Ain Shams Engineering Journal (2015) xxx, xxx–xxx

Ain Shams University
Ain Shams Engineering Journal
www.elsevier.com/locate/asej
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CIVIL ENGINEERING

Effect of pond ash and steel fibre on engineering properties of concrete

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Received 1 July 2014; revised 26 November 2014; accepted 12 March 2015

KEYWORDS

Pond ash;
Steel fibre;
Compressive strength;
Split tensile strength;
Flexural strength;
Modulus of elasticity

Abstract This paper presents an experimental study on engineering properties of pond ash-modified concrete reinforced by discrete steel fibres. Pond ash content was varied as 0%, 10%, 20% and 30% by weight of cement. Grooved steel fibres were varied as 0%, 0.5%, 1% and 2% by volume of concrete. Compressive strength, split tensile strength and flexural strength increased with increasing curing period for all fibre contents and pond ash contents. For a given fibre content, compressive strength decreased with increasing pond ash content. Split tensile strength did not show any marked change with increasing pond ash content for any fibre content. Flexural strength also increased with increasing fibre content for all pond ash contents. In general, the addition of steel fibres did not improve the values of modulus of elasticity. The effects of pond ash on modulus of elasticity were not as significant as those of pond ash on strength.

1. Introduction

The collection and disposal of residues such as rice husk ash, bottom ash, fly ash, pond ash and sludge produced as wastes from various industries became a potent environmental problem. However, these industrial wastes could be utilized to advantage in concrete industry. Rice husk ash (RHA) has amorphous silica content, and that large surface area can be produced by combustion of rice husk at controlled temperature. RHA of 30% replacement level reduces chloride penetration, decreases permeability and improve strength and corrosion resistance properties [1].

At 20% replacement of ground RHA, compressive strength of concrete attained values equivalent to that of control concrete [2]. The strength development pattern of bottom ash concrete is similar to that of conventional concrete, but there is a decrease in strength at all the curing ages. The decrease in the strength of concrete is mainly due to higher porosity and higher water demand on use of bottom ash in concrete [3].

The presence of bottom ash increases the bleeding time and the water release rate. The higher the bottom ash content used in concrete, the greater could be this effect [4]. The adsorption capacity of fly ash may increase after chemical and physical activation [5]. Workability measured in terms of slump was found to decrease with silica fume content (compared to blends without silica fume). Furthermore, the utilization of silica

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Peer review under responsibility of Ain Shams University.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.asej.2015.03.009
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fume in combination with fly ash was found to increase the compressive strength of concrete at early ages [6].

Unused fly ash and bottom ash from thermal power plants, mixed in slurry form and deposited in ponds, is known as Pond Ash. Studies on pond-ash in concrete showed that slump and air content of pond-ash might greatly differ according to the place of generation, which might also have a huge influence on the absorption and grading of pond-ash [7]. A marginal increase is observed in the workability as percentage of fly ash increases. Density of concrete is more as the percentage of steel fibre increases with fly ash content of 10% [8]. The properties of concrete containing fly ash and steel fibres were studied. Laboratory test results showed that addition of steel fibres to Portland cement concrete or fly ash concrete improves the tensile strength properties, drying shrinkage and freeze–thaw resistance [9]. Addition of fibres enhances the performance of concrete, while fly ash in the mixture adjusts the workability and strength losses caused by fibres and improves strength gain [10]. The utilization of high-volume coarse fly ash (HVFA) in concrete reduces concrete strength [11]. Fly ash prevents loss of strength in concrete against high temperatures. It contributes to the development of interfacial properties mainly by the pozzolanic effect [12]. Researcher reports that 50% replacement of cement by fly ash is found to be an optimum fly ash content in hybrid fibre composites [13]. Using high-calcium fly ash (HCFA) as an addition to concrete negatively affects the workability of the self-compacting concrete (SCC) mixture, accelerating its loss over time. It can cause a worsening of the properties of hardened concrete; namely their compressive and flexural strength, water absorption and water permeability [14].

The fly ash-scrap tyre fibre composite provides a sustainable supplement to traditional insulation that not only increases the efficiency of traditional insulation but can also help significantly reduce the environmental issues associated with disposal of these waste products [15]. Steel fibres were more efficient in increasing the toughness of concrete than macro-synthetic fibres. Steel fibres are often used to improve the flexural toughness of concrete and are used in various structural applications. Further synthetic fibres are widely used to reduce crack opening due to shrinkage [16].

The ultimate strength of sandwich pipes filled with steel fibre reinforced concrete (SFRC) under external pressure and longitudinal bending was investigated. The mechanical behaviour of SFRC was simulated using a Concrete Damaged Plasticity (CDP) model whose parameters were estimated by uniaxial tension, compression and four-point bending tests. It was found that adhesion between layers and lateral confinement effect on SFRC plays a dominant role in the ultimate strength of SP [17].

A comparative study on the behaviour of glass fibre reinforced polymer concrete (GFRPC) and steel fibre reinforced self-compacting concrete (SFRSCC) was carried by researchers. Results showed that pull-out failure occurred in all the specimens. SFRSCC cover thickness and bond length affected the ultimate value of bond stress of GFRP bars. Moreover, the GFRP bars with ribbed and sand-coated surface treatment showed different interfacial bond behaviour [18]. The strength of concrete decreased with increasing temperature ranging between 105 °C and 1200 °C. When steel fibres were incorporated at 1%, an improvement of fire resistance and crack resistance as characterized by the residual strengths was observed [19].

The behaviour of polymer modified steel fibre-reinforced concretes produced with addition of both steel fibres and a styrene butadiene rubber emulsion (SBR) was studied. The result shows that the addition of steel fibres increases both flexural and compressive strength of the composites. But, the compressive strength decreased with the addition of SBR [20]. A number of experimental tests were conducted to investigate uniaxial compressive strength and tensile strength for steel fibre reinforced concrete. During uniaxial compressive tests, the compressive strength of the material is less affected by the presence of fibres, whereas compressive failure mode of reinforced specimens considerably changes from fragile to ductile. Due to the bridging effect of fibres cubic specimens did not crush but they held their integrity up to end of the test [21]. This paper presents an experimental study on fibre-reinforced concrete modified by pond ash, an industrial waste. Important engineering properties such as compressive strength, split tensile strength, flexural strength and modulus of elasticity were investigated for varying fibre contents and pond ash contents.

2. Experimental investigation

2.1. Test materials

2.1.1. Cement

Ordinary Portland 53 grade cement was used for making the concrete specimens. The specific gravity of the cement was found to be 3.15. The initial setting time and the final setting time of the cement were found to be 140 min and 245 min respectively [22]. The chemical compositions of the cement and the pond ash are shown in Table 1.

2.1.2. Pond ash

The pond ash used in the test programme was obtained from Mettur-Thermal power station, TN, India. The specific gravity of the pond ash was found to be 2.04. The SEM images and the EDAX images of the ash are shown in Figs. 1 and 2 respectively. Pond ash content was varied as 0%, 10%, 20% and 30% by the weight of cement.

2.1.3. Aggregate

Aggregates of size ranging from 20 mm to 12 mm were used in this work. The specific gravity of the coarse aggregates was found to be 2.78, and the water absorption of the coarse aggregates was 0.5%. The specific gravity of the fine aggregates was 2.60 and its water absorption was 1.02% [23].

2.1.4. Fibre reinforcement

Discrete steel fibres conforming to ASTM A 820/A 820M – 04 were used [24]. They were Type 1 cold drawn wire grooved. The steel fibres had a length of 50 mm and a diameter of 1 mm. Hence, their aspect ratio was 50. The tensile strength of the fibre was found to be 1098 MPa using tensometer (Fig. 3). Stress–strain behaviour of the steel fibres is shown in Fig. 3. Fibre content was varied as 0%, 0.5%, 1% and 2% by volume of concrete.

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Table 1 Chemical compositions of cement and pond ash (%).

Parameter	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O	Na_2O	LOI
Cement	19.94	5.15	3.38	63.37	1.58	1.93	0.90	0.24	0.98
Pond ash	54.46	33.11	1.76	7.97	0.35	1.20	0.00	0.00	2.16

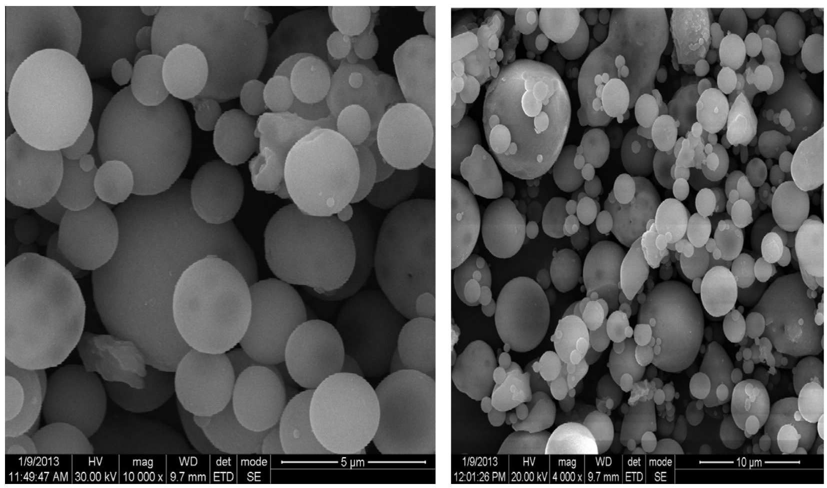
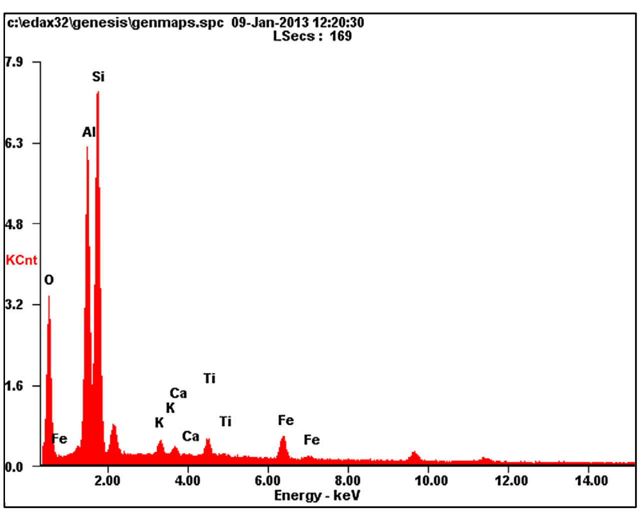


Figure 1 SEM images of pond ash.



Element	Wt (%)	At (%)
OK	43.71	58.37
AlK	19.73	15.63
SiK	30.91	23.52
KK	01.01	00.55
CaK	00.51	00.27
TiK	01.34	00.60
FeK	02.79	01.07
Matrix	Correction	ZAF

Figure 2 EDAX image of pond ash.

2.2. Tests performed and quantities determined

Workability measurements based on the slump value were carried out on fresh fibre-reinforced pond ash concrete. The results of the slump values are presented in Table 2. Inclusion of the steel fibres reduced workability. Increase in the steel fibre content caused additional reduction in workability. However, increase in the pond ash content increased workability.

2.2.1. Composition and preparation of mixtures

For each cubic metre of concrete, w/c + pond ash ratio was determined according to the pond ash content, and the mix was prepared accordingly. Table 2 shows the w/c + pond ash ratios for different ash contents. Mixture design was made in accordance with the Indian Standard Code 10262-2009 [25]. Fresh concretes containing 10%, 20% and 30% pond ash as cement replacement in mass basis were prepared by modifying the reference Portland cement concrete. Similarly, fresh fibre

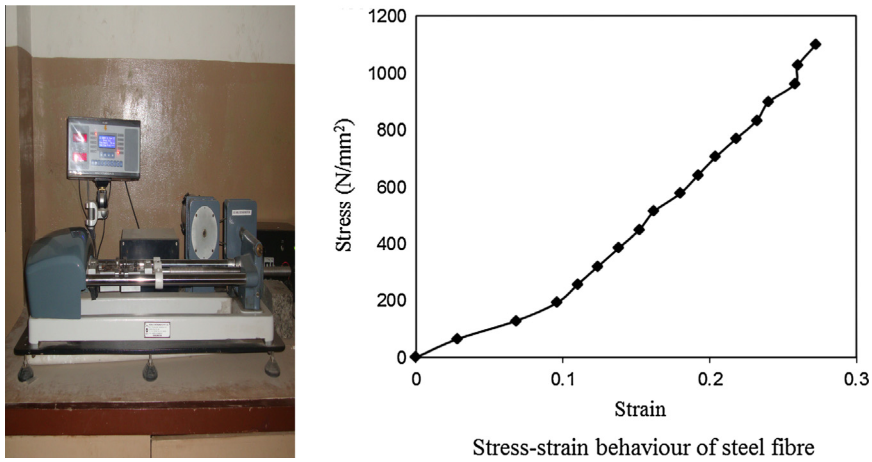


Figure 3 Tension test on steel fibre using tensometer.

Table 2 Mix variables.

Mixture no.	Pond ash content (%)	Steel fibre content (%)	Slump value (mm)	w/(c + pond ash) ratio
A1	0	0	28	0.45
A2	0	0.5	27	
A3	0	1	26	
A4	0	2	25	
B1	10	0	29	0.46
B2	10	0.5	28	
B3	10	1	27	
B4	10	2	27.5	
C1	20	0	30	0.47
C2	20	0.5	29	
C3	20	1	28.5	
C4	20	2	28	
D1	30	0	32	0.50
D2	30	0.5	31	
D3	30	1	29.5	
D4	30	2	29	

reinforced concretes containing 0.5%, 1.0% and 2.0% steel fibre in volume basis were also prepared. The procedures for mixing the fibre-reinforced concrete involved the following steps:

(i) gravel and sand were placed in a concrete mixer and dry mixed for 1 min; (ii) then, cement and fibre were spread and dry mixed for 1 min; (iii) after that, mixing water was added and mixed for approximately 2 min; (iv) and finally, the freshly mixed fibre-reinforced concrete was cast into specimen moulds and vibrated to remove entrapped air. After casting, each of the specimens was allowed to stand for 24 h before demoulding. Demoulded specimens were stored in water at 23 ± 2 °C until testing days. The specimens were named as A1, A2, etc. to indicate different pond ash contents and fibre contents. See Table 2. Curing period was varied as 7 days, 14 days and 28 days.

2.2.2. Compressive strength tests

Compressive strength of the specimens (100 mm × 100 mm × 100 mm) was determined according to the TS EN 12390-3 [26]. The cube specimen was placed under compression testing machine. The bearing surfaces of the testing machine were wiped clean and the specimen was placed in the machine in such a manner that the load was applied to the opposite sides of the cubes as cast, and not to the top and bottom faces. The axis of the specimens was carefully aligned with the centre of thrust of the spherically seated platen. No packing was placed between the faces of the test specimen and the steel platen of the testing machine. As the spherically seated block was brought to bear on the specimen, the movable portion was rotated gently by hand so that uniform seating was obtained. The load was applied without any shock or vibration and increased continuously at a rate of approximately 14 N/mm^2/min until the specimen failed. The failure load was recorded. The compressive strength of the specimen was calculated by dividing the failure load by the cross-sectional area of the specimen. Compressive strength of the cubes was determined at curing periods of 7 days, 14 days and 28 days (Table 3).

2.2.3. Split tensile strength tests

The split tensile strength of cylindrical specimens was determined as per ASTM C496 [27]. The cylindrical specimens were 200 mm in height and 100 mm in diameter. The split tensile strength was also determined at the curing periods of 7 days, 14 days and 28 days (see Table 4). Diametric lines on each end of the cylinder were drawn and it was ensured that they were in the same axial plane. One of the plywood strips along the centre of the lower bearing block was centred and the specimen placed on the plywood strip was aligned so that the lines marked on the ends of the specimen were vertical and centred over the plywood strip. A second plywood strip was placed lengthwise on the cylinder and centred on the lines marked on the ends of the cylinder. Load was continuously applied at a constant rate within the range 0.7–1.4 MPa/min until the specimen failed. The failure load was recorded. The type of the failure and the appearance of the concrete were noted. The split tensile strength (T) was determined from the equation

$$T = 2P/\pi ld \quad (1)$$

where P is the failure load.

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Table 3 Compressive strength and elastic modulus of hardened concrete.

Mixture	Compressive strength (N/mm^2)			Elastic modulus (GPa)
	7 days	14 days	28 days	28 days
A1	33.70	35.15	38.10	18.47
A2	31.13	32.16	35.52	14.51
A3	35.10	36.13	39.70	14.51
A4	35.68	36.76	39.92	16.95
B1	30.73	32.43	37.50	17.68
B2	31.13	33.76	36.40	15.36
B3	27.13	29.03	38.20	19.10
B4	23.20	25.13	38.80	14.22
C1	26.23	28.50	36.44	18.35
C2	25.23	27.20	37.60	20.70
C3	26.93	29.03	37.86	19.37
C4	25.23	26.66	38.90	15.64
D1	28.76	29.23	35.40	12.54
D2	26.26	27.96	35.60	12.10
D3	27.96	29.83	36.50	13.80
D4	27.33	29.13	37.34	14.12

Table 4 Split tensile strength and flexural strength of hardened concrete.

Mixture	Split tensile strength (N/mm^2)			Flexural strength (N/mm^2)		
	7 Days	14 Days	28 Days	7 Days	14 Days	28 Days
A1	2.15	2.33	2.50	4.915	5.2	6.925
A2	2.23	2.30	2.60	4.925	5.00	6.38
A3	2.38	2.44	2.72	5.20	5.175	7.175
A4	2.61	2.66	2.79	5.8	6.15	8.29
B1	1.81	2.24	2.48	4.53	4.875	5.3
B2	2.15	2.34	2.51	4.725	4.86	5.35
B3	2.18	2.42	2.61	4.96	5.15	6.175
B4	2.40	2.52	2.63	5.275	5.45	6.235
C1	1.75	2.23	2.31	4.825	5.89	5.945
C2	2.00	2.40	2.51	4.875	4.935	6.18
C3	2.13	2.45	2.61	5.11	5.175	7.06
C4	2.21	2.53	2.71	5.7	5.785	8.19
D1	1.66	2.11	2.18	4.75	5.89	6.225
D2	2.11	2.20	2.43	5.245	5.58	6.565
D3	2.15	2.30	2.55	5.53	5.825	6.475
D4	2.30	2.50	2.65	5.93	7.00	8.15

2.2.4. Flexural strength test

Flexural strength of the concrete prisms was determined as per the ASTM C293 [28]. The dimensions of the prisms were 500 mm × 100 mm × 100 mm. As already mentioned, flexural strength was determined for the curing periods of 7 days, 14 days and 28 days (Table 4). Preparation of the surfaces was not required, but the bearing surfaces of the supporting and loading rollers were wiped clean. The specimen was then placed in the machine in such a manner that the load was applied to the uppermost surface as cast in the mould, along two lines spaced 200 mm or 133 mm apart. The axis of the specimen was carefully aligned with the axis of the loading device. The load was applied without any shock or vibration and was increased continuously at such a rate that the extreme fibre stress increased at approximately 0.7 $N/mm^2/min$. The load was increased until the specimen failed, and the failure load was recorded. The appearance of the fractured faces of concrete and any unusual features in the type of failure were noted.

The flexural strength of the specimen was determined from the expression,

$$f_b = pl/bd^2 \qquad (2)$$

where f_b = modulus of rupture,
b = measured width in cm of the specimen,
d = measured depth in cm of the specimen at the point of failure,
l = length in cm of the span on which the specimen was supported, and
p = maximum load in kg applied to the specimen.

2.2.5. Elastic modulus test

Elastic modulus was determined for cylindrical specimens 150 mm (diameter) and 300 mm (height) for a curing period of 28 days (Table 3). The test was performed as per ASTM C469-02 [29]. Extensometers were attached on the opposite sides of the specimens parallel to the axis so that the gauge points were symmetrical about the centres of the specimens. In no case were the gauge points nearer to either end of the specimens than a distance equal to half the diameter. The extensometers were fixed with the recording points at the same end. The specimen was then immediately placed in the testing machine and centred. The load was applied continuously and without any shock or vibration at a rate of 14 $N/mm^2/min$ until an average stress of (C + 0.5) N/mm^2 is reached, where C is one-third of the average compressive strength of the cubes. The load was maintained at this stress for at least one minute and was then reduced gradually to an average stress of 0.15 N/mm^2 when the extensometer readings were taken. The load was applied a second time at the same rate until an average stress of (C + 0.15) N/mm^2 was reached. The load was maintained at this value while the extensometer readings were taken. The load was again reduced gradually and the readings were again taken at 0.15 N/mm^2. The load was then applied a third time and the extensometer readings taken at ten approximately equal increments of stress up to an average stress of (C + 0.15) N/mm^2. Readings were taken at each stage of loading with as little delay as possible. If the overall strains observed on the second and third readings differed by more than 5 per cent, the loading cycle was repeated until the difference in strains between consecutive readings at (C + 0.15) N/mm^2 did not exceed 5 per cent. The strains at the various loads in the last two cycles were calculated separately for each extensometer and the results were plotted graphically against the stress. The modulus of elasticity was taken as the slope of the chord from the origin to some arbitrary point on the stress–strain curve. The secant modulus calculated was for 40% of the maximum stress.

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3. Discussion of test results

3.1. Effect of pond ash content, fibre content and curing period on compressive strength

Fig. 4 shows the variation of compressive strength with pond ash content for a curing period of 7 days. The data shown pertain to various fibre contents (f_c) of 0%, 0.5%, 1% and 2%. Similar data were obtained for other curing periods also, which are not being presented here. For a curing period of 7 days, compressive strength decreased continuously with increasing pond ash content for $f_c = 0\%$ and 0.5% (Fig. 4). However, when fibre content (f_c) increased from 1% to 2%, compressive strength decreased rapidly up to a pond ash content of 10% and thereafter it increased. This increase in compressive strength beyond a pond ash content of 10% was notable when $f_c = 2\%$ and marginal for $f_c = 1\%$. While the addition of steel fibres to concrete did not improve its long-term compressive strength, the addition of pond ash positively decreased the average compressive strength.

Fig. 5 shows the effect of fibre content on compressive strength of concrete for a curing period of 7 days. Similar data were obtained for other curing periods also. For a pond ash content of 30%, compressive strength decreased from 28.76 N/mm^2 to 27.33 N/mm^2 when the fibre content increased from 0% to 2%. This was found to be true for all pond ash contents (Fig. 5). A similar observation was made by [9] regarding pozzolanic effects of fly ash on loss in strength in fibre reinforced concretes.

Fig. 6 shows the influence of curing period on compressive strength of concrete for a fibre content of 1%. For a curing period of 28 days, compressive strength decreased from 39.7 N/mm^2 to 36.50 N/mm^2 when the pond ash content increased from 0% to 30%. This was found to be true for all the curing periods (Fig. 6). A similar trend on slow pozzolanic reaction resulting in reduced initial strength was reported by [30]. Fig. 7 shows the effect of curing period on compressive strength of concrete for a pond ash content of 20%. Compressive strength increased from 36.44 N/mm^2 to 38.90 N/mm^2 when the fibre content increased from 0% to 2% for a curing period of 28 days. The increase in compressive strength was about 6% which was marginal. The variation observed in compressive strength of fibre-reinforced concrete may be due to a non-homogeneous distribution of the steel fibres within the concrete.

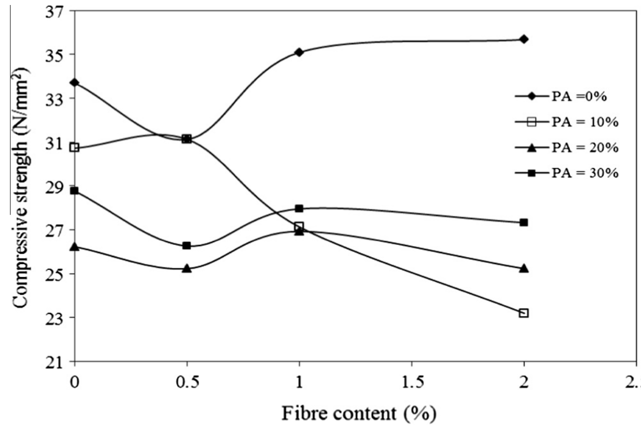

Figure 5 Effect of fibre content on compressive strength of concrete (7 days).

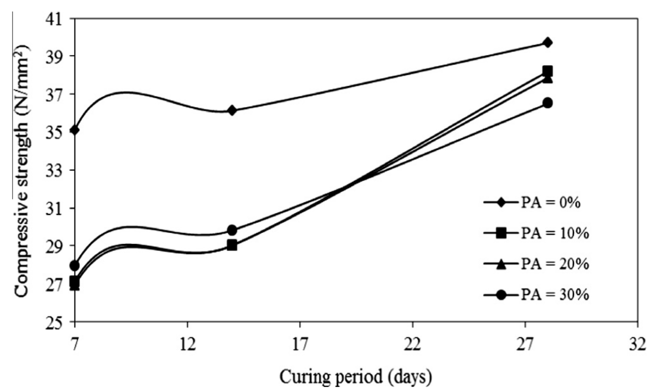

Figure 6 Effect of curing period on compressive strength of concrete ($f_c = 1\%$).

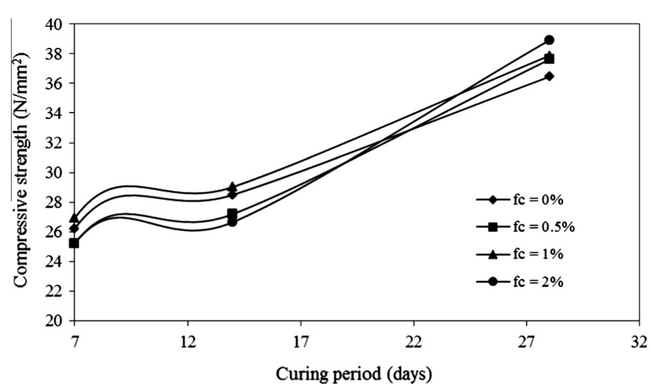

Figure 7 Effect of curing period on compressive strength of concrete (PA = 20%).

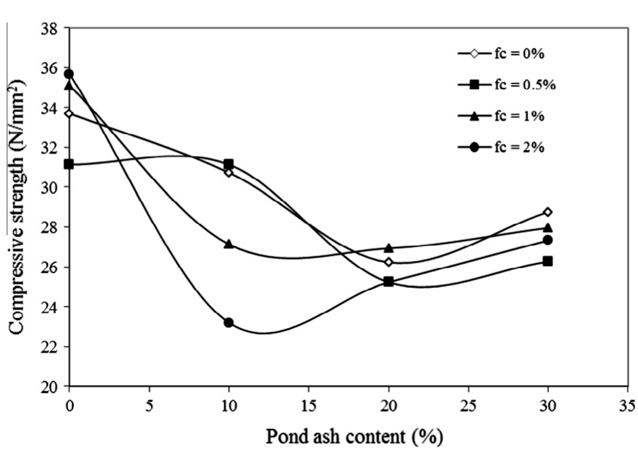

Figure 4 Variation of compressive strength with pond ash content (7 days).

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3.2. Effect of pond ash content, fibre content and curing period on split tensile strength

Fig. 8 shows the variation of split tensile strength with pond ash content for a curing period of 7 days. The data shown pertain to fibre contents (f_c) of 0%, 0.5%, 1% and 2%. Similar data were obtained for other curing periods also, which are not being presented here. Split tensile strength decreased consistently with increasing pond ash content. This was found to be true for all fibre contents (Fig. 8). However, for a given pond ash content split tensile strength increased significantly with increasing fibre content. For a given fibre content, split tensile strength decreased with increasing pond ash content because pond ash, which is a pozzolanic material, cannot contribute to tensile strength. Pond ash contributes to flocculation in the material and the flocs developed resist compressive stresses better than tensile stresses. With increasing pond ash content, development of flocs increases, a fact which reduces the ability of the material to resist tensile stresses.

Previous research report [31] also highlighted the formation of calcium–silicate–hydrate (C–S–H) matrix in such blends resulting in an increase in strength as pore spaces are filled. For example, for $f_c = 0\%$, split tensile strength decreased from 2.15 N/mm^2 to 1.66 N/mm^2 when pond ash content increased from 0% to 30%. Similar data were obtained for other values of f_c (Fig. 8). Because of variations in the physical properties of pond ash such as fineness and pozzolanic activity index, performance of concrete was observed to vary.

Addition of steel fibres to concrete contributes to increase in tensile strength. Fig. 9 shows the variation of split tensile strength with fibre content for a curing period of 7 days. Similar data were obtained for other curing periods also. Split tensile strength increased with increasing curing period. This was found to be true for all pond ash contents. Interestingly, for a given fibre content, split tensile strength increased with decreasing pond ash content (Fig. 9). For a pond ash content of 0%, split tensile strength increased from 2.15 N/mm^2 to 2.61 N/mm^2 when fibre content increased from 0% to 2%. Similar data can be observed for other pond ash contents also (Fig. 9). A similar trend was observed by [9] regarding increased split tensile strength in steel fibre-reinforced concrete.

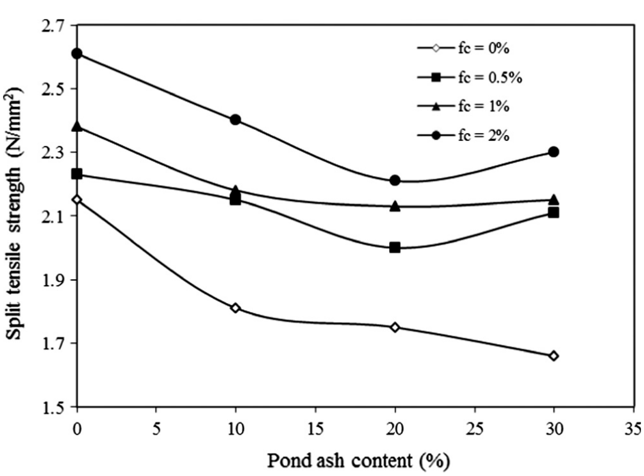

Figure 8 Influence of pond ash content on split tensile strength (7 days).

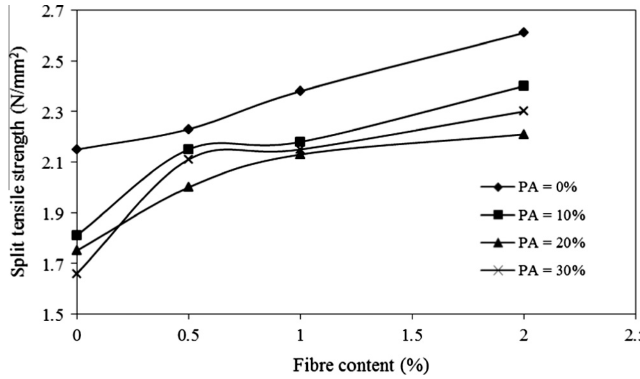

Figure 9 Effect of fibre content on split tensile strength of concrete (7 days).

Fig. 10 shows the influence of curing period on split tensile strength. The data shown pertain to $f_c = 1\%$ and to all the pond ash contents used in the test programme. Split tensile strength increased with increasing curing period. This was found true for all pond ash contents. Similar data were obtained for other fibre contents also. But they are not being shown here. As already mentioned, split tensile strength was the least for the highest pond ash content of 30%. This was found to be true for all the curing periods. For example, split tensile strength increased from 2.15 N/mm^2 to 2.55 N/mm^2 for a pond ash content of 30% when the curing period increased from 7 to 28 days. Further, at the curing period of 28 days, split tensile strength decreased from 2.72 N/mm^2 to 2.55 N/mm^2 when the pond ash content increased from 0% to 30%. With increasing curing period, the effect of flocculation increases which increases the split tensile strength. The flocs already developed during flocculation get hardened with increasing curing period, resulting in increased split tensile strength.

Fig. 11 shows the effect of curing period on split tensile strength for a pond ash content of 20%. The data shown pertain to different fibre contents used. Similar data were obtained for all pond ash contents. Split tensile strength increased with increasing curing period. This was found to be true for all the fibre contents. Further, for a given curing period, split tensile strength increased with increasing fibre content. This was also found to be true for all pond ash

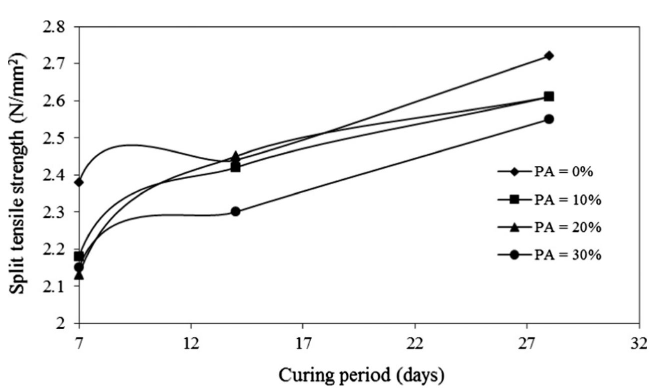

Figure 10 Effect of curing period on split tensile strength of concrete ($f_c = 1\%$).

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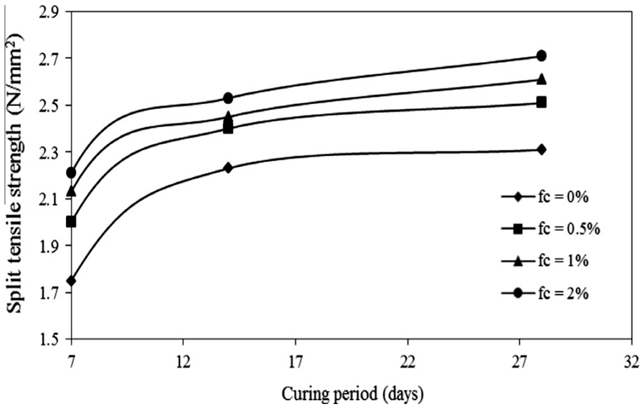

Figure 11 Effect of curing period on split tensile strength of concrete (PA = 20%).

contents. As steel fibres render concrete less brittle and more ductile, the tensile strength of the composite increases with increasing steel fibre content. Split tensile strength increased from 2.21 N/mm^2 to 2.71 N/mm^2 for f_c = 2% when curing period increased from 7 days to 28 days. At a curing period of 28 days, split tensile strength increased from 2.31 N/mm^2 to 2.71 N/mm^2 when f_c increased from 0% to 2%.

3.3. Effect of pond ash content, fibre content and curing period on flexural strength

Fig. 12 shows the variation of flexural strength with pond ash content for a curing period of 7 days. The data shown pertain to fibre contents (f_c) of 0%, 0.5%, 1% and 2%. Similar data were obtained for other curing periods also, which are not being presented here. Flexural strength decreased consistently with increasing pond ash content. This was found to be true for all fibre contents (Fig. 12). However, for a given pond ash content, flexural strength increased significantly with increasing fibre content. For a given fibre content, flexural strength decreased with increasing pond ash content. Pond ash contributes to flocculation in the material and the flocs developed resist compressive stresses better than tensile or flexural stresses. With increasing pond ash content, development of flocs increases, a fact which reduces the ability of the material to resist tensile or flexural stresses. For example, for f_c = 0%, flexural strength decreased from 4.91 N/mm^2 to 4.75 N/mm^2 when pond ash content increased from 0% to 30%. Similar data can be observed for other values of f_c (Fig. 12).

Fig. 13 shows the variation of flexural strength with fibre content for a curing period of 7 days. Similar data were obtained for other curing periods also. Flexural strength increased with increasing curing period. This was found to be true for all pond ash contents. Interestingly, for a given fibre content, flexural strength increased with decreasing pond ash content (Fig. 13). For a pond ash content of 0%, flexural strength increased from 4.91 N/mm^2 to 5.80 N/mm^2 when fibre content increased from 0% to 2%. Similar data can be observed for the other pond ash contents also (Fig. 13). Under bending loads, tensile stresses occur in the microstructure of concrete, and fibres withstand the tensile stress. Hence, flexural strength of concrete increased [10].

Fig. 14 shows the influence of curing period on flexural strength. The data shown pertain to f_c = 1% and to all the pond ash contents used in the test programme. Flexural strength increased with increasing curing period. This was found true for all pond ash contents. Similar data were obtained for other fibre contents also. But they are not being shown here. For example, flexural strength increased from 5.43 N/mm^2 to 6.47 N/mm^2 for a pond ash content of 30% when the curing period increased from 7 to 28 days. Further, at the curing period of 28 days, flexural strength decreased from 7.17 N/mm^2 to 6.47 N/mm^2 when pond ash content increased from 0% to 30%. With increasing curing period, the effect of flocculation increases which increases the flexural strength. The ductility and tenacity of steel fibre reinforced concrete (SFRC) increase when fibre content in volume increases [21]. This phenomenon is due to the higher deformability and energy absorption of SFRC during the cracking phase. SFRC shows a higher bending stiffness than normal concrete. Its cracking pattern is also different from that of normal concrete. Therefore, an increment in fibre content causes ductility to develop first crack strength and increases flexural strength.

Fig. 15 shows the effect of curing period on flexural strength for a pond ash content of 20%. The data shown pertain to different fibre contents used. Similar data were obtained for all pond ash contents. Flexural strength increased

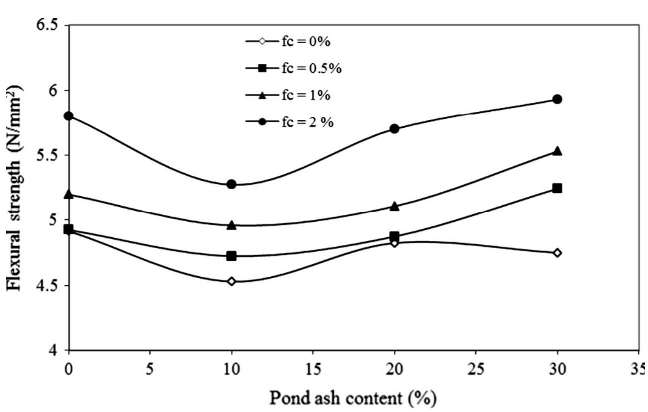

Figure 12 Effect of pond ash content on flexural strength (7 days).

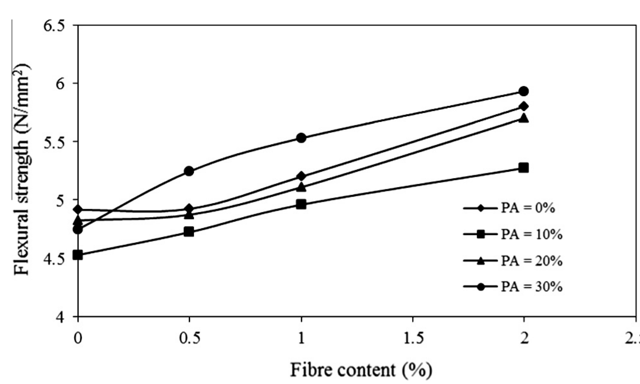

Figure 13 Effect of fibre content on flexural strength of concrete (7 days).

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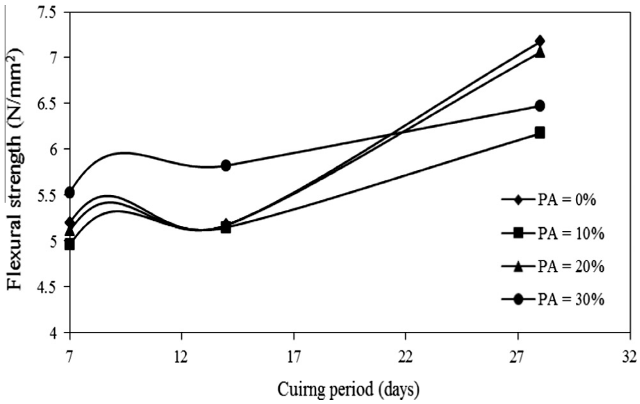

Figure 14 Effect of curing period on flexural strength of concrete (f_c = 1%).

with increasing curing period. This was found to be true for all the fibre contents. Further, for a given curing period, flexural strength increased with increasing fibre content. This was also found to be true for all pond ash contents. Flexural strength increased from 5.70 N/mm^2 to 8.19 N/mm^2 for f_c = 2% when curing period increased from 7 days to 28 days. At a curing period of 28 days, flexural strength increased from 5.95 N/mm^2 to 8.19 N/mm^2 when f_c increased from 0% to 2%.

3.4. Effect of pond ash content and fibre content on elastic modulus of concrete

Stress–strain behaviour of a cylindrical specimen for varying pond ash content and fibre content is shown in Figs. 16–19 for a curing period of 28 days. The modulus of elasticity is taken as the slope of the straight line portion from the origin to some arbitrary point on the stress–strain curve. The secant modulus was calculated for 40% of the maximum stress. For a pond ash content of 0%, elastic modulus decreased from 18.47 GPa to 16.95 GPa when the fibre content increased from 0% to 2% (Fig. 16). A similar reduction in elastic modulus was found in the case of 10% pond ash content also (Fig. 17). However, when the pond ash content was increased to 20%, elastic modulus increased from 18.35 GPa to 20.70 GPa when the fibre content increased from 0% to 0.5%. Elastic modulus decreased from 19.37 GPa to 15.64 GPa when the fibre content

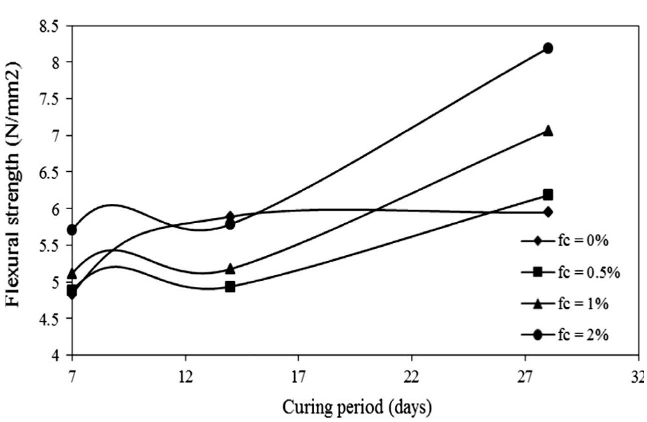

Figure 15 Effect of curing period on flexural strength of concrete (PA = 20%).

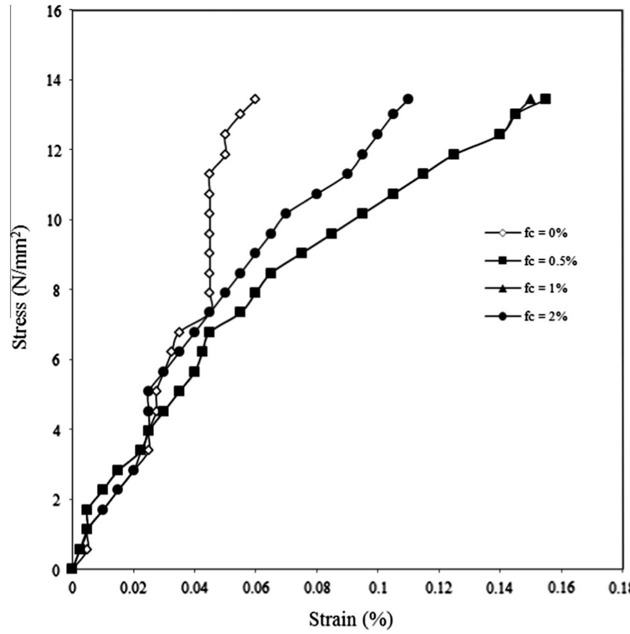

Figure 16 Stress–strain behaviour of the cylindrical specimen (0% pond ash content).

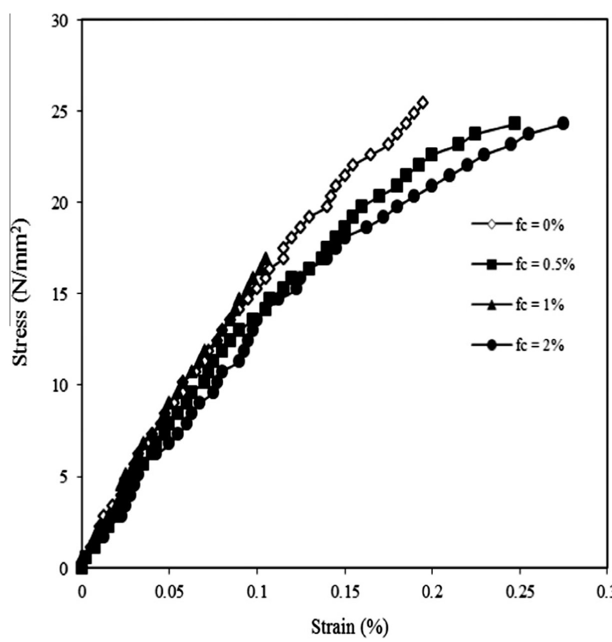

Figure 17 Stress–strain behaviour of the cylindrical specimen (10% pond ash content).

increased from 1% to 2% for a pond ash content of 20% (Fig. 18). Therefore, the addition of steel fibre did not improve the modulus of elasticity. Modulus of concrete is influenced by density, porosity, mix proportion, moduli of elasticity of the ingredients and the characteristics of the transition zone. Further, void space and micro-cracks influence the stress–strain behaviour. Cracks in the transition zone, orientation of calcium hydrate (C–H) crystals and void spaces make the transition zone weak. This causes the elastic modulus to decrease gradually with increasing applied loads.

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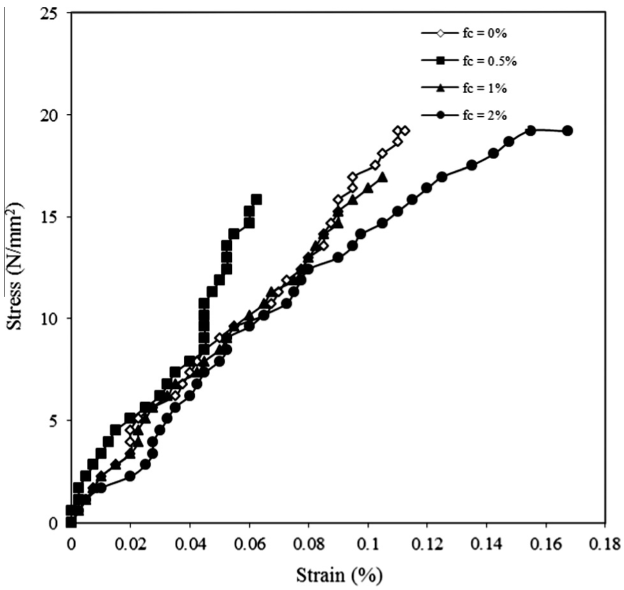

Figure 18 Stress–strain behaviour of the cylindrical specimen (20% pond ash content).

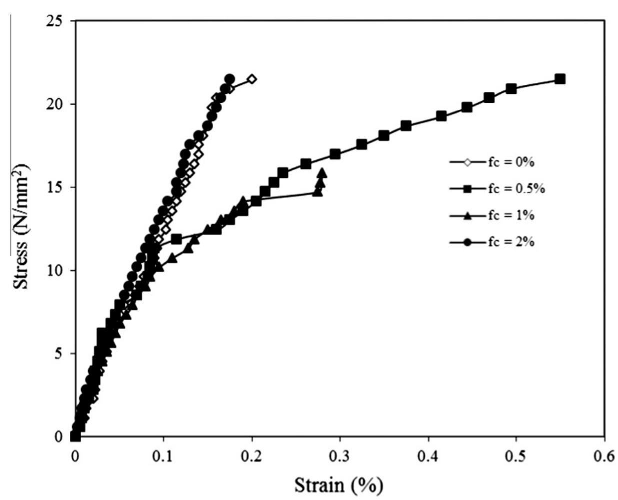

Figure 19 Stress–strain behaviour of the cylindrical specimen (30% pond ash content).

Fig. 19 shows the stress–strain behaviour of a cylindrical specimen for a pond ash content of 30% and for varying fibre content (f_c). The elastic modulus of 30% pond ash concrete increased from 12.54 GPa to 14.12 GPa when the fibre content increased from 0% to 2%. When the pond ash content increased from 0% to 30%, the elastic modulus decreased from 18.47 GPa to 12.54 GPa for a fibre content of 0%. Hence, the effects of pond ash on modulus of elasticity were not as significant as the effects of pond ash on the strength.

4. Conclusions

A series of laboratory experiments was conducted to find compressive strength, split tensile strength, flexural strength and modulus of elasticity of fibre-reinforced pond ash modified concrete. The effect of pond ash content, fibre content and curing period was studied. The following are the conclusions that can be drawn from the experimental investigation:

1. The average compressive strength of concrete respectively increased by 5% and 4% when fibre content increased from 0% to 2% for pond ash contents of 0% and 10%. For a pond ash content of 20%, the average compressive strength increased by 7% when fibre content increased from 0% to 2%. The average compressive strength increased for 20% pond ash content and 0.5% steel fibre content in comparison with 0% pond ash and 0.5% steel fibre. The increase in compressive strength was about 6%. Therefore, only a small increase in compressive strength was achieved with increase in fibre content. Further, when pond ash content increased from 20% to 30%, the average compressive strength decreased for all fibre contents.
2. The increase in split tensile strength was about 12% when fibre content increased from 0% to 2% for plain concrete for a curing period of 28 days. When fibre content increased from 0% to 2% for a pond ash content of 20%, the average split tensile strength increased by about 17%. Further, for a pond ash content of 30%, the average split tensile strength increased to 22% when fibre content increased from 0% to 2%. Addition of steel fibre improved the split tensile strength of concrete when compared with plain concrete.
3. When fibre content increased from 0% to 2% at 0% pond ash, the average flexural strength increased to 20% for a curing period of 28 days. For pond ash contents of 10% and 20%, the increase in flexural strength was respectively 18% and 38% when fibre content increased from 0% to 2%. Further, for a pond ash content of 30%, the increase in flexural strength was about 31% when fibre content increased from 0% to 2%.
4. The modulus of elasticity decreased by 6%, when fibre content increased from 0% to 2% for plain concrete. Further, for a pond ash content of 10% and 20%, the modulus of elasticity reduced by 24% and 17% respectively when fibre content increased from 0% to 2%. There was a marginal increase of about 12% for a pond ash content of 30%, when the fibre content increased from 0% to 30%. But it cannot be concluded that modulus of elasticity increased when pond ash content increased, since the elastic modulus decreased by 5%, 0.7% and 47% for pond ash contents of 10%, 20% and 30% when compared with 0% fibre content concrete specimens. From the data on elastic modulus, it can be concluded that 20% pond ash can be effectively used as a replacement of cement in concrete.
5. Hence, pond ash which is a waste material available abundantly can be effectively utilized as a replacement of cement in concrete, in combination with steel fibres to increase the long term strength of concrete.

Acknowledgements

The authors gratefully acknowledge the Department of science and technology-SERB Fast Track scheme for Young Scientist in Engineering Sciences for funding. The authors would like thank to VIT University for providing support to conduct the experiments in the laboratories.

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