Strength Properties of Processed Fly Ash Concrete

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Abstract. The present paper reports on the mechanical treatment of fly ash for improving the delayed reactivity of fly ash with the hydration product of cement. Grinding of fly ash was carried out in a ball mill for different time durations and processing time was optimized for maximum fineness. Concrete mixes were prepared using various proportions of processed and unprocessed fly ash replacement in cement (25% and 50%). The influence of steel fiber addition on the mechanical properties of the concrete was studied for different curing periods. The test results on pozzolanic activity and lime reactivity indicate that the processed fly ash exhibited a higher strength gain than the unprocessed fly ash, with a maximum increase in compressive strength of up to 12%. Improved pozzolanic properties were noticed due to the increase in fineness of the fly ash particles.

Keywords: *ball mill; compressive strength; fly ash; pozzolanic activity; processing; strength gain.*

1 Introduction

The production of high-strength concrete incorporating fly ash has been studied widely and is being applied successfully in the field. However, the negative effects on the setting properties and deceleration of the rate of strength gain restricts the maximum replacement levels of fly ash in cement concrete. The efficiency of fly ash addition to concrete is also influenced by the mix design parameters, strength range, addition level and age. High-volume fly ash blended cements containing ground fly ash exhibit an increase in compressive strength. Ondova, *et al.* [1] in their research showed that the improvement in strength seemed to increase with an increase in the fineness of the fly ash and was particularly significant compared to coarser fly ash and also showed that the fineness of the fly ash significantly increased the surface area due to the effect of the grinding process, which improved the strength gain properties of the concrete. Berryman, *et al.* and McCarthy, *et al.* [2,3] noted that the processing of fly ash envisages the early setting properties and improves micro-structural

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properties of fly ash mixed concrete. This can guarantee an accelerated strength gain and improved long-term durability properties of the fly ash concrete.

Processing generally refers to the grinding of fly ash particles or selective use of fine-graded fly ash particles and removal of unburnt carbon particles. Bharatkumar, *et al.* and Poon, *et al.* [4,5] indicate that a slow strength gain primarily leads to negative effects in the use of fly ash for fast track concreting such as concrete pavement applications. Processing of fly ash is a promising technique that can completely offset the negative effects of fly ash addition on the rate of strength gain in concrete. Ganesh Babu, *et al.* [6] reported that the beneficial properties of fly ash can be realized in terms of improved mechanical properties of concrete after a longer curing period. However, the early-age setting properties of cement concrete are greatly affected when fly ash is partially replaced with cement due to the delayed pozzolanic activity of the fly ash. Paya, *et al.* [7] indicated a similar trend in processed fly ash, which can have improved setting and hardening properties with cement since the fineness of the fly ash particles induces early reactivity. Air-classified finer varieties of fly ash with an average particle size of 10 microns resulted in marginal improvements in strength of up to 22% after 28 days. Ukita, *et al.*, Sharma, *et al.* and Ganesh Babu, *et al.* [8-10] concluded that the cementing efficiency of fly ash depends on many of its characteristics. Physical properties like particle shape, size and distribution, and chemical properties like composition and glass content are known to affect the reactivity of fly ash. Several investigators have reported the effect of fly ash on concrete by comparing the compressive strength of fly ash concrete with that of normal concretes. Finely ground fly ash can significantly improve the setting properties of concrete and increase the compressive strength after 3 days and it was also shown that for various levels of fly ash replacement in concrete the durability properties of the concrete were enhanced at different curing ages and well-crystallized hydrogarnet was formed. Hassan, *et al.* and Erdogu, *et al.* [11,12] demonstrate that they successfully enhanced the strength of the concrete by including coarse and fine fly ashes of similar chemical admixture and mineralogical composition at a different percentage of replacement with filler materials. Haque, *et al.* [13] reported that fly ash has little cementing efficiency at early ages and acts as filler material for the replacement of fine aggregate and also concluded that the strength properties were improved at later ages, without affecting the durability properties of the concrete. Ehm, *et al.* [14] in their study focused on the removal of coarse size fractions from fly ash, which can result in a significant improvement of the concrete properties. Concrete made with processed fly ash showed good reduction of porosity and permeability.

1.1 Research Significance

The importance of this study is to show the influence of processing fly ash (by mechanical grinding) for improving the pozzolanic reaction with the cement hydration product. Experimental investigations were focused towards the beneficial addition of high-volume replacements of processed fly ash in the reference concrete without affecting the strength-gain properties of the fly ash based concrete. This study also focused on the various mechanical characterizations of the processed fly ash concrete and providing a comparative assessment of unprocessed fly ash.

2 Experimental Methodology

2.1 Materials Used

In this study a 53 grade ordinary Portland cement of specific gravity 3.14 with a consistency of 31% and a class F fly ash of specific gravity value 2.41 were used. Table 1 shows the chemical composition of the low-calcium class F fly ash.

Table 1 Chemical Composition of Class F Fly Ash.

Sl. No.	Chemical composition	IS: 3812-2003 [15]Specifications	Ennore fly ash
1	SiO_2	35 (min)	51.7
2	$Al_2O_3 + Fe_2O_3 + MgO$	70 (min)	85.25
3	S_2O_3	5 (max)	3.25
4	CaO	-	6.27
5	Loss on ignition (LOI)	12 (max)	1.98

2.2 Mechanical Treatment/Grinding of Fly Ash

Processing of fly ash was carried out by means of a mechanical grinding machine of which a snapshot is shown in Figure 1. The grinding of the fly ash was performed in a 3-kg capacity ball mill. About 1 kg of fly ash was added into the machine and cast iron balls (50 pcs) of 30-mm diameter and each weighing approximately 200 gms were added into the ball mill. The ball mill was driven by means of an electric motor with a vertical rotating speed of 60 rpm and was operated for different durations. The fly ash was emptied from the ball mill and sieving was carried out using a 45-micron sieve. The material passing through the sieve as well as retained on the sieve was poured into separate drying pans. The above procedure was repeated for varying time periods. The different time periods of grinding were adopted to obtain varying degrees of fineness, viz. 4 hour, 1 hour, 40 minutes, 30 minutes and 20 minutes. The ground fly ash sample is referred to as Stage II (processed fly ash) in this study. The basic properties of the processed fly ash at various levels of grinding are provided in Table 2.

Figure 1 Mechanical grinding of fly ash.

Table 2 Physical Characteristics and Reactivity Index of Processed and Unprocessed Fly Ash Samples.

Grinding period of fly ash in ball mill	% Retention on 45-micron sieve	Blaine's fineness (m^2/kg)	Specific gravity	Lime reactivity (MPa)	Pozzolanic activity IS 1727-1981 [16] (%)
2 hour	1	412	2.61	6.08	98
1 hour	3	392	2.51	5.87	94
40 minutes	10	350	2.35	4.21	87
30 minutes	15	341	2.3	4.01	82
20 minutes	25	315	2.24	3.46	76
0 minutes (unprocessed fly ash)	33	290	2.18	3.12	72
ASTM C-618 [17]	34	340	-	-	-
IS 3812 (2003) Grade I	-	-	-	4	75

2.3 Aggregates

Crushed blue metal stone was used as coarse aggregate passing through a 12.5-mm sieve and river sand passing through 2.36 mm sieve was used as fine aggregate.

2.4 Glued steel fibers

Both end hooked steel fibers were added at 0.5% and 1% by volume fraction of concrete. Detailed properties of the steel fibers are given in Table 3 and a snapshot of the glued steel fibers is shown in Figure 2. Potable water was used for mixing the fresh concrete constituents along with 1% of accelerator and polycarboxylate ether based superplasticizer (PCE) was added to improve consistency. The dosage of chemical admixture was varied to achieve the desired slump range of 75 to 100 mm.

Table 3 Properties of Glued Steel Fibers (GSF).

Material	Glued steel fibers
Relative Density	7.65 kN/m^3
Length	35 mm
l/d ratio	70
Thickness	0.5 mm
Width	1.25 mm
Tensile strength	1700 MPa
Failure strain	3 to 5 %

Figure 2 Snapshot of glued steel fibers.

2.5 Concrete Mix Design

The various mixture proportions are given in Table 4. The reference concrete (M) was designed according to the mix proportion concept. Stage I stands for unprocessed fly ash (raw material) consisting of four different concrete mixture proportions, designated as MA1, MA2, MB1, and MB2. Stage II stands for processed fly ash designated as M1, M1C1, M1C2, M1D1, and M1D2. These mixtures were proportioned based on a low water to binder ratio (0.3) and the fine to coarse aggregate (F/c) ratio was kept at 0.6. The replacement level of fly ash was kept at 25% and 50% with addition of polycarboxylic ether based superplasticizer (PCE) at 1% and 1.5%, depending on the binder content. Further, a constant dosage of accelerator of up to 1% by weight of binder content was added and also steel fibers varying at 0.5% and 1% by volume fraction (V_f) were included for various mixture proportions of concrete to maintain the workability and uniformity of the mixes.

Table 4 Details of various concrete mix proportions.

Stages	**Mix Id**	**w/b ratio**	**F/c ratio**	**GSF (%)**	**Cement (kg/m^3)**	**Fly ash (kg/m^3)**	**Fine Aggregate (kg/m^3)**	**Coarse Aggregate (kg/m^3)**	**Water (kg/m^3)**	**Acl (%)**	**PCE (%)**
Reference	M	0.3	0.6	0	473	0	672	1113	166	1	1
Stage I (unprocessed fly ash)	MA1	0.3	0.6	0.5	355	118	672	1113	166	1	1
	MA2	0.3	0.6	1.5	355	118	672	1113	166	1	1
	MB1	0.3	0.6	0.5	227	226	672	1113	166	1	1.5
	MB2	0.3	0.6	1.5	227	226	672	1113	166	1	1.5
Reference	M1	0.3	0.6	0	355	118	672	1113	166	1	1
Stage II (processed fly ash)	M1C1	0.3	0.6	0.5	355	118	672	1113	166	1	1
	M1C2	0.3	0.6	1.5	355	118	672	1113	166	1	1
	M1D1	0.3	0.6	0.5	227	226	672	1113	166	1	1.5
	M1D2	0.3	0.6	1.5	227	226	672	1113	166	1	1.5

Note: In order to obtain a constant workability of 75 mm to 100 mm, Acl (accelerator), GSF (glued steel fibers), and PCE (polycarboxylic ether based superplasticizer) were added at different dosage levels based on the fly ash content.

2.6 Specimen Preparation and Testing

The concrete ingredients were mixed in a rotating drum mixer for approximately 3 to 5 mins to maintain uniform consistency for various proportions of concrete. Specimen details are presented in Table 5. For each mix three specimens were casted and the average value of the strength is reported. After the required curing period, the specimens were tested in a compression and flexural testing machine.

Table 5 Details of Concrete Specimens.

Shape	Size of the concrete specimens	Tested	Rate of loading	Indian Standard testing method
Cubes	100 x 100 x 100 mm	Compression	2.5 kN/sec	516-1959 [17]
	100 x 100 x 100 mm	Ultrasonic pulse velocity	50 kHz	13311-1992 part 1 [18]
Cylinder	100 mm diameter and 150 mm height	Split Tensile strength	2.0 kN/sec	5816-1970 [19]
Prism moulds	100 x 100 x 500 mm	Flexural strength for third point loading	1.0 mm/min	516-1959 [17]

3 Experimental Test Results and Discussions

In the present study it was found that the effect of pozzolanic activity of processed fly ash was better than that of unprocessed fly ash. It was noted that the fineness of fly ash increased with a longer grinding duration and resulted in improved reactivity of the fly ash. The pozzolanic activity of the processed fly ash showed the direct measure of its surface activation and strength activity and the coarser particles did not react faster in the early stages of hydration.

3.1 Compressive Strength

The compressive strength test results for various concrete mixes are given in Table 6. It was noted that in the case of unprocessed fly ash concrete the compressive strength of the reference concrete (without fly ash and steel fibers) was 38.40 MPa and 43.20 MPa at 28 days and 56 days, which was far better than of the unprocessed 25% fly ash based concrete. In the case of 25% fly ash added with 1.5% steel fibers a marginal improvement was observed at 28 and 56 days, with a strength value of around 41.50 MPa and 48.70 MPa respectively. The unprocessed fly ash (MB2) based concrete with 50% substitution showed a slight reduction in compressive strength of 39.71 MPa as compared to the low-volume fly ash addition, as can be seen in Figure 3. In the case of processed fly ash (1 hour grinding) an appreciable improvement of the rate of strength gain was measured, as can be seen in Figure 4.

The various replacement levels of processed fly ash for different percentages of steel fiber addition denoted that a good interaction existed for the overall strength improvement compared to the unprocessed fly ash concrete. It can be justified that micro-structural improvements resulted from a higher substitution of processed fly ash when compared to the unprocessed fly ash. The test results show that the various levels of fly ash with different percentages of steel fiber addition and the inclusion of accelerator along with superplasticizer showed significant improvement of the compressive strength for all types of fly ash based fiber reinforced concretes at different curing days. Higher compressive strength was noted for 25% processed fly ash addition in concrete with steel fiber inclusion, which showed a compressive strength of 49.20 MPa. It can be noted that a similar trend was observed in the case of 50% processed fly ash concrete with addition of 1.5% of steel fibers, which exhibited a strength increase of up to 17.79% and 12.11% at 28 and 56 days respectively. It showed the maximum strength gain when compared to the unprocessed fly ash at 25% fly ash replacement as well as the reference concrete. It is understood that the rate of strength gain in fly ash concrete is dependent on the fineness of the fly ash particles, which provides more active surface for the pozzolanic reaction. Hence, large-volume fly ash addition in concrete can be beneficial in terms of a higher strength gain as compared to unprocessed fly ash concrete.

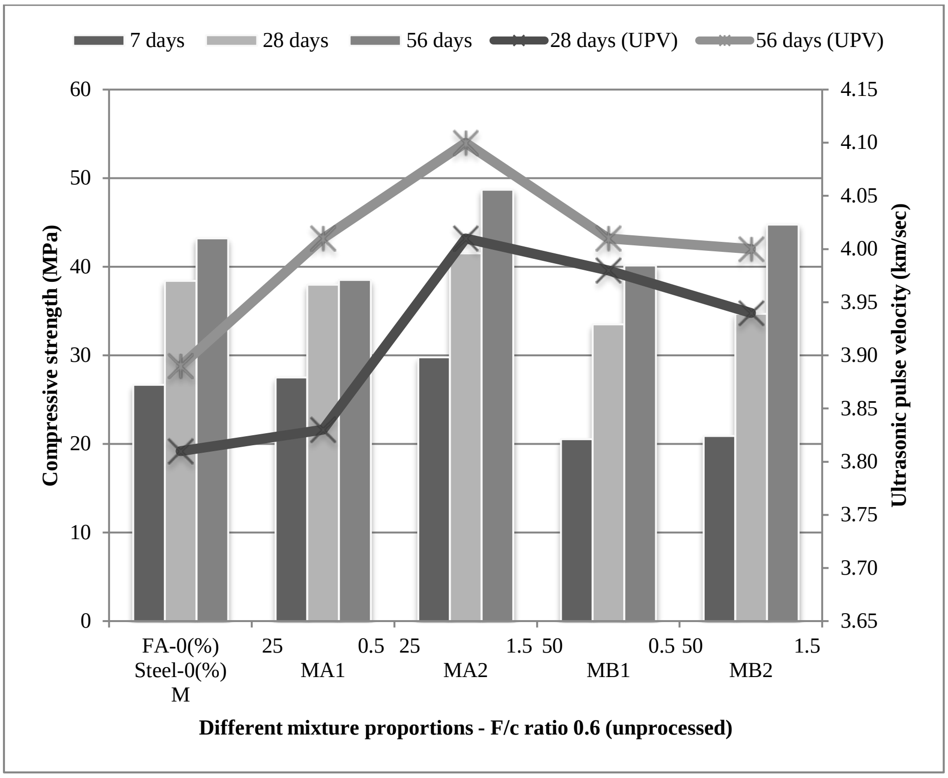

Figure 3 Compressive strength and ultrasonic pulse velocity for various mixes concrete at F/c ratio 0.6 (unprocessed).

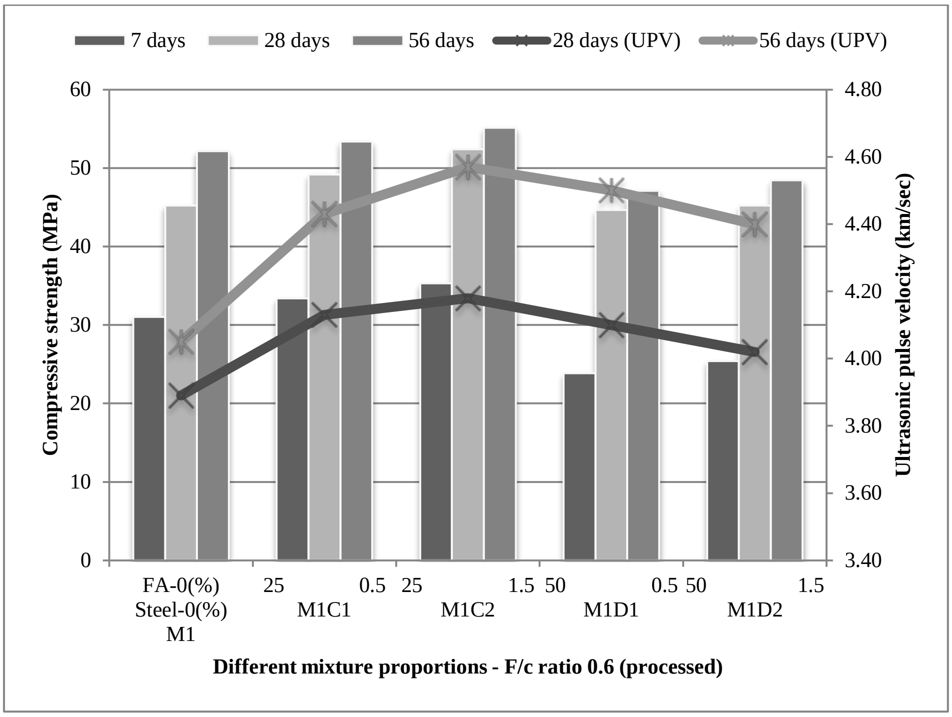

Figure 4 Compressive strength and ultrasonic pulse velocity for various mixes concrete at F/c ratio 0.6 (processed).

3.2 Split Tensile Strength

The experimental test results are provided in Table 6 and are represented in Figure 5. They showed a lower split tensile strength value for the unprocessed fly ash concrete compared to the processed fly ash concrete at 28 days. The addition of unprocessed fly ash indicated a strength loss at early ages of testing due to delayed pozzolanic reaction. An improvement was noticed at a longer curing period (28 days). A maximum split tensile strength of 5.12 MPa was recorded at 25% (by weight of cement) of processed fly ash concrete with 1.5% of steel fibers added (MC2), as shown in Figure 6. This increase in strength value was higher compared to that of the 25% unprocessed fly ash concrete and it can be noted that the percentage improvement in strength was also higher. The trends observed for high-volume fly ash addition at 50% also showed remarkable improvements of the split tensile strength gain. However, further addition of fly ash beyond 50% did not result in strength improvement due to the reduction of minimum cement content for effective binding of the constituent materials. The strength of fly ash concrete in tensile crack resistance depends on the contribution of steel fibers and enhanced micro-structural formation.

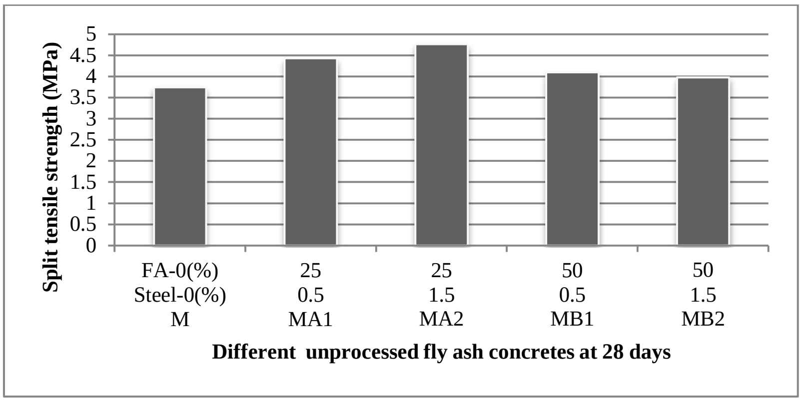

Figure 5 Split tensile strength for various mixture proportions of concrete (unprocessed fly ash).

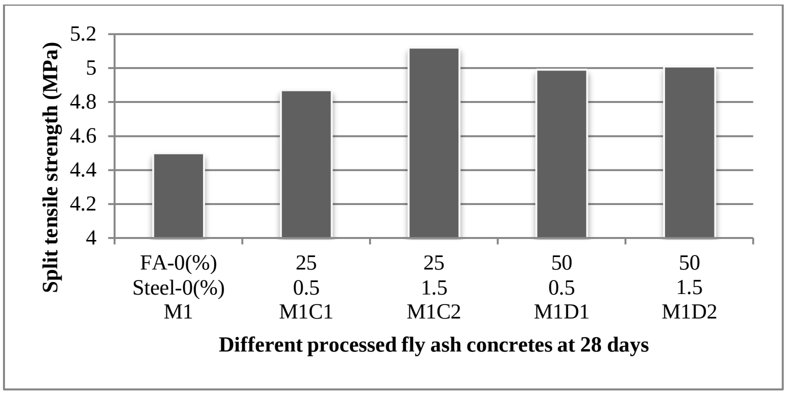

Figure 6 Split tensile strength for various mixture proportions of concrete (processed fly ash).

3.3 Flexural Strength

It was observed from the test results that the flexural strength of the reference concrete substituted with fly ash and addition of steel fibers showed improved flexural strength. The addition of 25% of unprocessed fly ash and 1.5% steel fibers (MA2) to the concrete exhibited a higher flexural strength of 5.56 MPa, as can be seen in Figure 7. Meanwhile in the case of the addition of 25% of processed fly ash (M1C2) and 1.5% steel fibers, the concrete demonstrated a maximum flexural strength of 5.43 MPa, which was higher than for the unprocessed fly ash (as shown in Figure 8). A higher substitution of fly ash content (50%) exhibited a marginal reduction in strength as compared to 25% of unprocessed fly ash replacement. The test results in this study denote that the crack bridging property of steel fibers and additional calcium silicate hydrate gel formation resulted in improved strength properties. This clearly demonstrates an improved pozzolanic reaction in the processed fly ash and adequate curing of fly ash concretes can significantly improve the strength gain properties at much earlier days. Also, the formation of hardened solid hydration product takes place in water-filled pores and produces sufficient gel formation and requires a minimum amount of water for further hydration of gel formation.

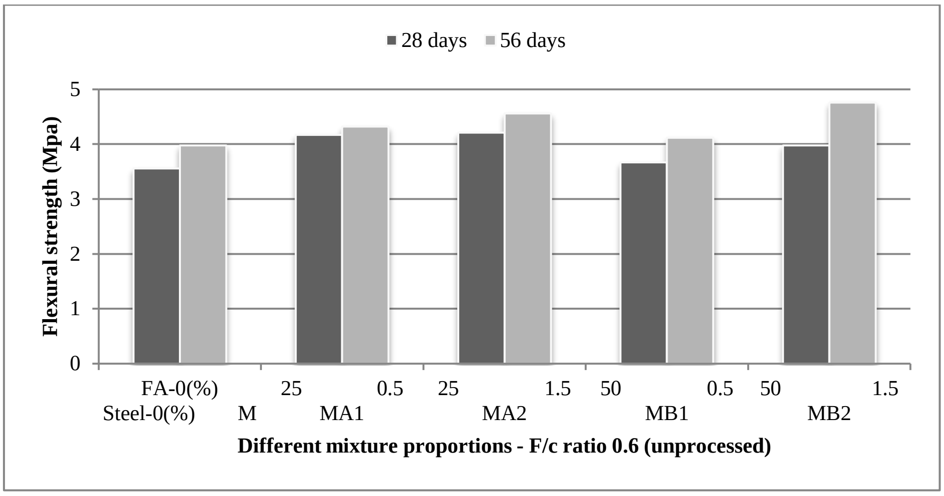

Figure 7 Flexural strength for various mixes concrete at F/c ratio 0.6 (unprocessed).

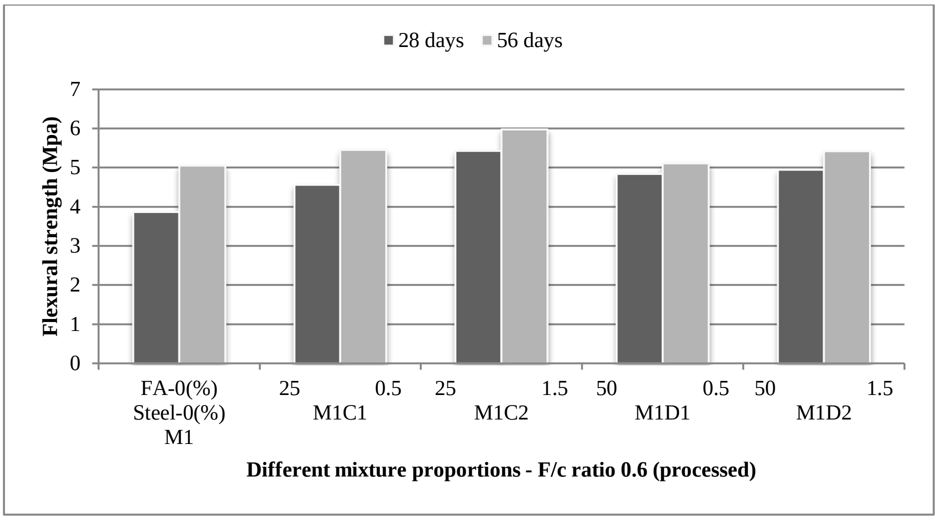

Figure 8 Flexural strength for various mixes concrete at F/c ratio 0.6 (processed)

Table 6 Variation of Strength for Different Mixture Proportions of Concrete.

Mix id	w/b ratio	F/c ratio	Dosage of steel fibers % (Vf)	Acl %	PCE %	Fly ash %	Compressive strength (MPa)			σ (MPa)	COV (%)	Split tensile strength	Flexural strength (MPa)		UPV (km/sec)	
							7 days	28 days	56 days			28 days	28 days	56 days	28 days	56 days
M	0.3	0.6	0	0	1	0	26.70	38.40	43.20	1.70	3.57	3.74	3.56	3.98	3.81	3.89
MA1	0.3	0.6	0.5	1	1	25	27.50	37.98	38.51	1.16	2.78	4.43	4.17	4.32	3.83	4.01
MA2	0.3	0.6	1.5	1	1	25	29.78	41.50	48.70	0.16	0.43	4.76	5.21	5.56	4.01	4.10
MB1	0.3	0.6	0.5	1	1.5	50	20.54	33.50	40.13	0.16	0.36	4.10	3.67	4.12	3.98	4.01
MB2	0.3	0.6	1.5	1	1.5	50	20.91	39.71	44.78	0.40	1.10	3.98	3.98	4.76	3.94	4.00
M1	0.3	0.6	0	0	1	0	31.03	45.21	52.15	1.03	2.54	4.50	3.87	5.05	3.89	4.05
M1C1	0.3	0.6	0.5	1	1	25	33.40	52.40	53.40	0.50	1.40	4.87	4.13	5.45	4.13	4.43
M1C2	0.3	0.6	1.5	1	1	25	35.30	49.20	55.13	1.13	2.73	5.12	5.43	5.98	4.18	4.57
M1D1	0.3	0.6	0.5	1	1.5	50	23.85	44.65	47.11	1.10	2.67	4.99	4.99	5.41	4.10	4.50
M1D2	0.3	0.6	1.5	1	1.5	50	25.40	45.23	48.43	0.49	1.38	5.01	4.9	5.11	4.02	4.40

Note: For each type of mix, 5 numbers of specimens were casted and tested; σ is the standard deviation,COV is the co-efficient of variation.

3.4 Ultrasonic Pulse Velocity

The pulse velocity was recorded and compared with the compressive strength of the concrete at different curing ages for different concrete mixture proportions, as shown in Figures 3 and 4. The ultrasonic pulse velocity showed a maximum value of 4.18 Km/sec for the 25% fly ash substituted concrete and 4.10 Km/sec for the 50% fly ash substituted concretes at 28 days. It is also noted that the concrete mixes with addition of steel fibers showed a corresponding increase in the rate of hardening, which is exhibited in terms of higher pulse velocity values. The enhanced micro-structural formation can be attributed to the careful selection of fine filler materials such as processed fly ash. This led to improved concrete properties and exhibited an earlier pozzolanic reaction compared to the untreated fly ash concrete mixes. The ultrasonic pulse results demonstrated better strength properties and integrity of the concrete. However, there was no significant difference in the pulse velocity values for the reference concrete. The pulse velocity values for the processed fly ash based concretes showed good agreement with the standard requirements for good quality concrete.

4 Conclusions

The following specific conclusions can be drawn based on the experimental work in this study.

The workability of high-strength concrete mixes was lower for concretes with and without fly ash. With a low water to binder (w/b) ratio of 0.3, the required slump in the range of 75 to 100 mm was obtained only by the addition of high-range water reducing admixtures. The addition of superplasticizer showed higher workability for the processed fly ash concretes compared to the unprocessed fly ash concretes. Mechanical treatment of the fly ash by grinding in a ball mill was found to be effective to improve the fineness of the fly ash. This contributed to the subsequent enhancement of micro-structural formation in the fly ash blended cement concretes.

The compressive properties of the processed fly ash concretes exhibited improved mechanical properties due to the high fineness of the fly ash as well as due to early-age pozzolanic reaction. A maximum ultimate compressive strength of 52.40 MPa was obtained in the case of the processed fly ash concrete containing 25% fly ash with the inclusion of 1.5% steel fibers. This increase in strength of 36.46% was higher than that of the reference and unprocessed fly ash concrete.

It can be noted that the maximum improvement in flexural strength was measured for processed fly ash concrete (5.43 MPa), which was higher than for the unprocessed fly ash concrete. The compressive strength and ultrasonic pulse velocity in all processed fly ash based specimens increased with the curing age of the concrete specimens. The maximum compressive strength and UPV were noted in the processed fly ash concrete mixes.

The test results showed that the split tensile and flexural strength exhibited a similar increasing trend for the processed fly ash concretes. In summary, the mechanical properties of the processed fly ash based concrete with 50% OPC replacement had equal or better strength gain at later ages than the unprocessed fly ash based concrete with 25% OPC replacement. The use of high-volume fly ash addition can result in significant cost savings, because the addition of finer varieties of fly ash in concrete are instrumental for achieving early-age strength gain and long-term durability properties.

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