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Research article

An Experimental Study on Strength and Durability of Glass Fiber Reinforced Cement Concrete with Partial Replacement of Cement and Sand with Coal Ashes Available in Central Chhattisgarh Region

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Abstract

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transient method;

guideline for mix proportion;

energy efficient concrete

Chhattisgarh ranks 3rd in coal production in India and plenty of coal is mined daily in the central Chhattisgarh region of India. Hence, a lot of steel and power plants have been established in this region. From these power plants, a huge amount of fly ash and pond ash is generated daily, and these ashes are occupying large landfill areas. The carbon dioxide released from the chimneys of these plants not only pollutes the local air mass but also creates the problem of carbonation of local concrete structures. The corrosion of RCC structures in this highly industrialized local region surrounded by industry is accelerated due to the high emission of carbon dioxide. Hence, the strength and durability of concrete must be checked for the partial replacement of cement and sand with locally available industrial wastes in order to ascertain its long-term performance. The present investigation was taken up to do a detailed study on workability, durability, and strength of concrete by replacing cement with fly ash by weight up to 40% and sand with pond ash by volume up to 20% with a constant dose of glass fiber of 0.1% of the volume of the concrete. Various tests like rheology, shrinkage, electrical resistivity, ultrasonic pulse velocity, heat conductivity, leaching, compressive strength and flexural strength were conducted on various mixes of new coal ash fiber reinforced concrete. From these results, a mixed design process was proposed for the preparation of sustainable concrete from locally available industrial by-products.

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1. Introduction

In the present scenario, the continuous growth of urbanised areas in developing countries has increased due to rapid industrialization. A large amount of new construction has accompanied this rapid urbanization such as buildings for housing and industries, mass transit system for moving people, and facilities for handling drinking water and sewage for all of India's people [1]. India has witnessed unprecedented urbanization, with a high rate of population growth. Most of the Indian cities are growing due to economic, social, environmental as well as technological change [2, 3]. To fulfill the demand for mass construction, developing countries are facing a shortage of conventional building materials. Hence, such developing countries must utilize abundantly available industrial by-products like fly ash, pond ash, red mud, blast furnace slag, etc. as new building materials [4, 5]. Chhattisgarh is one of the few states of India that is resource-rich and a source of electricity and steel for the country. According to the Government of Chhattisgarh Mineral Resources Department, Chhattisgarh state has 16% of the total coal deposits of India, and it ranks 3rd in coal production. About 44483 million tonnes of coal have been mined from the 12 coalfields of the Chhattisgarh state located in Surguja, Koriya, Raigarh and Korba districts, and major steel and power industries are established in the area of Bhilai, Raipur, Bilaspur, Raigarh, Champa, and Korba. In Central Chhattisgarh region, there are 10 power plants that generate 20 million tons of coal ash annually. Both pond ash and fly ash impact badly on the environment. Bhanumati and Kalidas [6] reported that every million tons of fly ash used in concrete as a binding material may save a million tons of limestone, 0.25 million tons of coal and over 80 million units of power. It will also reduce the emission of 1.5 million tons of CO_2 to the atmosphere. Many researchers reported that fly ash used as a supplementary cementitious material shows different flow characteristics under different experimental conditions [7-9]. Several laboratory experiments have been conducted using pond ash as a cement or sand replacement material in concrete. Bharathi *et al*. [10] performed a detailed SEM analysis of particle size and shape of pond ash. They reported that particles of fly ash were very fine and generally had a smooth surface with a spherical shape whereas particles of pond ash were angular or lumped along with cenospheres. They also reported that since the particle size distribution curve was similar to the particle size distribution curve of fine aggregate, pond ash could be used as a sand replacement material. Jung and Kwon [11] collected pond ash from two sites in South Korea and used it in cement mortar as a sand replacement material. They took two w/cs and three different percentages of sand replacement by weight, i.e 0%, 30% and 60%. They found that as the replacement of sand with pond ash increased the workability, the flow value of mortar decreased. They got the highest compressive strength at the age of 90 days when 30% of sand was replaced with pond ash, and that was 25% higher than that of control mortar at 90 days curing. Bapat *et al*. [12] used pond ash in concrete up to 65% and found lower compressive strength than control concrete at 3 days of curing. However, the compressive strength of pond ash concrete at one year curing was greater than that of control concrete. Also, they reported that the setting time of pond ash concrete was more than fly ash concrete at the same replacement level. Tumingan *et al*. [13] replaced sand partially with pond ash by 12.5%, 25% and 50% in concrete. They found that at the age of 90 days, the compressive strength of the concrete achieved 95.13%, 89.73%, 85.74% and 81.87% of normal concrete, with different percentages of fine aggregate replacement such as 12.5%, 25%, 37.5% and 50%, respectively. Mishra *et al*. [14] investigated early-age shrinkage of OPC, PPC and PSC concrete in which fine aggregate was partially replaced with slag and pond ash up to 50%. They found that the shrinkage of PPC concrete and PSC concrete with 50% sand replaced with pond ash were 50% and 60% respectively lower than shrinkage of OPC with the same replacement of sand with pond ash. Moreover, they stated that low shrinkage occurred when sand was replaced with slag up to 50%, and in addition the slag provided a durable structure. It was found that a higher percentage of replacement of cement or sand with industrial by-products hampered the strength of concrete. To compensate for that decreased strength, people use fibers in concrete. The added fiber does not directly improve the concrete strength but the addition of fiber can arrest the cracks that develop in structures during the application of load. Hence, fiber reinforced concrete can better resist more compressive as well as tensile load than normal concrete. Over the last couple of decades, there has been a growing interest among researchers in developing a strain hardening fiber-reinforced concrete containing randomly distributed short fibers of relatively low volume fractions. Fiber-reinforced concrete is cement-based concrete reinforced with short random fibers, which exhibit strain-hardening and multiple-cracking behaviors under uni-axial tension. Fiber-reinforced concrete differs from other concretes in the areas of ductility, durability, permeability, and other important properties. Developing and enhancing the mechanical properties and durability of such type of concrete by adding fibers has been the focus of numerous studies. Banfill *et al*. [15] concluded that increasing the fiber volume and fiber length increases both the yield stress and plastic viscosity. Talukdar [16] performed a rheological experiment using steel fiber and concluded that increasing cement content, fiber volume and aspect ratio increased the yield stress and plastic viscosity. Vairagade and Kene [17] compared the compressive strength of concrete with steel fiber and polypropylene fiber and found that when copper-coated crimped rounded steel fiber of length 50 mm, aspect ratio 53.85 and 0.5% volume of the fraction was used in M20 grade concrete, maximum compressive strength was achieved. Mohammadi *et al*. [18] observed that when a 2% volume fraction of steel fiber was added, the compressive strength of the concrete increased by about 26% compared to that of plain concrete, and the 2% fraction of fiber represented the optimum value. The addition of fiber beyond this percentage reduced the compressive strength. Ramezanianpour *et al*. [19] introduced polypropylene fiber and found that the maximum tensile and flexural strengths were obtained from a mixture containing 0.7 kg/m^3 of polypropylene fiber (PPF), and extra addition of polypropylene fiber reduced the compressive strength. Furthermore, both splitting tensile and flexural strengths increased at first and then decreased with higher amounts of fiber. Ramli *et al*. [20] used coconut fiber in concrete and found better durability in terms of chloride penetration, intrinsic permeability, and carbonation depth with increase in fiber content. The intrinsic permeability improved because the fiber played a role in restraining the development of cracks. They recommended that the maximum dose of coconut fiber should be restricted to 1.2% of the binder volume, due to the drawback of its natural degradation. Dawood and Rami [21] showed that the uses of 0.25-0.5% of the palm and Barchip fibers with 1.5-1.75% of steel fiber gave better compressive strength, flexural strength and durability. They found that 2% steel fiber reduced the permeability value from 7.36X10^{-18} m^2 to 4.21X10^{-18} m^2. According to Banthia and Yoo [22], the tensile strengths of various fibres such as glass fiber (1000 to 2600 MPa), polyvinyl alcohol fiber (900 to 1600 MPa) and polypropylene fiber (200 to 760 MPa). Therefore, the addition of glass fiber at lower dose may increase the strain hardening property of concrete. Sujivorakul *et al*. [23] investigated glass fiber-reinforced specimens for water absorption, bending strength, bending strain, and toughness at 7, 28, 56, and 180 days after replacing cement with fly ash, rice husk ash and palm oil fuel ash.

As Chhattisgarh State has a lot of coal reserves, it becomes one of the major coal ash generating states in India. Because of this, a detailed study of concrete with up to 40% cement replacement with fly ash and 20% sand replacement with pond ash, both with the addition of 0.1% glass fiber is necessary to determine the effects on the workability, strength, and durability of concrete before use at the site. The present research proposes a method of preparation of a possible economical durable concrete with the required compressive strength for further practical use. In addition, the utilization of industrial by-products in concrete can reduce the amount of energy consumed in the preparation of cement.

In recent years, research has been focused on increasing the durability of high-performance concrete that incorporates supplementary cementitious material (SCM). There is limited research on the durability of concrete in which cement is replaced with fly ash and sand with pond ash. Cement companies when manufacturing Portland Pozzolana Cement (PPC), generally replace up to 25% cement with fly ash. Furthermore, the construction industry is always demanding an alternate material for partial replacement of sand due to the shortage of good quality natural sand. The main objective of the present study is to assess the suitability of concrete matrices prepared with pond ash and fly ash as alternate fillers and cementitious materials to sand and ordinary Portland cement (OPC), respectively, with the addition of a constant percentage of glass fiber to all mixes. This will save natural resources, enhance the utilization of waste material, reduce construction costs, and keep the environment green.

2. Materials and Methods

The present experimental research was undertaken to know the actual effect on concrete due to replacements of cement and sand by fly ash and pond ash with a constant dose of glass fiber. A good concrete should be workable in the plastic stage and should also provide the required strength and durability in the hardened stage. Because of this, a detailed experimental program was designed to know the behavior of the concrete in the fresh and hardened stages. The physical properties of various ingredients of concrete used in present research are shown in Table 1. Different properties of concrete such as workability, rheology, durability, and strength were studied. The mix design was prepared using three types of water-cement ratios, i.e. 0.35, 0.4 and 0.45, which are shown in Table 2. Fly ash replaced cement by 20% and 40% of the weight of cement whereas pond ash replaced sand by 10% and 20% of the volume of sand. In this research, to get the maximum benefit for the addition of glass fiber, the maximum size of coarse aggregate was kept at 10 mm, because the length of fiber used in this research was 12 mm [24, 25]. If the size of aggregate were to be smaller, the lap length of fiber with two aggregates would be larger. Hence, the strain-hardening property would be increased. The gradation curve for coarse aggregate, sand and pond ash is shown in Figure 1. The control concrete mix is denoted as $C_{x\text{-}y}$ and fiber reinforced concrete is denoted as $F_{x\text{-}y}$. Here 'x' denotes cement replacement and 'y' denotes sand replacement in percentage. All the above materials were mixed in a 40-liter capacity mixer. Weighed quantities of cement, sand and coarse aggregate were dry mixed until a uniform color was obtained. A measured quantity of water was added with adding admixture of 0.75% of cementitious materials. The mixes were prepared using three water-cement ratios with and without glass fiber and replacement of cement and sand by fly ash and pond ash, individually and simultaneously, at different percentages as given in Table 2. After completion of mixing, cubes and beam moulds were filled with concrete and compacted on a vibration table. After casting, top portions of all test specimens were finished with a steel trowel. They were covered with wet gunny bags at room temperature and then demoulded after 24 h. After demoulding of the cube specimens, they were put into a curing water tank for 28 and 119 days. For each mix, three samples of 100 X 100 X 100 mm cubes and 100 x 100 x 500 mm beams were cast as per BIS recommendations.

A detailed experimental program was designed to reveal the behavior of the concrete with pond ash and fly ash, in the fresh and hardened stages. The fresh concrete test consisted of rheology, slump, compaction factor, electrical resistivity and shrinkage whereas the hardened concrete tests consisted of compressive strength, flexural strength, bulk electrical resistivity, ultrasonic pulse velocity, carbonation, thermal conductivity and leaching. To assess the thermal conductivity of concrete, the Steady-State Method and Transition Method were used. In the steady-state method, two box chambers, a cold chamber and a hot chamber, were used. In between these two chambers, each concrete specimen was sandwiched and the thermal coefficient K was determined by applying

Table 1. Physical properties of various ingredients of concrete

Particulars	Bulk Density (kg/m^3)	Specific Gravity	Surface index	Fineness Modulus	Grading Zone
Cement	1445	3.12	---	---	---
Fly Ash	1315	2.07	---	0.89	---
Sand	1850	2.65	1.15	2.66	Zone-II
Pond Ash	1205	2.15	1.08	1.48	Zone-IV
Aggregate (10 mm)	1550	2.72	0.44	5.7	

Table 2. Concrete mix proportions for various water to cementitious materials ratios

Mix	Cement (kg/m^3)	Sand (kg/m^3)	Aggregate (kg/m^3)	Fly Ash (kg/m^3)	Pond Ash (kg/m^3)	Water (kg/m^3)	Admixture (kg/m^3)	Fiber (kg/m^3)
				w/c=0.35				
C_{0-0}	450	920	954	0	0	157	3.5	0
F_{0-0}	450	920	954	0	0	157	3.5	2.7
F_{20-0}	360	920	954	90	0	157	3.5	2.7
F_{40-0}	270	920	954	180	0	157	3.5	2.7
F_{0-10}	450	840	954	0	80	157	3.5	2.7
F_{0-20}	450	760	954	0	160	157	3.5	2.7
F_{20-10}	360	840	954	90	80	157	3.5	2.7
F_{20-20}	360	760	954	90	160	157	3.5	2.7
F_{40-10}	270	840	954	180	80	157	3.5	2.7
F_{40-20}	270	760	954	180	160	157	3.5	2.7
				w/c=0.4				
C_{0-0}	415	915	965	0	0	167	3.2	0
F_{0-0}	415	915	965	0	0	167	3.2	2.7
F_{20-0}	329	915	965	86	0	167	3.2	2.7
F_{40-0}	243	915	965	172	0	167	3.2	2.7
F_{0-10}	415	837	965	0	78	167	3.2	2.7
F_{0-20}	415	759	965	0	156	167	3.2	2.7
F_{20-10}	329	837	965	86	78	167	3.2	2.7
F_{20-20}	329	759	965	86	156	167	3.2	2.7
F_{40-10}	243	837	965	172	78	167	3.2	2.7
F_{40-20}	243	759	965	172	156	167	3.2	2.7
				w/c=0.45				
C_{0-0}	365	935	980	0	0	164	2.76	0
F_{0-0}	365	935	980	0	0	164	2.76	2.7
F_{20-0}	290	935	980	75	0	164	2.76	2.7
F_{40-0}	215	935	980	150	0	164	2.76	2.7
F_{0-10}	365	855	980	0	80	164	2.76	2.7
F_{0-20}	365	775	980	0	160	164	2.76	2.7
F_{20-10}	290	855	980	75	80	164	2.76	2.7
F_{20-20}	290	775	980	75	160	164	2.76	2.7
F_{40-10}	215	855	980	150	80	164	2.76	2.7
F_{40-20}	215	775	980	150	160	166	2.76	2.7

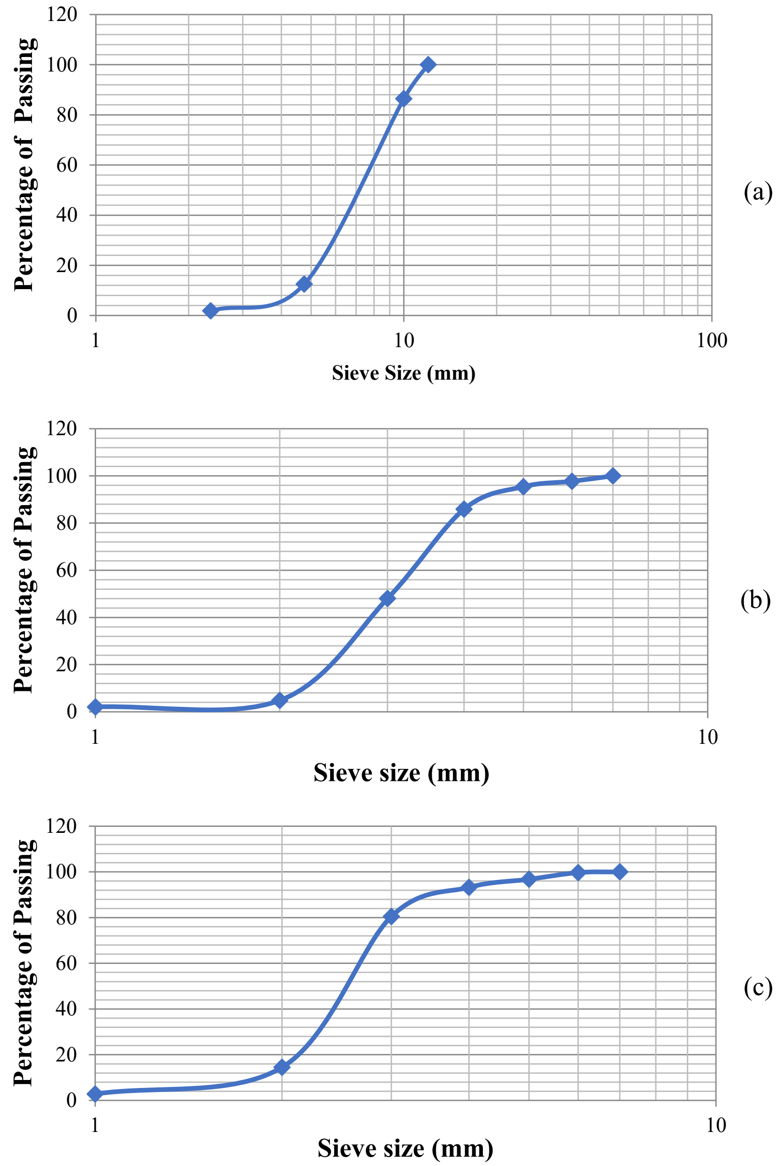

Figure 1. Granulometric curve for coarse aggregate, fine aggregate and pond ash: (a) Granulometric curve of coarse aggregate, (b) Granulometric curve of fine aggregate, and (c) Granulometric curve of pond ash

the second law of Thermodynamics. But in the Transition method, the thermal conductivity of each specimen was determined by a cone calorimeter, as per ASTM E 1354 [26]. Heat was applied on one side of the concrete specimen at the rate of $50KW/m^2$ for 1 h. By using thermocouples, the temperature change on the concrete surface was determined. The leaching test for different mixes was conducted to analyze the heavy metals present in the concrete. The concrete specimen cubes were taken from the water after completion of the required curing period and converted into powder form. Those powders were sieved through a 600 µm sieve. Then five grams of sieved sample were mixed with 100 ml of extraction fluid. Two types of fluids were prepared according to the pH of the sample. When the pH value was below 5, the extraction fluid consisted of 5.7 ml of glacial acetic acid and 64.3 ml of 1 N NaOH solution. When the pH value was above 5, the extraction fluid consisted of only 5.7 ml of glacial acetic acid. For measuring the pH of all 30 concrete mixes, five grams of each powdered sample were mixed with 96.5 ml distilled water and pH was measured. Since the pH values of all samples were found to be above 5, the second type of extraction fluid, i.e 5.7 ml of glacial acetic acid was prepared in 1 litre of distilled water in a conical flask and a five-gram sample was poured and stirred for two min. Then the flask was kept in the incubator for 18 h at about 23^{o}C. After that, the leachate extract was filtered and tested for heavy metals.

3. Results and Discussion

In the present research, the effects of partial replacement of cement and sand with locally available industrial by-products (along with glass fiber) on rheological properties, shrinkage properties, strength, and durability were studied and suitable suggestions for the local construction industry were made. To develop sustainable fly ash concrete, various percentages of fly ash and pond ash were incorporated into the mix as partial replacement of cement and sand. Furthermore, it was also explored to find the best proportion of materials that could provide enhanced life span of the concrete. In the present research, three w/cs ratios (0.35, 0.4 and 0.45) were used to discover the effects of water-cement ratio on the performance of the proposed fly ash or pond ash concrete with fiber. The research findings will also be useful in the proposition of a mixed design procedure for practical use. A lot of observations were made and the scientific basis of the results from various tests, such as concrete mixing with a constant volume of a fraction of glass fiber, replacing cement by fly ash, replacing sand by pond ash individually and simultaneously, are discussed.

3.1 Test results for 0.1% addition of fiber to control concrete (mix F_{0-0})

Slump cone test and compaction factor test: From Figures 2 and 3, it can be noticed that when 0.1% of glass fiber was added in traditional concrete, the slump height and compaction factor decreased by 30% and 8%, respectively. This happened because the thickness of glass fiber was in microns and the surface area was greater. The introduced glass fiber in concrete required more water as a result of workability of concrete decreased.

Rheology: From Figure 4, it can be seen that yield stress increased by up to 51%, and relative viscosity increased by up to 14% for all three w/c ratios when 0.1% of glass fiber was added to cement concrete. Due to the higher surface area of glass fiber, it required more water to wet its surface. Also due to the addition of glass fiber, the cohesiveness of concrete increased. This was because of the incrreased creation of frictional resistance between the glass fibers and the fresh plain concrete.

Electrical resistivity of fresh concrete: The electrical resistivity of fresh fiber reinforced concrete showed a higher value than control concrete of the same combination (Figure 5). Due to the addition of fiber in concrete, the surface area of the fresh concrete mix increased as a result of water film thickness over various particles reduced. That's why the amount of current passed through the fresh concrete was very low. Hence, the electrical resistivity of fresh fiber reinforced concrete was increased by about 44% compared to the control concrete.

Shrinkage: The early-age shrinkage value decreased by 57% when compared to the control concrete for all w/cs due to the addition of 0.1% of glass fiber, as shown in Figure 6. This was because the glass fiber had high tensile strength. By providing means for stress to be transferred across shrinkage cracks, crack bridging occurred, which prevented the crack growth.

Carbonation test: The carbonation depth of fiber-reinforced concrete was decreased by up to 25% compared to the control concrete for all w/c (Figure 7). The glass fiber resisted the changing of volume (i.e. shrinkage) of concrete at the hydration process. It resisted the process of crack formation on the surface of the concrete. Hence, carbon dioxide could not enter the concrete.

Bulk electrical resistivity: From Figure 8, it can be noticed that bulk electrical resistivity increased 40% relative to the control concrete, which was more than 10 kΩ cm at 28 days curing and 20 kΩ cm at 119 days curing. This indicated a good capacity of resistance against corrosion. Fiber acted as a crack arrester, and hence permeability of concrete was reduced. As a result, the bulk electrical resistivity of concrete increased. Hence, corrosion resistance of rebars increased in fiber reinforced concrete than control concrete.

UPV test: As 0.1% glass fiber was mixed in traditional concrete, UPV increased by 2.8% at 28 days and 3.27% at 119 days curing relative to the control concrete (Figure 9). Due to the addition of fiber, shrinkage cracks were arrested, and this decreased the liquid permeability of concrete. Hence, the UPV value increased in fiber reinforced concrete.

Compressive strength and flexural strength test: After the addition of glass fiber to the control concrete, both compressive and flexural strength at 28 days curing increased by up to 21% and 41%, respectively (Figures 10 and 11). The addition of glass fiber arrested the formation of cracks due to compressive or flexural stress. In this research, the size of coarse aggregates was less than 10 mm and the length of fiber was 12 mm. Hence, there was a sufficient lap length in between the two aggregates and fiber. So, the fiber did not detach from the surface of the fine aggregate or coarse aggregate at the time of failure.

Heat conductivity: From both the steady-state method and the transient method, it was observed that the thermal conductivity of control concrete and glass fiber reinforced concrete were about the same (Figure 12). There were no major changes in the k-value, but a lower heat conductivity was found in fiber reinforced concrete due to the addition of fiber arrested the shrinkage cracks of concrete. Hence, the entry of moisture into the inside of the concrete was also restricted. As a result, the thermal coefficient k was lower in fiber reinforced concrete than the control concrete. The thermal conductivity was also increased due to an increase in relative humidity.

Leaching test: The leaching test of different mixes were conducted to evaluate the concentration of heavy metals in concrete due to the presence of glass fiber, fly ash and pond ash. From Figure 13, it was found that the introduction of glass fiber produced no significant change in presence of heavy metals in concrete as compared to control cement concrete for the three different w/c ratios. The glass fiber did not affect the concentration of heavy metals in concrete.

From the above test results, it can be concluded that the addition of fiber into ordinary concrete significantly improves the durability and strength of the concrete for all water-cement ratios. The test results for bulk electrical resistivity, ultrasonic pulse velocity, compressive strength and flexural strength increased along with lower values of shrinkage and carbonation depth. Hence, it is strongly recommended that 0.1% glass fiber should be added into the concrete made with a higher water-cement ratio, i.e. more than 0.4. However, in order to regain the loss of workability of low w/c concrete, superplasticizer may be added.

3.2 Test results for replacement of cement with fly ash up to 40% to fiber reinforced control concrete (mix F_{20-0}, F_{40-0})

Slump cone test and compaction factor test: When the fly ash was replaced with cement at 20%, the slump value increased by 16% and the compaction factor increased by 6%. Again at 40% of cement replacement, the slump value increased by 28% and the compaction factor increased by 10% (Figures 2 and 3). The improvement in the fluidity of fresh mixtures with the inclusion of fly ash can be attributed due to the small spherical shape of fly ash particles providing lubrication in the form of a ball bearing effect [27, 28]. Lower water loss occurred in the concrete due to the lower heat of hydration contributed by fly ash. When fly ash was added to concrete, the slump height increased, and thus it acted as a plasticizer [29].

Rheology: The yield stress decreased by 16% and 30% when 20% and 40% of cement were replaced with fly ash, respectively (Figure 4). The yield stress of concrete was decreased by the replacement of cement with fly ash, as it proportionally decreased the cement particle density [30]. Therefore, the number of flocculated cemented particles was reduced by decreasing the dilution effect and increasing the ball bearing effect inside the concrete [31]. Due to this the concrete pumpability also improved by reducing frictional losses during the pumping process and flatwork finishability.

Electrical resistivity of fresh concrete: When fly ash was used in partial replacement of cement, the electrical resistivity decreased in the fresh state (Figure 5). The electrical resistivity value was lower in fresh concrete when fly ash was added due to better packing and lubrication action [32].

Shrinkage: The early-age shrinkage of concrete was decreased about 26% and 47% as compared to plain fiber reinforced concrete when cement was replaced by fly ash 20% and 40%, respectively by weight (Figure 6). It was also noticed that the early-age concrete shrinkage was reduced by the higher replacement of cement with fly ash [33]. Due to the lower specific gravity of fly ash as compared to cement, the volume of fly ash was found in more quantity than the cement of equal weight. Hence, a huge volume of cementitious materials was added to concrete when fly ash replaced the cement by 20% by weight. Furthermore, finer particles were increased in number and the bleeding of concrete decreased significantly [34].

Carbonation test: When 20% of cement was replaced by fly ash, the carbonation depth was increased 2.5 to 3 times that of the control concrete. But when the replacement of cement with fly ash was increased up to 40%, the carbonation depth increased by 5 times that of the control concrete (Figure 7). The carbonation depth was more at 0.45 w/c than at 0.35 w/c. As the percentage of replacement of cement with fly ash increased, the depletion of Ca $(OH)_2$ reduced the pH, which increased the carbonation depth. In the hydration process, C-S-H gel and $Ca(OH)_2$ were produced due to the reaction between cement and water. When the cement was partially replaced with fly ash, extra C-S-H gel was produced due to reaction with $Ca(OH)_2$ and silica present in fly ash. Replacing cement with fly ash led to a lower Ca $(OH)_2$ content in the hardened cement paste so that a smaller amount of CO_2 was required to remove all the $Ca(OH)_2$ by producing $CaCO_3$. Hence, the pH value of concrete decreased which was due to the increase of carbonation depth.

Bulk electrical resistivity: When fly ash was used to replace cement by 20% and 40% of its weight in GFRC, ER value increased by 20% and 50%, respectively, in comparison to the control GFRC at 28 days (Figure 8). At 119 days curing, ER values of F_{20-0} and F_{40-0} were 113% and 168% of F_{0-0} at 28 days curing. The addition of 40% fly ash increased durability leading to better particle packing, however, it also reduced the strength. The addition of fly ash also reduced cracks due to lower heat of hydration. Because of the addition of fly ash, an extra amount of CSH gel was formed, which improved the microstructure of concrete [35]. Hence, higher replacement may be recommended for the higher saving of cement.

UPV test: When fly ash replaced 20% of cement by weight, UPV increased by 1.35% at 28 days curing period, and by 6.71% at 119 days curing, compared to the control GFRC at 28 days (Figure 9). Again, these values were increased up to 3.73% and 9.88% for 28 days and 119 days curing, respectively, when 40% of cement was replaced with fly ash by weight. The increment of UPV values in fly ash concrete was due to the formation of extra CSH gel, better packing due to increased workability, and the presence of finer fly ash particles. During the hydration process, fly ash converted the surplus lime to form secondary mineralogy like the reduction of glucose into energy by insulin, which increased the strength and durability [6].

Compressive strength and flexural strength test: Replacing 20% of cement with fly ash by weight, the compressive strength and flexural strength at 28 days curing increased by 15% and 18%, respectively. The 40% replacement of cement with fly ash decreased compressive and flexural strength by 22% and 24%, respectively, at 28 days curing (Figures 10 and 11). The main effect on the strength of concrete is due to the reaction between silica of fly ash and hydrated calcium hydroxide in concrete which results in better packing in the matrix [36]. The formation of CSH gel takes place to a greater extent in mix $C_{20\text{-}0}$ compared to $C_{0\text{-}0}$. Due to the formation of extra CSH gel, the microstructure of concrete improves. Hence, the energy absorption capacity of the beam against flexural strength increases with up to 20% cement replacement with fly ash. The 40% cement replacement with fly ash shows lower strength which may be due to lower availability of $Ca(OH)_2$ as the cement quantity was much lower [37].

Heat conductivity: It was found that as the percentage of replacement of cement with fly ash was increased, the thermal conductivity of concrete was decreased gradually (Figure 12). As the replacement of cement by fly ash went up to 20%, the k value reduced to about 10% and at 40% replacement with cement, the k value decreased 35% compared to that of the traditional mix. The interesting thing was that the thermal conductivity decreased rapidly when the fly ash was replaced with more than 20% of cement. The thermal conductivity of the concrete depends upon the porosity and the size of the pores formed. As the amount of porosity was increased, the pores inside the concrete were filled with air. It is well known that the thermal conductivity of air is less than that of the solid substances. The cement replacement by fly ash beyond 20% increased the pore size and reduced the thermal conductivity. The heat transfer rate of each specimen from the hot end to the cold end was also determined with the help of thermal diffusivity, and a decreasing trend as the replacement percentage increased was observed.

Leaching test: The comparison between the heavy metal concentrations of the control sample of fiber reinforced concrete ($F_{0\text{-}0}$) and the samples incorporated with different doses of fly ash was shown in Figure 13. By replacement of cement with fly ash up to 40%, the chromium concentration reached the highest concentration of leaching among other heavy metals. The leaching potential was affected by several factors such as extraction of fluid, solid to liquid ratio, length of test duration, and the number of extractions. The w/c ratio also affected the concentration of heavy metals. More heavy metals were found at lower w/c than at higher ones because at lower w/c the amount of cementitious materials was greater than at higher w/c. Hence, a greater amount of fly ash was found in the lowest w/c of the same mix, which increased the concentration of heavy metals at a later stage. It was found that the pH value of the solution also directly affected heavy metals leachate concentrations. The Cu and Pb lead concentrations increased slightly with the replacement of cement with fly ash up to 40%. The Ni and Fe concentrations also showed similar trends of leaching.

From the above test results, fly ash is the better option for increasing workability. Also, the addition of fly ash can compensate for the loss of workability due to the addition of fiber. Hence, it is strongly recommended that fly ash should be added or replaced with cement in fiber reinforced concrete. Based on the carbonation depth test result, the maximum water-cement ratio should be 0.4 with 0.1% of glass fiber in case of 40% cement replacement with fly ash, to reduce the carbonation depth and increase the service life of the structure. Since using a higher percentage of fly ash in concrete improves its heat reducing properties, this approach can help minimize the use of artificial energy in the buildings. As the curing period increased, both the strength and durability of concrete increased. In addition, the hydration process of high-volume fly ash concrete is very slow at early-age but gains strength at the later age of curing. Hence, it is strongly recommended that proper curing of concrete with fly ash should be strictly followed by contractors and builders for up to 119 days to achieve full strength and durability of concrete.

3.3 Test results for sand replacement by pond ash up to 20% in fiber reinforced control concrete (mix F_{0-10}, F_{0-20})

Slump cone test and compaction factor test: When pond ash was mixed in concrete by replacing 10% sand, the slump value decreased to 4% while the compaction factor increased to 3% (Figures 2 and 3). However, when 20% of sand was replaced with pond ash, the slump height as well as the compaction factor decreased by 12% and 4%, respectively. Generally, pond ash is coarser than fly ash. Its shape is not spherical and its surface is not as smooth as fly ash. Hence, it does not play any role of lubricant like fly ash. For these reasons, the slump value decreased [12]. However, pond ash is finer than sand particles. Hence, it filled the voids inside the sand, which increased the compaction factor. When 20% was replaced with pond ash, the specific surface was increased due to increasing fineness and the greater amount of water needed for the mixed ingredients to get closer packing. Hence, both slump height and compaction factor decreased at 20% replacement of sand with pond ash.

Rheology: For replacement of sand with pond ash at 10% and 20%, yield stress increased by 5% and 13%, respectively (Figure 4). When more pond ash was used to replace sand, the specific surface of the mix increased due to increasing its fineness [10]. Hence, a greater amount of water was needed to cover all the ingredients.

Electrical resistivity of fresh concrete: The electrical resistivity value of fresh concrete increased by 7% and 14% when sand was replaced with pond ash at 10% and 20%, respectively (Figure 5). For the replacement of sand with pond ash above 20%, greater amounts of void were formed inside the concrete. The designed quantity of water was mixed in concrete for accelerating the hydration process, formed a film around the pond ash particle.Those films covered around the pond ash particles possessed similar charges and repelled to each other by increasing the voids. Hence, there was a shortage of water to fill those voids created by additional pond ash. Thus, the electrical resistivity of the concrete mix increased.

Shrinkage: The reduction of early-age shrinkage was observed to be 14% for 10% replacement of sand and 22% for 20% replacement of sand with pond ash, respectively (Figure 6). The water-absorbing capacity of pond ash was larger due to its larger surface area. The addition of the formulated quantity of water formed a thin film around the pond ash particle. Hence, a lower amount of water evaporated because of the lower amount of bleeding associated with the reducing shrinkage of the concrete.

Carbonation test: It was also observed that the presence of pond ash resulted in more rapid carbonation but this was less pronounced than in the case of added fly ash. The carbonation depth increased 1.5 times and 3 times more than control concrete when pond ash replaced sand at 10% and 20% by volume, respectively (Figure 7). The replacement of cement with pond ash in concrete consumes $Ca\ (OH)_2$ and contributes extra C-S-H gel. The silica gel, which is consequently formed, has large pores, which facilitate further carbonation. A higher percentage of replacement of sand with pond ash reduced the amount of $Ca\ (OH)_2$ in hardened cement paste so that a smaller amount of carbon dioxide was required to remove all the $Ca\ (OH)_2$ through production of $CaCO_3$. Hence, the presence of pond ash in concrete resulted in more rapid carbonation.

Bulk electrical resistivity: A higher percentage of replacement of sand with pond ash decreased the electrical resistivity value of the concrete. When pond ash was used to replace10% of sand by volume, the ER value increased by 5%, but when sand replacement was increased to 20%, the ER value decreased by 12% (Figure 8). The higher percentage of replacement of sand with pond ash decreased the workability. That meant that the packing density of internal concrete materials was decreased due to the formation of more void. Hence, the internal voids were filled with water when the concrete cubes were kept for curing [13]. After the desired curing period, the cubes were taken from the tank and resistivity was checked immediately. Hence, the current passes through the water easily and decreased the resistivity of concrete. The workability of concrete was also reduced due to the replacement of sand with pond ash up to 20%. That results in lower packing and hence electrical resistivity decreased.

UPV test: When pond ash replaced sand at 10% by volume, the UPV values were less than 1% at 28 days curing, and had slightly increased at 119 days curing. But 20% replacement of sand with pond ash decreased the UPV value compared to the mix $F_{0\text{-}0}$ (Figure 9). This was due to the increase in packing density caused by the partial replacement of sand with pond ash. The fine particles of pond ash were packed into the concrete matrix which became less permeable and formed a solid skeleton of the concrete mass. Hence, ultrasonic waves took less time to reach the receiving transducer. Therefore, the transit time decreased and velocity increased.

Compressive strength and flexural strength test: It was observed that up to 10% replacement of sand increased both compressive strength and flexural strength at 28 days curing by 18% and 20%, respectively, while up to 20% replacement of sand with pond ash decreased the compressive and flexural strength by 15% and 14%, respectively (Figures 10 and 11). Replacement of sand with pond ash up to 10% increased the packing density and as a result increased the compressive strength. The factors responsible for the decrement of compressive strength beyond 20% replacement of sand with coal ash (pond ash) were due to the replacement of the stronger material with the weaker material and the absence of pozzolanic activity by the pond ash.

Heat conductivity: The conductivity of heat decreased as the replacement of sand with pond ash was increased, but it was found the reduction of thermal conductivity was influenced more in cement replacement with fly ash compared to sand replacement with pond ash (Figure 12). The replacement of sand with pond ash by more than 10% influenced the reduction of thermal conductivity in a positive way. Since the specific gravity of sand was more than pond ash, sand replacement of more than 10% produced a higher volume of fraction of aggregate in the concrete mix. The higher the volume of a fraction of aggregate had produced a lower thermal conductivity of concrete.

Leaching test: It was found that as the percentage of replacement of sand with pond ash increased, the heavy metal concentration also increased, but the increment rate was lower than the replacement of cement with fly ash (Figure 13). The highest peak of Cr leaching was 0.686 at 20% replacement of sand with pond ash at w/c=0.35. The concentrations of Zn and Ni were found to be lower than the control fiber reinforced concrete. This meant that the percentage of replacement of sand with pond ash helped to decrease the concentration of Zn and Ni.

From the above test results, it can be concluded that a combination of sand (Zone-II) and pond ash (Zone-IV) may be progressively finer than sand particles and confirmed grading limits of Zone-III when sand was replaced with pond ash up to 20%. Hence, it is recommended that coarser natural sand or crushed stone which is coarser than that of Zone-I be partially replaced with pond ash to confer the desired grading and allow its use in concrete. Also, it was observed that up to 10% of sand replacement by pond ash increased the packing density. Hence, it is recommended that sand must be replaced with pond ash by 10% for local construction. The concrete that contains beyond the10% of sand replacement with pond ash with 0.1% glass fiber, 0.75% superplasticizer should be added to achieve the required strength with better workability.

3.4 Test results for both cement replacement and sand replacement to fiber reinforced control concrete by coal ash (mix F_{20-10}, F_{20-20}, F_{40-10}, and F_{40-20})

Slump cone test and compaction factor test: In case of both replacement of cement and sand with fly ash and pond ash simultaneously, it was noticed that slump height was greater for the highest cement replacement by fly ash (i.e. 40%) and lowest sand replacement by pond ash (i.e. 10%) for present fiber reinforced concrete (Figures 2 and 3). The presence of a higher amount of fly ash increased the workability, and pond ash decreased the workability. Hence, on both replacement of cement and sand with fly ash and pond ash, the test results of slump and rheology fell between the test results of F_{40-0} and F_{0-20}. Also, the added fly ash was able to compensate for the loss of workability due to the addition of pond ash and fiber [38]. Improvement in slump was greater for the lower water-cement ratio [39]. This may have been due to higher water film thickness at higher w/c.

Rheology: In present glass fiber reinforced concrete, the yield stress was minimum for the mix F_{40-10} which was 22% less than mix F_{0-0} (Figure 4). The presence of a higher amount of fly ash increased the workability, and pond ash decreased the workability. Hence, the test results of a slump, compaction factor and rheology fell between the test results for C_{40-0} and C_{0-20}, for both cement replacement and sand replacement by fly ash and pond ash. Improvement in the slump value was greater for a higher water-cement ratio. This may have happened due to higher water film thickness at higher w/c. The higher slump could have resulted in the lower requirement of compaction.

Electrical resistivity of fresh concrete: The ER value of fresh concrete lay between F_{40-0} and F_{0-20} when both sand and cement were replaced with pond ash and fly ash simultaneously (Figure 5). Fly ash improved the workability of concrete whereas pond ash decreased the workability. In this case, fly ash compensated for the loss of workability due to pond ash.

Shrinkage: A good result was found when simultaneous replacement was attempted for both sand and cement with pond ash and fly ash, respectively, compared to individual replacement. The early-age shrinkage was reduced by 83% with cement replacement by fly ash at 40% and sand replacement by pond ash at 20% (Figure 6). Since the size of fly ash and pond ash were less than 300 microns, bleeding of concrete was possible to stop. Also, the finer particles of fly ash and pond ash reduced the porosity of concrete. A better packing density was achieved by filling all the voids between coarse aggregates and fine aggregates with pond ash and fly ash after vibrating the concrete mould fully [40]. Hence, entrapped air was reduced inside the mix, resulting in a lower amount of settlement of the concrete materials [41]. Due to the lower settlement of cement at the bottom side of the mould, the packing density of the concrete mix increased. Also, it was noticed that both pond ash and fly ash had a good water-retaining capacity. The amount of pore water was also found in very lower amounts due to higher compactness, higher surface area, and high amount of water absorption. Hence, the shrinkage value was much lower for simultaneous replacement of sand and cement with pond ash and fly ash [42]. The reaction of both pond ash and fly ash with water was also a slow process. Hence, during the hydration process, the evolution of heat was very low for the first eight hours. The evaporation of water from the cement paste was much lower due to the difference between concrete temperature and atmospheric temperature. Thus, a reduced rate of shrinkage of concrete was the result of simultaneous introduction of pond ash and fly ash in concrete.

Carbonation test: Since both fly ash and pond ash accelerated the rate of carbonation, the carbonation depth increased with their simultaneous introduction. The carbonation depth was 6.5 times more than the carbonation depth of control concrete when cement was replaced with fly ash at 40% by weight and pond ash at 20% by volume (Figure 7). At a higher water-cement ratio and a higher percentage of fly ash and pond ash, the potential for carbonation increased substantially. Both fly ash and pond ash addition in concrete decreased the $Ca(OH)_2$ concentration in concrete. When

$Ca(OH)_2$ was consumed, the formation of calcium silicate hydrate (CSH) was also possible due to a secondary reaction with pozzolanic silica present in fly ash and pond ash. When this occurred, more $CaCO_3$ was formed, but also secondary CSH gel formed which had large pores. Hence, it facilitated further carbonation.

Bulk electrical resistivity: For replacement of sand with pond ash and cement with fly ash simultaneously, mixes F_{40-10} had shown better durability than other mixes of glass fiber reinforced concrete. The ER value increased by 38% at 28 days curing and 141% at 119 days curing w.r.t F_{0-0} at 28 days curing (Figure 8). The addition of both fly ash and pond ash in concrete reduced the interconnecting voids due to their higher fineness. Also, the reduction of the alkali-silica reaction of concrete was possible due to the high efficiency of fly ash and pond ash. As the replacement of cement with fly ash took place, it reduced the alkalinity of the pore solution. Also using pond ash as sand replacement material improved the packing arrangement of particles. Thus, it reduced the aggregate dissolution and mitigated the alkali-silica reaction due to the binding of hydroxyl ions in the pore solution. Therefore, the combination of fly ash and pond ash samples exhibited low liquid permeability compared to control concrete, as shown by high electrical resistivity value.

UPV test: For the replacement of sand with pond ash and cement with fly ash simultaneously, the UPV value increased relaticve to the UPV value of control concrete. The UPV values were 2.3% and 12% higher for the mix of F_{40-10} mix than for the F_{0-0} at 28 days and 119 days curing, respectively (Figure 9). When fly ash was introduced into the concrete, spherical fly ash particles were replaced by ettringite due to the pozzolanic reaction. The voids between aggregates were filled by pond ash and the voids between the pond ash particles were filled by a large number of ettringite needles. Furthermore, the vacant spaces between longer ettringite needles were filled by matrix. Hence, the pozzolanic reaction of fly ash continuously filled the voids between the aggregates and pond ash with the ettringite needles. Therefore, concrete containing both fly ash and pond ash created a denser binder matrix compared to the conventional concrete and showed high ultrasonic pulse velocity values.

Compressive strength and flexural strength test: The compressive strength for all curing periods was decreased for all combinations of both cement and sand replacement except for F_{20-10}, compared to mix F_{0-0} (Figures 10 and 11). The combination of coarse fly ash and pond ash which produced high surface area and contained a high amount of amorphous silica compared with Ordinary Portland Cement, imparted the pozzolanic reaction and packing density, and hence an improved compressive strength over a longer period.

Heat conductivity: It was found that the combined replacement of sand and cement with pond ash and fly ash produced better thermal resistivity (Figure 12). However, the better thermal resistivity and diffusivity were found for both mixes F_{20-10} and F_{40-20}. The k values found were 1.6 W/m-K and 1.5 W/m-K for the F_{20-10} and F_{40-20} mixes, respectively. Since fly ash replaced cement by 20% and pond ash replaced sand by 10%, a higher packing density was achieved more than other mixes. Hence, the pore water saturation of that concrete mix decreased, which led to a decrease in thermal conductivity. In this case, also the hydrated cement paste shrank which improved the density of concrete of that particular mix more than other remaining mixes. Hence, the interlocking forces between cementitious paste and aggregate became strengthened. But in the case of F_{40-20}, a lower thermal conductivity was produced due to the increased porosity of concrete. A higher volume of air packets formed, which helped to decrease the thermal conductivity of concrete.

Leaching test: When both cement and sand were replaced with fly ash and pond ash simultaneously, chromium was found to be a major heavy metal compared to those corresponding samples. The highest value was recorded as 1.258 mg/l for the F_{40-20} mix (Figure 13). This likely occurred due to the high percentage of fly ash and bottom ash when compared to other samples. The concentrations of Cu, Pb and Ni were slightly higher than the controlled fiber reinforced concrete, but the Zn concentration went down for the highest replacement of cement and sand with coal ashes.

3.5 Cost analysis

The production cost of all twenty-seven mixes of fiber reinforced concrete of one cubic meter of concrete are shown in Table 3 and compared with the production cost of traditional concrete. There are two types of production costs analysed. One is the total cost of different mixes per one cubic meter volume in Rs/m^3, and the second one is the total cost of different mixes per unit strength in Rs/MPa at 28 days curing. Table 4 shows the market price of various ingredients used in the proposed concrete. It was found that the total cost per cubic meter of fiber reinforced concrete (F_{0-0}) was 20% higher than the traditional cement concrete (C_{0-0}) for the same volume. To analyze the effect of curing on the cost of concrete, the cost per unit strength of control mixes at different curing periods is shown in Figure 14. It can be observed that the production cost of concrete for achieving compressive strength of 1 N/mm^2 shows a lower value for long-age curing. From Figure 14, it can be seen that the rate of decreasing cost is very high up to 56 days curing. Beyond this, the cost per unit strength gradually increases. The cost per unit strength of concrete at 119 days curing is slightly higher than at 56 days curing. It happens because the cost of curing increases more as compared to an increase in compressive strength at a higher age curing period. Hence, curing of structure for a minimum of 56 days is strongly recommended for local contractors. Also, the best performance among the mixes; cost per unit strength at 28 days curing is tabulated in Table 3. Table 4 shows the cost of various ingredients used in concrete. It is seen that the cost values of control concrete at water-cement ratios of 0.35, 0.4 and 0.45 are lower than the same mixes of water-cement ratios of fiber reinforced concrete. But it can be seen that cost per unit strength for fiber-reinforced concrete gradually decreases as the water-cement ratio decreases. It can be observed that fiber reinforced concrete is cost-effective when the water-cement ratio is less than 0.4. The cost of glass fiber reinforced concrete is higher compared to non-fiber reinforced concrete for gaining unit strength. Hence, the use of water curing is the cheapest method to gain the required strength and is cheaper than using an additive such as glass fiber.

Table 3. Cost analysis of different mixes at 28 days curing

Mix	Total Cost of Different Mixes at 28 Days Curing in Rs/m^3			Total Cost per Unit Strength of Different Mixes at 28 Days Curing in Rs/MPa		
	w/c=0.35	w/c=0.4	w/c=0.45	w/c=0.35	w/c=0.4	w/c=0.45
C_{0-0}	4545	4253	3917	113	127	139
F_{0-0}	5472	5181	4845	112	127	140
F_{20-0}	4942	4698	4414	86	98	108
F_{40-0}	4411	4208	3978	118	132	148
F_{0-10}	5458	5165	4829	93	105	116
F_{0-20}	5443	5151	4814	131	147	162
F_{20-10}	4927	4683	4399	81	93	103
F_{20-20}	4911	4671	4387	110	123	137
F_{40-10}	4396	4166	3934	96	142	158
F_{40-20}	4381	4178	3947	140	158	176

Table 4. Cost of different ingredients used in concrete

Particulars	Cement	Sand	Aggregate	Admixture	Fiber
Rate (Rs/Kg)	6	0.45	0.55	225	350

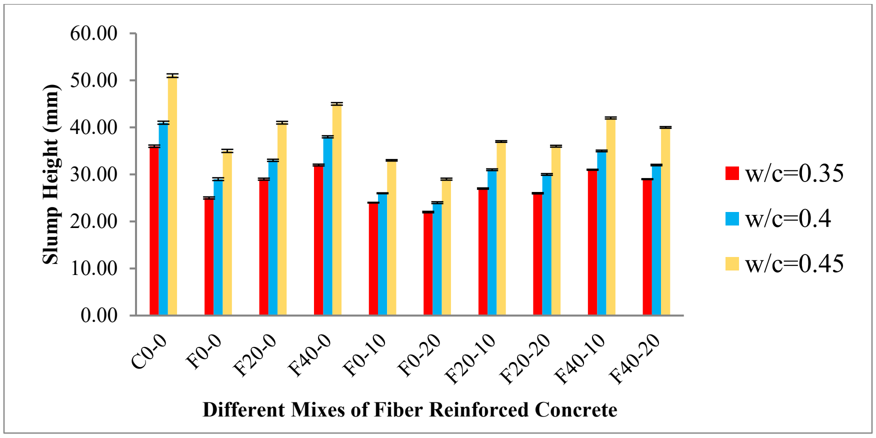

Figure 2. Slump height of different mixes

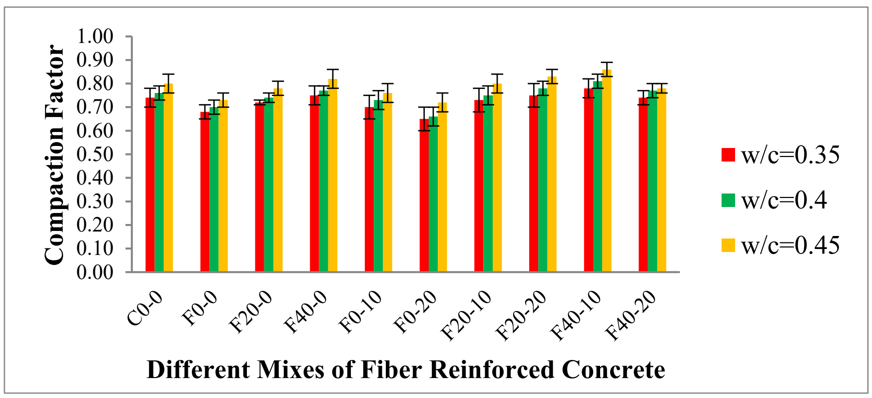

Figure 3. Compaction factor of different mixes

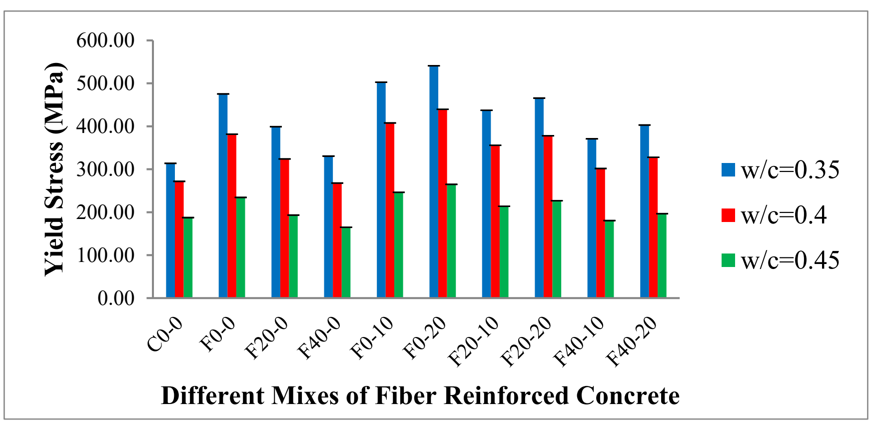

Figure 4. Yield stress of different mixes

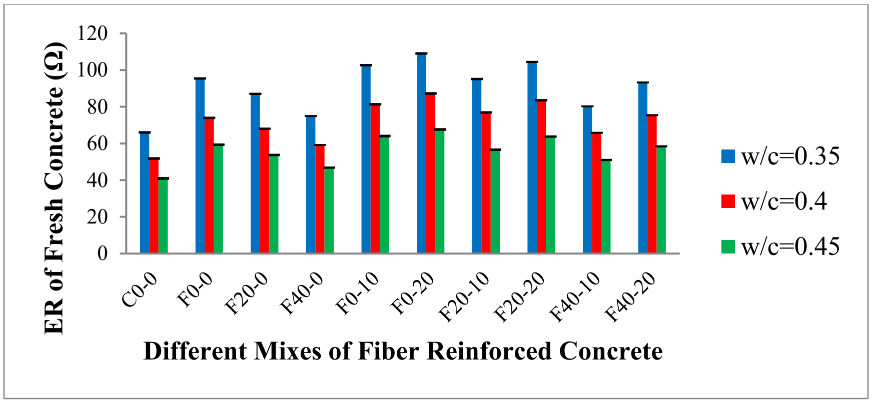

Figure 5. Electrical resistivity of fresh concrete

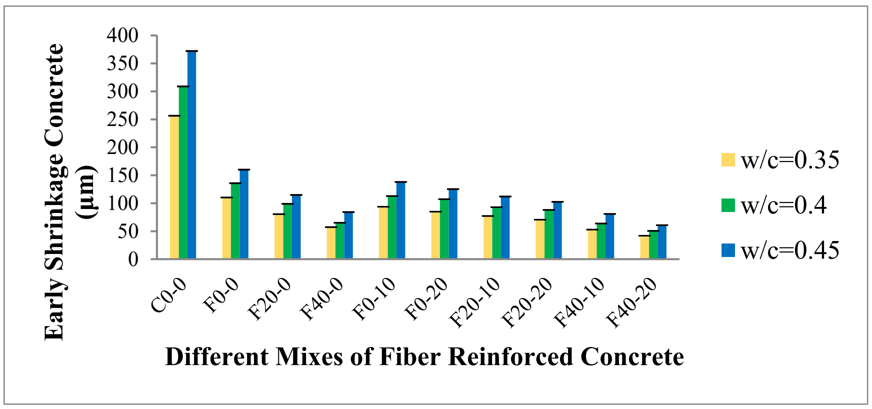

Figure 6. Early shrinkage of fresh concrete

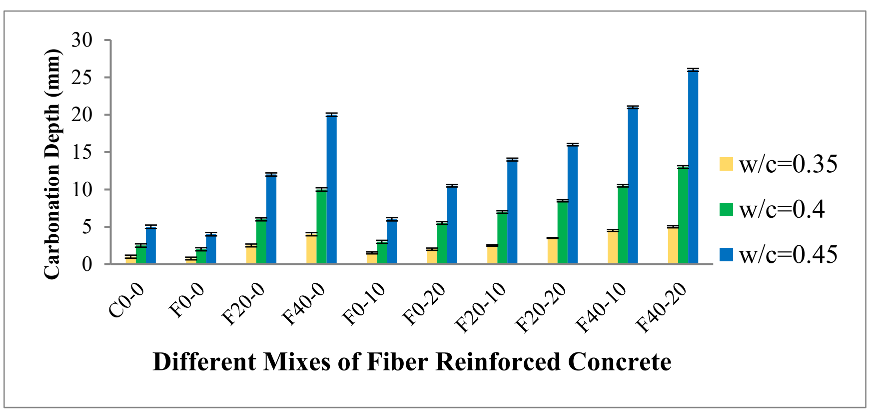

Figure 7. Carbonation depth of hardened concrete at 28 days curing

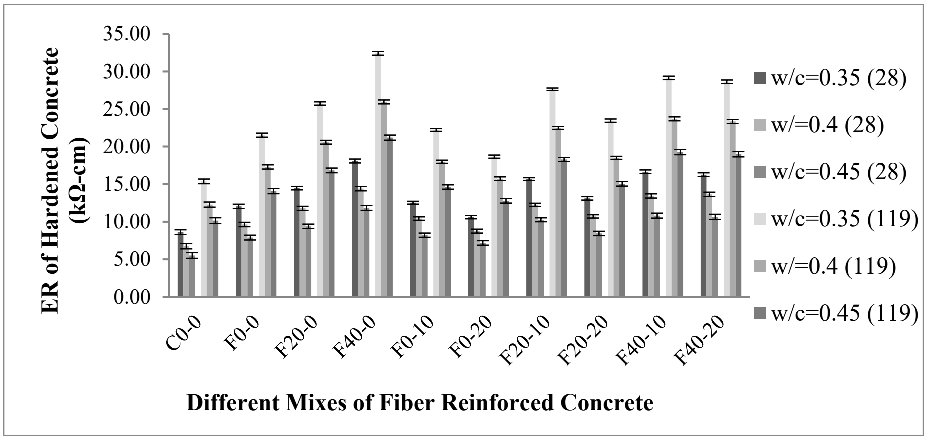

Figure 8. Bulk ER of hardened concrete at 28 and 119 days curing

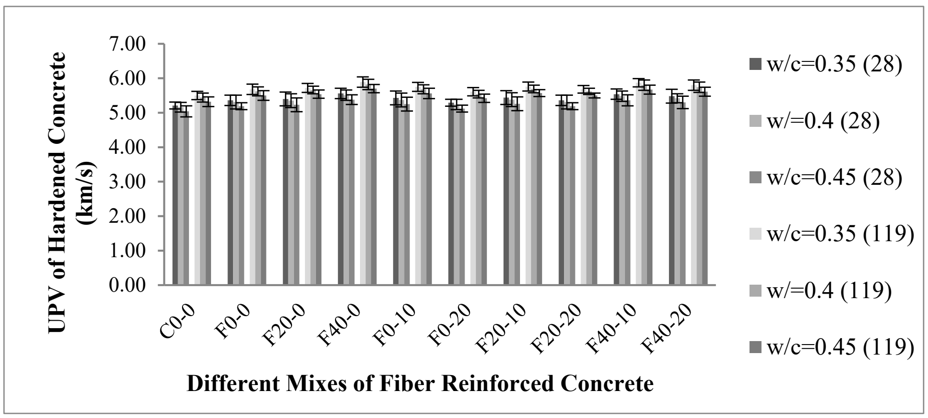

Figure 9. Ultrasonic pulse velocity of hardened concrete at 28 and 119 days curing

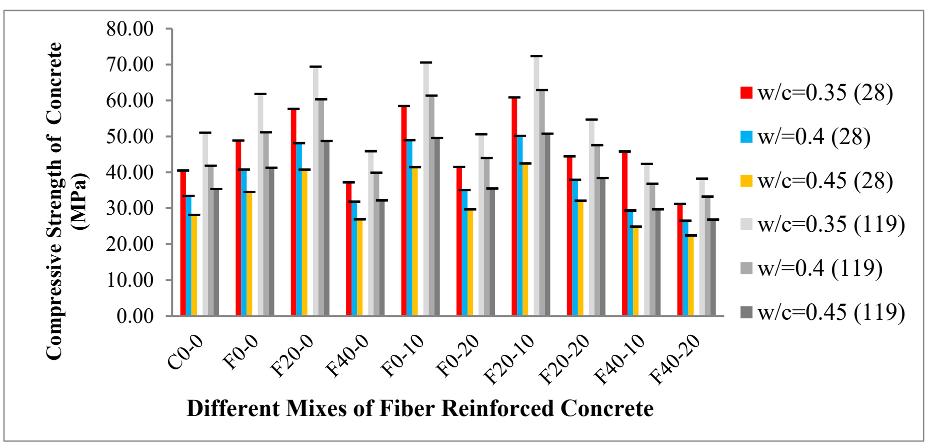

Figure 10. Compressive strength of hardened concrete at 28 and 119 days curing

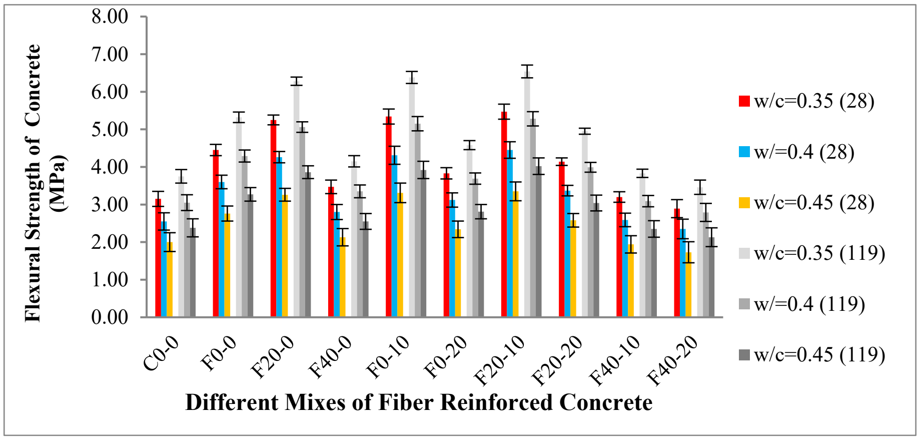

Figure 11. Flexural strength of hardened concrete at 28 and 119 days curing

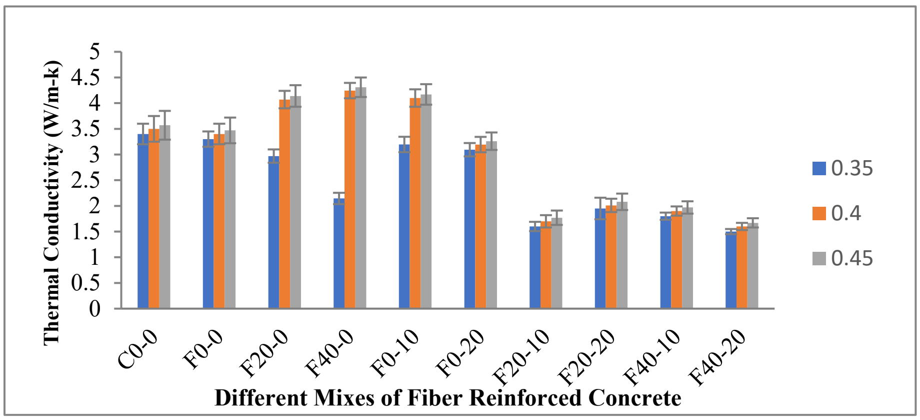

Figure 12. Thermal conductivity of different mixes of fiber reinforced concrete

From the above test results, it can be recommended that with respect to achieving the maximum 28 days compressive strength, replacement of cement with fly ash should not be more than 20% and sand with pond ash should not be more than 10%. For higher cement replacement with fly ash either fiber should be used or higher curing days must be recommended to achieve the required strength. Based on the durability of the plain concrete, 10% sand replacement with pond ash and 40% cement replacement with fly ash along with 0.1% glass fiber is highly recommended for durability. It is strongly recommended that both pond ash and fiber should be used in concrete to compensate for the loss of strength that occurs when more than 20% cement is replaced by fly ash. Fiber and fly ash have been found to complement each other; hence their simultaneous use is recommended. In order to achieve optimal service life and sustainability, the use of 20% fly ash, 10% pond ash and 0.1% fiber, individually or in combination, is recommended.

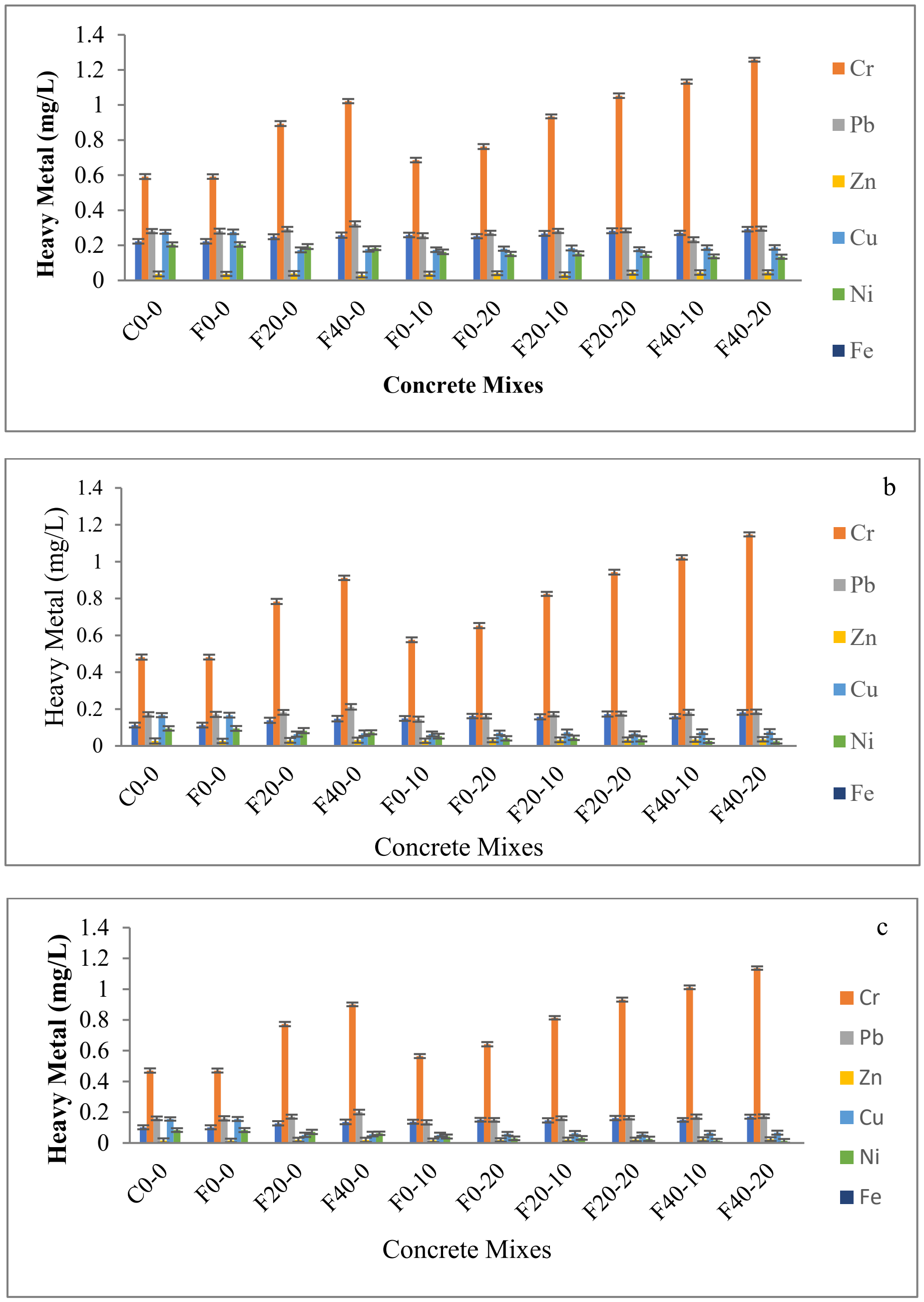

Figure 13. Heavy metals results of of different mixes of fiber reinforced concrete at 28 days curing for different w/cs
(a) w/c=0.35, (b) w/c=0.4, and (c) w/c=0.45

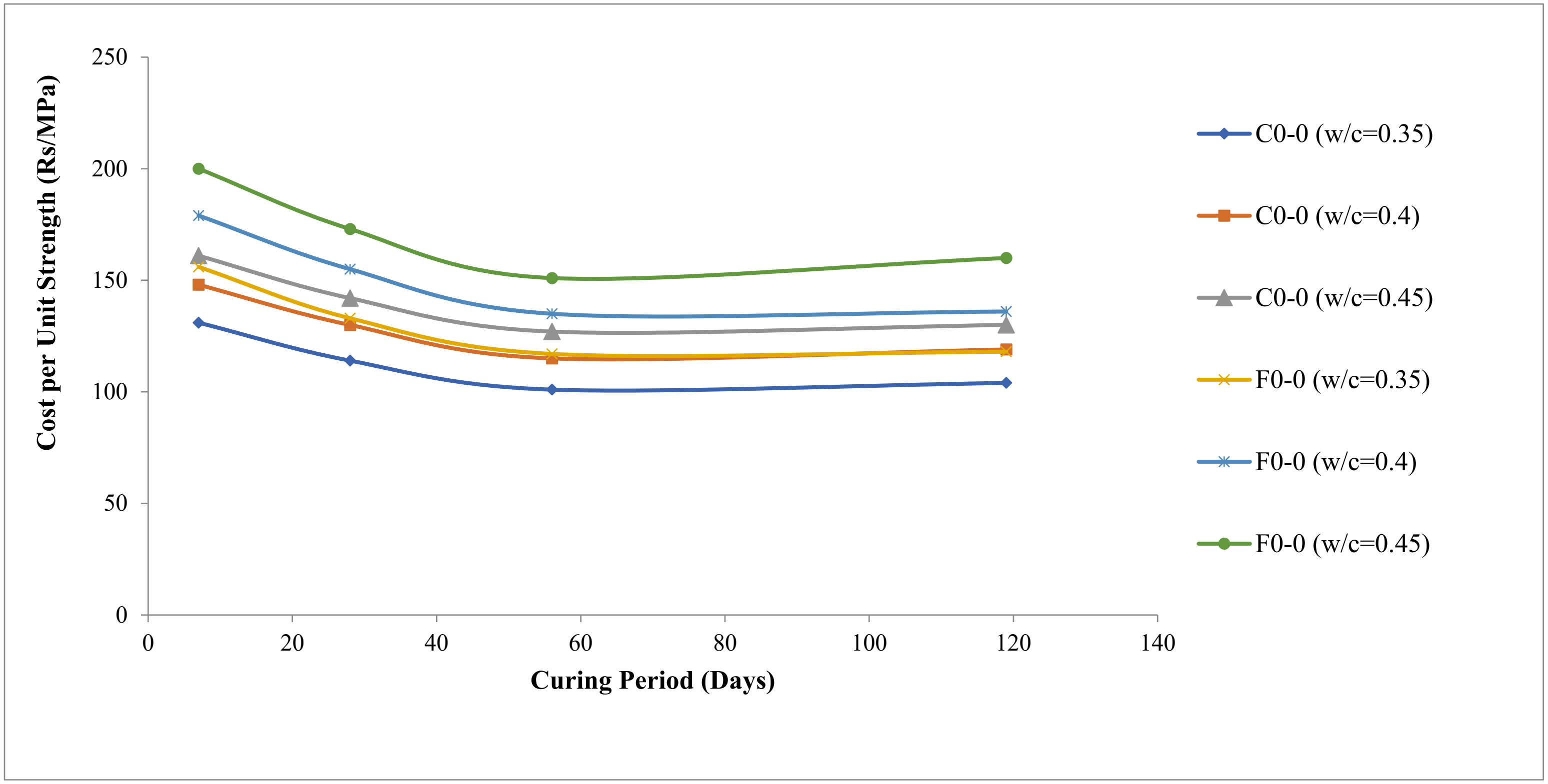

Figure 14. Cost per unit compressive strength (Rs/MPa) for different curing periods

By seeing all the possibilities for both sand replacement and cement replacement with pond ash and fly ash individually or simultaneously, a mix proportioning procedure for concrete has been proposed for local contractors or builders, which can help them prepare an eco-friendly energy efficient durable concrete as follows.

The replacement of cement was by fly ash in the amount of 20% and 40% by weight, and replacement of sand was by pond ash in the amount of 10% and 20% by volume. The I.S. code suggests that the mix design of concrete is to be prepared on a volume basis. Hence, sand was replaced up to 20% with pond ash by volume. However, I.S. 10262:2009 suggests that the cement should partially be replaced with fly ash by weight [43]. Hence, up to 40% of cement replacement was conducted with fly ash by weight. The test results of both fresh and hardened concrete tests are analyzed (Shown in Figure 2 to Figure 13) and a strong recommendation is given to the contractor and builders about the preparation of sustainable concrete as follows. Different researchers and construction practitioners have proposed various mixed design methods to prepare durable structures. The new mix design process involves a reduction in the quantity of paste, with maintenance of both the performance and quality of concrete. In the present research, nine mix proportions were prepared by considering up to 40% of cement replacement and 20% sand replacement by fly ash and pond ash, respectively. A mix design procedure was proposed according to which the maximum strength of concrete could be achieved. Hence, in our design, the extra amount of compressive strength due to SCM is deducted from the mean target strength, and the water-cement ratio is selected accordingly. Due to this, the amount of water used is increased and amount of cement decreased, without hampering the compressive strength. Then, the extra amount of water can be optimized by gradually reducing it until the required slump height is obtained. For example, from the test result, it was found that the compressive strength of mix F_{20-0} was 18% greater than that of traditional fiber reinforced concrete F_{0-0}. Hence, the target strength of concrete was decreased by 18%, and a new target strength has been proposed, i.e. 0.82 times of the minimum target strength of concrete in mix design procedure for cement replacement with fly ash up to 20%. Similarly, the minimum target strength for F_{0-10} has been proposed as 0.8 times of the minimum target strength of concrete, since the compressive strength of mix F_{0-10} was greater than that of mix F_{0-0} by 20%. In this way, the target strengths of concrete for both cement and sand replacement has been fixed according to their compressive strength results. For concrete mix F_{20-10}, F_{20-20} and F_{40-10} the new target strengths are found by multiplying constant factors such as 0.78, 0.87 and 0.88, respectively, by their actual target strength. Since the compressive strength of mix F_{40-10} is less than F_{0-0}, it is recommended that this type of mix can be used for low-cost non-important structures. Due to lower target strength, the w/c will increase. which will help to increase the workability and decrease the cement content. As the cement and sand quantity decreases, the production cost of concrete also decreases. It is required to balance both strength and workability of concrete. If the desired workability can not be achieved, then the addition of a limited quantity of superplasticizer is recommended. Sometimes the target strength cannot be achieved due to the higher replacement of cement or sand with supplementary materials. If the target strength cannot be achieved, then the addition of a limited quantity of fiber is recommended. The fiber cannot increase the strength, but it can increase the strain hardening properties. The addition of fiber has been recommended for the F_{0-20}, F_{20-20} and F_{40-10} mixes to compensate for the loss of strength due to the inclusion of supplementary materials. The above mix design process can serve as a guideline for local contractors and builders to help them prepare workable and low-cost concrete without compromising the strength of the concrete.

3.6 Proposed mix design process for local contractor

Propsed mix design process for local contractors are summarized in Figures 15-17.

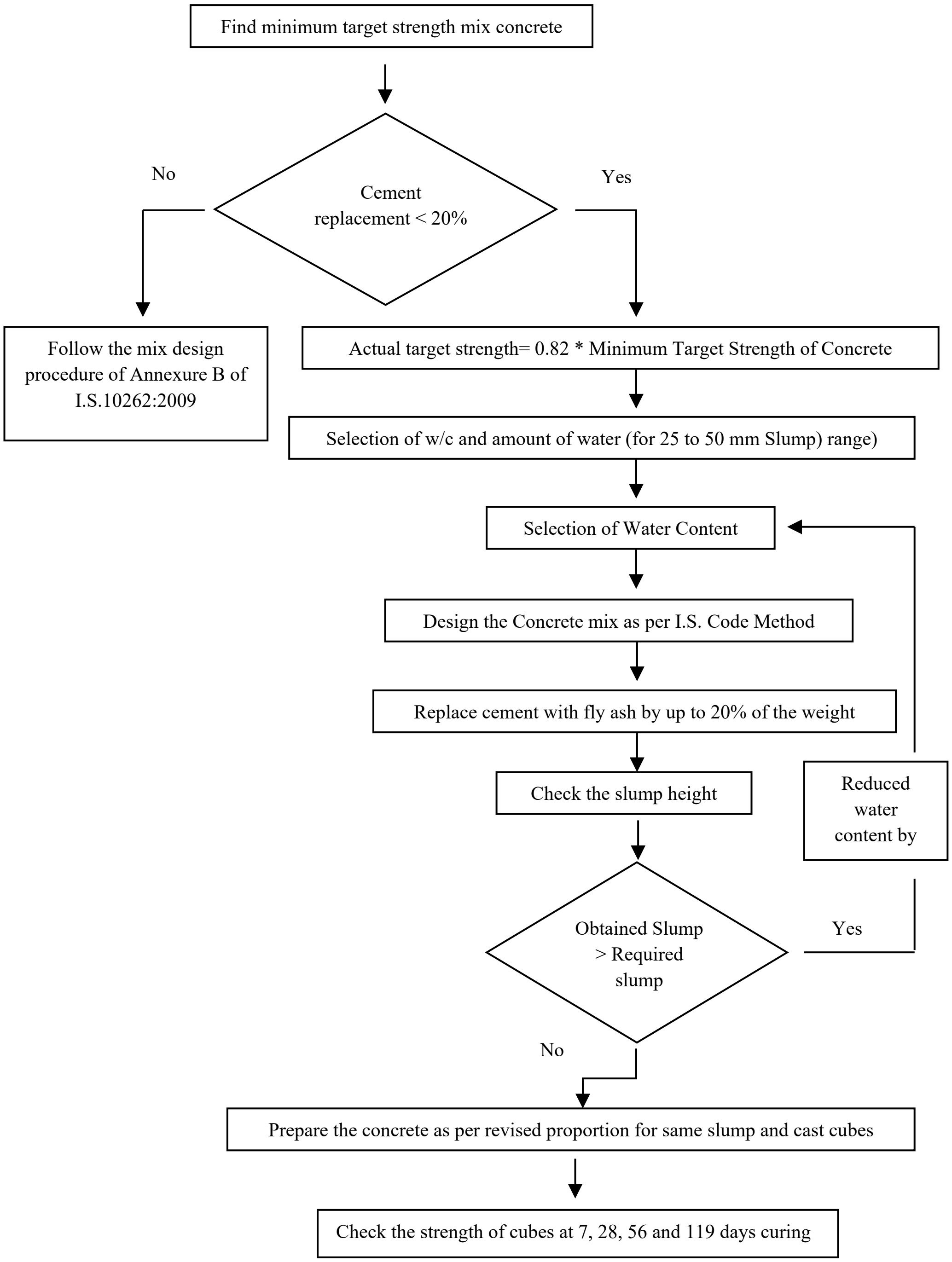

Figure 15. Mix design procedure for cement replacement with fly ash.

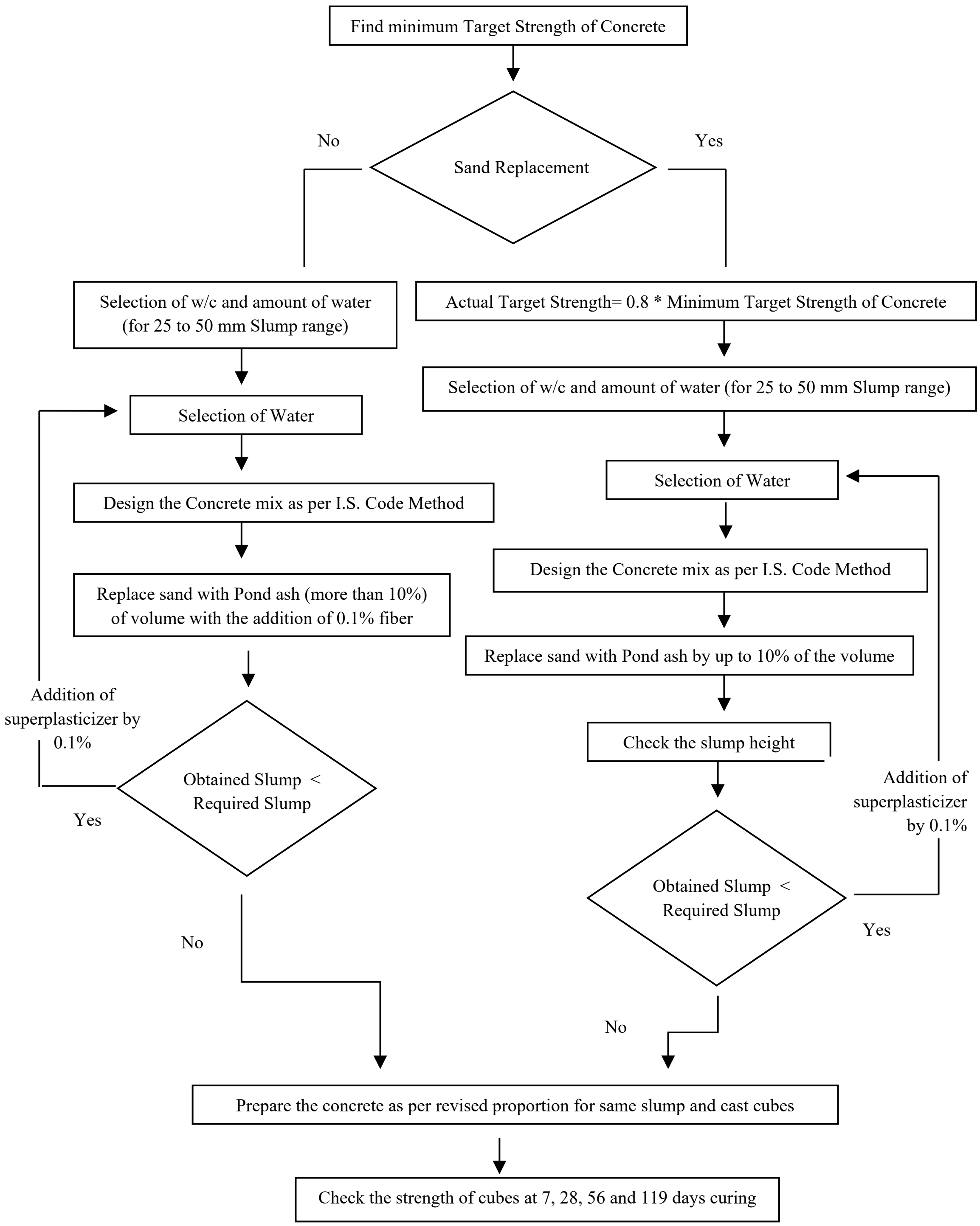

Figure 16. Mix design procedure for sand replacement with pond ash .

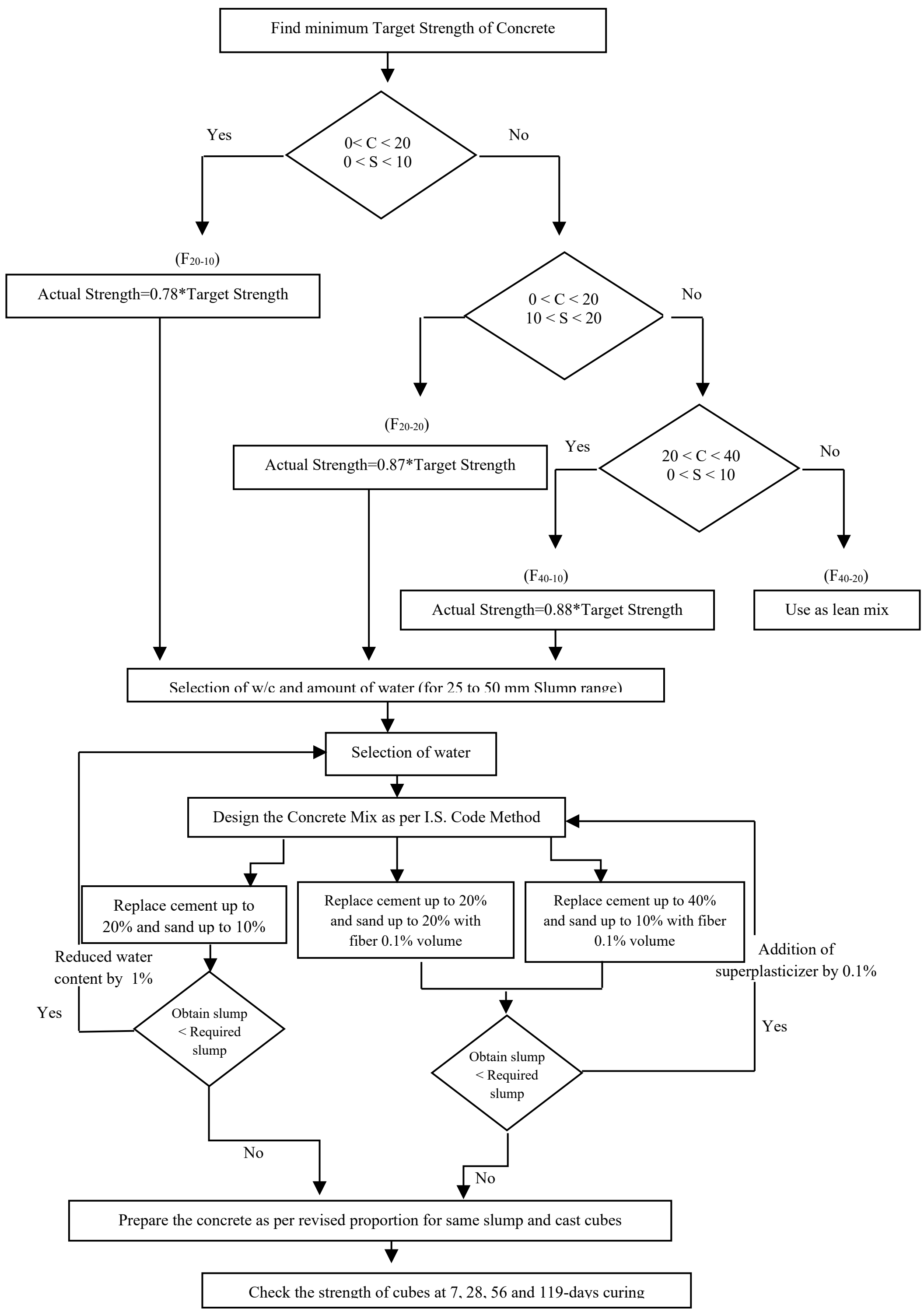

Figure 17. Mix design procedure for simultaneous replacement of cement and sand with fly ash and pond ash.

4. Conclusions

The present investigation indicates with a high degree of confidence that locally available pond ash and coarse fly ash can successfully be used as partial substitutes for sand and cement in concrete making as they are alternate building materials that can supply additional strength and durability of concrete. In order to achieve better compressive strength than control concrete at 28 days, cement can be replaced with locally available fly ash at up to 20%, and sand replaced with locally available pond ash at 10% for concrete with or without fiber at a water-cement ratio less than 0.4. For the combination of both cement and sand replacement, F_{20-10} mix is recommended. However, based on workability and durability, the cement should be replaced with fly ash up to 40%. Replacement of sand with 20% pond ash can be allowed in cases of lower availability of sand. However, the mix should be properly proportioned to have similar workability. It was found that the addition of fly ash and pond ash in concrete could produce workable and durable concrete, and concrete of the required strength with cost and energy savings for cement and sand. Up to 90 kg of cement (20% cement replacement) can be saved by replacing cement with fly ash without compromising strength. Similarly, up to 76 kg of sand (10% sand replacement) can be saved by replacing sand with pond ash without compromising the strength. Hence, a 20% saving of energy can be obtained via the consumption of less cement and sand in the present type of concrete. For sustainable development, an increased use of fly ash and pond ash in concrete can facilitate reductions in landfill areas and in the mining of sand from river basin, and minimization of destruction of hills due to the search for and mining of lime.

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