durability of concrete. Hence partial replacement of cement and fine aggregate by fly ash together with glass fiber results in durable concrete.

- For combine replacement, up to 20% cement and 40% sand by fly ash along with 0.6 kg/m^3 of glass fiber is strongly suggested in general practice use. Without hampering strength, durability and cost of concrete, it will consume a high volume of fly ash and minimize the amount of cement and natural sand and make the concrete more durable and sustainable.

- By using high-volume fly ash in concrete as a partial substitute material for cement and sand, we tend to rescue natural resources to maintain the green environment and increase the durability of the structure at the bottom potential cost.

5. Future Scope of Present Investigation

Considering the surplus amounts of fly ash and use of limited amount of cement and availability of natural sand, the partial alternative of cement and natural sand by fly ash has economic and environmental benefits. The present investigations pertain to study on workability, durability and strength of concrete with separate and combine replacement of cement and natural sand by available fly ash in local region of India together with low doses of glass fiber for making durable and sustainable concrete. In context of the future scope of the present work could be as given below.

- Glass fiber has high tensile strength and arrests the cracks in the specific area and cracks propagation of concrete, hence self-healing capacity may be checked for different mixes.
- For comparison of the results among proposed mixes single constant dose of admixture for all W/C ratios is intentionally used in present investigation. Different doses of admixture with different W/C ratios suggested on case-to-case basis.
- Fly ash as sand replacement up to 40% increases the concrete durability and strength. More than 40% sand replacement by fly ash is suggested to reduce the use of natural sand and increased the strength and durability of concrete.
- Partial replacement of cement and sand by available fly ash together with hybrid fiber is suggested to enhance the concrete strength and durability.

Acknowledgement

I would like to thank, Civil Engineering Department NIT Raipur, for providing the facilities in the Concrete Technology Lab. I am very thankful to Dr. Sourabh Rungta, Director, Rungta College of Engineering & Technology Raipur, Chhattisgarh, India. I would like to also thank all the faculty and staff in the Department of Civil Engineering, NIT, Raipur for their help, inspiration and moral support, which have greatly contributed to the success of my work.

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