Journal of Asian Concrete Federation
Vol. 6, No. 2, pp. 50-65, December 2020
ISSN 2465-7964 / eISSN 2465-7972
https://doi.org/10.18702/acf.2020.12.6.2.50

Technical Paper

Evaluation of mechanical and durability properties of concrete made with Indian bottom ash as replacement of fine aggregate

P. N. Ojha, Amit Trivedi, Brijesh Singh*, Abhishek Singh

(Received June 5, 2020; Revised October 28, 2020; Accepted December 5, 2020; Published December 31, 2020)

Abstract: Bottom ash is a major by-product of the coal-based power generation process and it has particle size ranging from 45 μm to 150 μm. As per current provisions of IS: 383-2016, bottom ash can be used as replacement of natural fine aggregate up to 25% in case of lean concrete (less than M15 Grade) only. However, its use in reinforced and plain concrete is not permitted. Therefore, it is imperative to study the feasibility of using coal based bottom ash as a replacement of conventional fine aggregates (i.e., natural and crushed sand) in plain and reinforced concrete to increase the utilization of this industrial byproduct. In this study, natural and crushed sand were replaced with bottom ash at various percent-ages for preparation of concrete and study its effect on fresh, hardened and durability properties of concrete. Bottom ash was collected from Vindhyachal thermal power plant of India. Experimental studies were conducted at w/c ratio of 0.65 and 0.40. Concrete mixes were studied and analyzed for various mechanical and durability properties. Based on fresh concrete properties i.e., workability, slump retention and strength development, it was observed that up to 50% replacement of conventional fine aggregate with bottom ash is technically feasible.

Keywords: Bottom ash; fine aggregate; characterization; mechanical property; durability.

1 Introduction

Bottom ash is a major by-product of the coal-based power generation process. In coal based Thermal Power Plant, at the bottom of the furnace, there is a hopper for collection of bottom ash. The bottom ash can be collected by wet cooling and wet removal process or dry cooling and dry removal process from the bottom of boilers. Characteristics of bottom ash depend on the process of removal of bottom ash from the boiler. In wet cooling and wet removal process, a hopper is always filled with water to quench the ash. Bottom ash consists of heavier particles that fall to the bottom of the furnace. Bottom ash is composed primarily of amorphous or glassy alumino-silicate materials derived from the melted mineral phases. Bottom ash differs from fly ash collected from electrostatic precipitators in a dry form in that it contains significant amount of relatively coarser particles (greater than 45 μm and up to 150 μm). Coal bottom ash has angular, irregular, porous and rough surface textured particles. Coal bottom ash is lighter and more brittle as compared to natural river sand. The specific gravity of coal bottom ash varies from 1.8 to 2.6 depending upon the source and type of coal. Coal bottom ash derived from high Sulphur coal and low rank coal is not very porous and is quite dense. In India, over 70% of electricity generated is by coal fired plants. As per Central Electricity Authority [1] data 2014-15 the annual production of Ash is 180MT out of which 30-35MT is bottom ash and rest is fly ash.

BIS has incorporated the provision of manufactured aggregates to be used in concrete in IS: 383-2016. It mentions that bottom ash can be used as replacement of natural fine aggregate up to 25% in case of lean concrete (less than M15 Grade) only. However, it is not permitted to use bottom ash in reinforced and plain concrete. At national and international level, researchers have carried out study on usage of bottom ash as a replacement of fine aggregate at different percentage levels ranging from 10% to 100%. Fresh and hardened concrete properties

***P. N. Ojha** is a Joint Director at National Council for Cement & Building Materials, India.*
***Amit Trivedi** is a General Manager at National Council for Cement & Building Materials, India.*
***Corresponding author Brijesh Singh** is a Group Manager at National Council for Cement & Building Materials, India.*
***Abhishek Singh** is a Project Engineer at National Council for Cement & Building Materials, India.*

(strength-based properties) have been studied. However, limited studies are available on durability properties of concrete. Abdulhameed et al. [2] have carried out the studies on usage of bottom ash as replacement of fine aggregate in concrete. The coal bottom ash was obtained from Tanjung Bin power plant. Natural sand was partially replaced with bottom ash in the range of 5, 10, 15 and 20%. Decrease in the workability of fresh concrete in terms of slump and compacting factor was observed with increase in percentage of bottom ash. Reduction in compressive strength and density of concrete was observed with increase in percentage of bottom ash.

Ratchayut et al. [3] have carried out the studies on usage of bottom ash as replacement of fine aggregate in concrete. The study was conducted on self-compacting concrete having w/binder ratio of 0.31. Bottom ash was obtained from Saraburi Power Plant, Thailand. Natural sand was replaced with bottom ash up to 30%. Slump flow decreased continuously with increase in bottom ash content. It was considered that such decrease was due to increased aggregate to aggregate friction from highly irregular shape and rough texture of bottom ash particles. Mehdi et al. [4] carried out the studies on usage of bottom ash as replacement of fine aggregate in concrete. Coal bottom ash was obtained from Malaysian Power Plant. Concrete specimens were prepared incorporating 0, 20, 50, 75 and 100% of bottom ash replacing sand and 20% of coal fly ash by mass, as a substitute for ordinary Portland cement. Workability of concrete reduces on increasing the percentage of bottom ash. At the age of 28 days, no significant effect was observed in compressive, flexural and tensile strengths of all concrete samples. The drying-shrinkage of experimental concrete mixtures containing 50%, 75% and 100% Bottom ash and 20% fly ash was lower than the control mix.

Kim et al. [5] have carried out the studies on chloride resistance of high-strength concrete incorporating bottom ash. The results showed that, although there was no significant effect on the chloride diffusion, bottom ash in high-strength concrete can significantly reduce the amount of chloride diffusion as chloride did not readily diffuse to the cement paste in the vicinity of bottom ash. Malkit et al. [6] carried out the studies on usage of bottom ash as replacement of fine aggregate in concrete. At fixed water cement ratio, workability and loss of water from bleeding decreased with the use of coal bottom ash as a replacement of river sand in concrete. Compressive strength of bottom ash concrete at the curing age of 28 days was not significantly affected. However, after 90 days of curing age, compressive strength of bottom ash concrete surpassed that of conventional concrete. Splitting tensile strength of concrete improved at all the curing ages. The modulus of elasticity decreased with the use of coal bottom ash at all the curing ages. Andrade et al. [7] carried out the studies on the influence of the use of coal bottom ash as a replacement for natural fine aggregates on the properties of concrete in the fresh state. In the fresh state the concretes produced with the bottom ash are susceptible to water loss by bleeding and the higher the percentage of bottom ash used as a natural sand replacement the lower the deformation through plastic shrinkage. Aggarwal et al. [8] carried out studies on concrete (*w/c* of 0.43) by replacing up to 40% fine aggregate (by weight) with coal bottom ash obtained from thermal power plant in Panipat, Haryana (India) was used in the investigation. The density of concrete decreased with the increase in bottom ash content due to the low specific gravity of bottom ash as compared to fine aggregates. Mix containing 30% and 40% bottom ash, at 90 days, attains the compressive strength equivalent to 108% and 105% of compressive strength of normal concrete at 28 days and attains flexural strength in the range of 113-118% at 90 days of flexural strength of normal concrete at 28 days. Kadam et al. [9] carried out studies on concrete (*w/c* of 0.45) by replacing up to 100% fine aggregate (by weight) with coal bottom ash from Eklahare thermal power plant in India. The compressive strength for 7, 28, 56 and 112 days was increased up to 20% replacement and after that compressive strengths were decreased from 30% to 100% replacement. The split tensile and flexural strength was increased at 7, 28, 56 and 112 days for 10% to 30% replacement and after that it was decreased for remaining replacement. Arumugam et al. [10] carried out studies on concrete (*w/c* of 0.5) by replacing up to 60% fine aggregate (by weight) with coal bottom ash study. The unit weight of concrete gets reduced through the addition of bottom ash as replacement of fine aggregate since it has lesser specific gravity than fine aggregate. The 7 days, 28 days and 56 days strength shows that the strength increases from standard concrete up to the addition of 20% replacement of fine aggregate with bottom ash.

Raju et al. [11] carried out studies on concrete by replacing up to 30% fine aggregate (by weight) with coal bottom ash obtained from Hindustan News Print Limited, Kottayam, Kerala (India). Slump reduced with increase in percentage of bottom ash due to higher water absorption of bottom ash. Compressive strength, split tensile strength and flexural strength increased up to 20% replacement of Bottom ash. Based on the review of existing literature, it can be inferred that there is a potential for use of bottom ash as replacement of fine aggregate in concrete.

2 Experimental plan

2.1 Sampling, screening and separation of bottom ash into different fractions

In this study 'B' stands for bottom ash and 'Y' stands for Vindhyachal. About 200 bags containing Bottom Ash were collected from Vindhyachal site. Bottom ash "as such" i.e.,, without screening/sieving has been referred as 'BY' in this study. After that, separation of bottom ash samples was carried out by mechanical sieving. No part of sample was retained on sieve size 4.75mm. Material finer than 75 µm was found to be 9.6% by wet sieving method, while it was 8-11% by dry sieving method. When, material finer than 75 µm was removed from the BY (as such sample), it was designated as 'BY2' (fraction between 4.75 mm and 75 µm) for this study. Both bottom ash samples BY and BY2 were used to replace fine aggregates for preparation of concrete for further study.

2.2 Study of fundamental properties of bottom ash and other concrete making materials

Studies on fundamental properties of bottom ash samples (BY and BY2) by conducting physical, chemical and microstructural characterization of all the three fractions of bottom ash separately in order to assess the feasibility of the use of bottom ash as construction material were carried out. Characterization by means of analysis of engineering properties of bottom ash as fine aggregate in concrete includes properties such as specific gravity, fineness, gradation, texture, physical and chemical characteristics etc. This also included petrographic examinations, Scanning electron microscopy (SEM) examination and X-ray diffraction (XRD) analysis. Along with evaluation of bottom ash samples, other concrete making materials such as OPC 43, aggregates 20 mm, 10 mm, natural sand and crushed sand and PC based/naphthalene-based superplasticizer were also evaluated.

2.3 Replacement of conventional sand by bottom ash in concrete mixes

Varying proportions of bottom ash and fine aggregate were tried in an effort to determine the optimum ratio of bottom ash to fine aggregate. The performance of concrete was evaluated in terms of fresh concrete properties, mechanical properties and durability properties. The present study shall include 25, 50, 75 and 100% replacement of natural sand and crushed sand by bottom ash "as such" (BY) and fraction between 4.75 mm and 75 µm (BY2). The concrete mixes given in Table 1 below shall be studied:

2.4 Casting and testing of concrete samples

Casting and testing of concrete samples as per relevant IS/ASTM/DIN/ISO methods were carried out to determine the engineering properties/characteristics of mixes. Fresh concrete properties such as slump, air content, wet density and initial & final setting time of concrete along with compressive strength at 3, 7, 28 and 56 days were evaluated for all the 32 mixes. Hardened concrete properties such as flexural strength, static modulus of elasticity along with drying shrinkage and moisture movement were evaluated at the age of 28 days for 5 selected experimental mixes and 2 control mixes. Evaluation of durability properties of concrete such as pH value, water permeability, volume of permeable voids, Water absorption, rapid chloride penetration test, electrical resistivity using four-point Wenner probe, air permeability and accelerated carbonation test were carried out for 5 selected experimental mixes and 2 control mixes.

Table 1 – Details of level of replacements and total number of mixes

w/c	% fine aggregate replacement by bottom ash	No. mixes
0.65 and 0.40	Without Bottom Ash i.e., Control Mixes, with natural river sand (100 %) & crushed sand (100 %)	4
0.65 and 0.40	100 % of BY2 (i.e., after removing particles greater than 4.75 mm and less than 75µm) as fine aggregate.	2
0.65 and 0.40	100 % BY (as such) as fine aggregate.	2
0.65 and 0.40	25, 50 and 75 % replacement of natural river sand by BY2 (i.e., After removing particles greater than 4.75 mm and less than 75µm) at	6
0.65 and 0.40	25, 50 and 75 % replacement of crushed sand by BY2 (i.e., after removing particles greater than 4.75 mm and less than 75µm) at	6
0.65 and 0.40	25, 50 and 75 % replacement of natural river sand by BY(as such)	6
0.65 and 0.40	25, 50 and 75 % replacement of crushed sand by BY(as such)	6
Total no. of mixes		32

3 Characterization of bottom ash and concrete making materials

Only bottom ash samples bottom ash “as such” i.e.,, without screening/sieving (BY) and fraction between 4.75 mm and 75 µm (BY2) which were used to replace fine aggregates for preparation of concrete were evaluated for sieve analysis, physical and chemical properties. BY and BY-2 samples were also subjected to petrographic examination, X-ray diffractometry and analyzed using scanning electron microscope.

3.1 Sieve analysis of bottom ash fractions

Sieve analysis of Bottom Ash “as such” (i.e.,, BY) and fraction between 4.75 mm and 75 µm (i.e.,, BY2) was carried out as per IS 383:2016 and the results are given in Table-2 and gradation curve has been shown in Fig. 1.

For BY (bottom ash ‘as such’) sample the percentage passing through sieve size 600 µm is 82% which corresponds to Zone-IV as per IS: 383-2016. However, the percentage passing through 300 µm & 150 µm are 58% & 29% respectively which are more than the grading requirement of Zone-IV as per IS: 383-2016 and therefore bottom ash “as such” (i.e.,, BY) is finer than Zone-IV. For BY2 (fraction between 4.75 mm & 75 µm) sample, the percentage passing through sieve size 600 µm is 82% which corresponds to Zone-IV as per IS: 383-2016. However, the percentage passing through 300 µm and 150 µm are 57% & 19% respectively which are more than the grading requirement of Zone-IV as per IS: 383-2016 and therefore bottom ash BY2 (fraction between 4.75 mm & 75 µm) is finer than Zone-IV.

3.2 Physical characterization of bottom ash

The results of physical characterization of bottom ash sample BY (as such) after screening from 4.75mm and BY2 (fraction between 4.75 mm and 75µm) sieve are given in Table 3.

3.3 Chemical characterization of bottom ash

The results of chemical characterization of bottom ash sample (As such) after screening from 4.75mm sieve and BY2 (fraction between 4.75 mm and 75 µm) sieve are given in Table 4.

Table 2 – Sieve analysis of bottom ash fractions BY and BY2

IS Sieve Size	Percentage Passing (%)		Percentage Passing for Grading Zone IV as per IS: 383-2016 Table 9
	BY	BY2	
10 mm	100	100	100
4.75 mm	100	100	95 – 100
2.36 mm	96	97	95 – 100
1.18 mm	92	92	90 – 100
600 µm	82	82	80 – 100
300 µm	58	57	15 – 50
150 µm	29	19	0 – 15

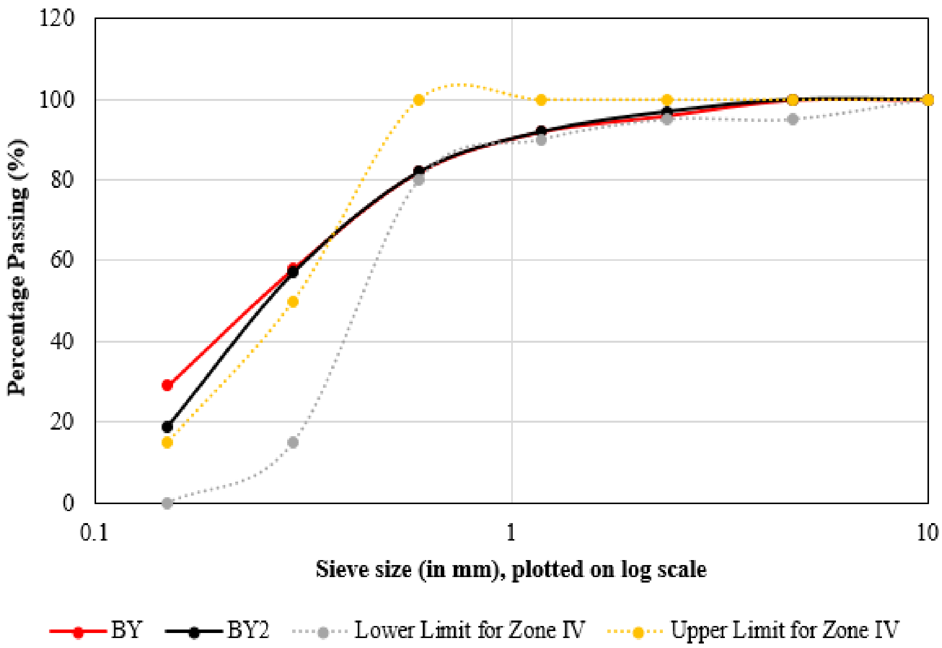

Fig. 1 – Gradation curve for sieve analysis of bottom ash BY and BY2

3.4 Mineralogical and microstructural investigations

In order to investigate the possibility of occurrence of undesirable and deleterious phenomenon such as alkali silica reaction or alkali aggregate reaction due to presence of reactive forms of silica, both bottom ash samples (BY and BY2) were subjected to petrographic examination, X-ray diffractometry and analyzed using scanning electron microscope.

3.4.1 Petrographic examination of bottom ash

BY (As such): The glass content in this sample is 11%. The other mineral constituents are quartz, orthoclase –feldspar, plagioclase-feldspar, muscovite, iron oxide and other opaque minerals. Grain size of glass varies from 4 µm to 74 µm. Glass grains are of various shapes and sizes. Grain size variation in glass is too large. Common form of glass grains is rounded, sub-rounded, polygonal, lath and micro globular. Subhedral to anhedral quartz grains with rounded grain margins are uniformly distributed in the sample. Grain size of quartz varies from 6 µm to 171 µm. Subhedral to anhedral opaque minerals with corroded margins are also uniformly distributed. The microphotograph of this Bottom Ash sample is given in Fig. 2. BY2 (fraction between 4.75 mm and 75 µm): The glass content in this sample is 16%. The other mineral constituents are quartz, orthoclase – feldspar, plagioclase-feldspar, iron oxide and other opaque minerals. Grain size of glass varies from 3 µm to 52 µm. Glass grains are of various shapes and sizes. Common form of glass grains is rounded, sub rounded, lath, rectangular, polygonal and micro globular. Subhedral to anhedral quartz grains with sharp angular grain margins are uniformly distributed in the sample. Grain size of quartz varies from 4 µm to 150 µm. The microphotograph of this Bottom Ash sample is given in Fig. 3.

3.4.2 X-Ray diffraction analysis (XRD) of bottom ash

BY (as such): XRD studies of the random sample revealed the presence of quartz, mullite, tridymite and hematite phases. These minerals are further classified as predominant, major and minor constituents. BY2 (fraction between 4.75 mm and 75 µm): XRD studies of the random sample revealed the presence of quartz, mullite, tridymite and hematite phases. These minerals are further classified as predominant, major and minor constituents. The list of phases identified, their chemical formulae and relative abundance is given in the Table 5.

Table 3 – Results of physical properties of bottom ash samples BY and BY2

Sl.No.	Test Carried out	BY (As such)	BY2 (fraction between 4.75 mm and 75 µm)
1	Specific gravity	2.08	2.06
2	Water absorption, %	1.5	1.7
3	Material finer than 75 µm % (wet sieving)	9.45	2.1
4	Soundness, MgSO4 %	9.23	11.4
5	Fineness modulus	1.465	1.541
6	Organic impurities %	Nil	Nil
7	Clay lumps %	Nil	Nil
8	Total deleterious material, % (except coal & lignite)	Nil	Nil
9	Lime reactivity (N/mm^2)	0.74	0.194

Table 4 – Results of chemical properties of bottom ash samples BY and BY2

Sl. No.	Test Carried out	BY (As such)	BY2 (fraction between 4.75 mm and 75 µm)
1	Loss on ignition (LOI) %	1	1.58
2	Silica (SiO2) % & iron oxide (Fe2O3) %	67.2 & 12.29	56.74 & 18.84
3	Aluminum oxide (Al2O3) %	15.76	17.78
4	Calcium oxide (CaO) %	1.03	1.74
5	Magnesium oxide (MgO) %	1.11	1.25
6	Sulphate (SO3) %	Nil	0.07
7	Total alkalis %: Na^2O & K^2O	0.09 & 0.55	0.16 & 0.66
8	Chloride (Cl), Acid soluble %	0.013	0.011
9	Reactive SiO2 %	29.15	25.38
10	Water soluble Cl %	0.004	0.004
11	Sulphide Sulphur %	0.032	0.02

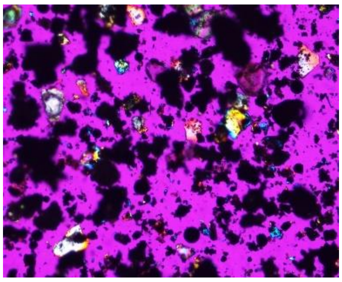

Fig. 2 – BY- Bottom Ash (As such) distribution of mineral grains (5x)

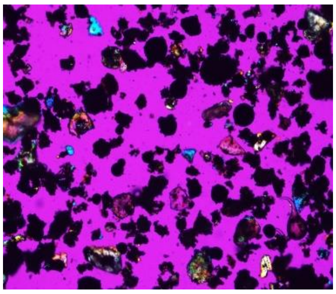

Fig. 3 – BY2- Bottom Ash (fraction between 4.75 mm and 75 µm) Distribution of mineral grains (5x)

3.4.3 Scanning electron microscopy examination (SEM) of bottom ash

BY (As such): The sample contained coarse particles with sizes ranging from 10 to 550 micron. Large particles of unburnt carbon were abundant in the sample. Most of the particles are irregularly shaped and agglomerated. Few amorphous particles were also observed. The surface of the glassy material has rough texture. The microphotograph of this Bottom Ash sample is given in Fig. 4. BY2 (fraction between 4.75 mm and 75 µm): Sample predominantly contained irregular shaped crystalline compounds of quartz, hematite and magnetite. The particles were having the sizes in the range of 10 to 400 microns. Most of the particles were in agglomerated form. The microphotograph of this bottom ash sample is given in Fig. 5.

After analysis of results of petrographic examination, X-ray diffractometry and study using scanning electron microscope, it was observed that no deleterious minerals or compounds were present in both bottom ash samples which can cause long term durability related issues in concrete prepared using bottom ash as a replacement of fine aggregate.

3.5 Characterization of other concrete making materials

Cement (OPC-43), coarse aggregate (10 and 20 mm), fine aggregate (natural and crushed) and chemical admixture – PC based (BASF Master Glenium Sky 8777) and Naptha (BASF Rheobuild 1100) were used in this study. These concrete making materials were tested as per relevant Indian Standards and showed conformance to the required standards.

a) Cement OPC-43: The cement sample of OPC-43 (Ultratech Brand) was tested for various physical and chemical properties and the test results are presented in Table 6. Results of OPC-43 (Ultratech Brand) showed conformance to the requirements of IS 269:2015.

b) Coarse aggregates (10 mm and 20 mm): coarse aggregates (10 mm and 20 mm) samples were evaluated for various properties as per IS: 2386-1963. The test results (Tables 7 and 8) of coarse aggregate samples (CA 10 mm and 20 mm) showed conformance to the requirements of IS: 383-2016.

c) Fine aggregate (natural & crushed): fine aggregate (natural & crushed) samples were evaluated for several properties as per IS: 2386-1963. Test results (Table 9 and 10) showed that the fine aggregate (natural & crushed) samples meet the various physical requirements of IS: 383-2016.

d) Chemical admixtures: chemical admixtures BASF Rheobuild 1100 (Naptha based) and BASF Master Glenium Sky 8777 (PCE based) sample met the various physical requirements of IS: 9103-1999.

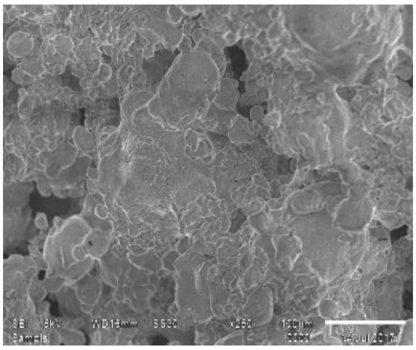

Fig. 4 – SEM image of BY- bottom ash (as such)

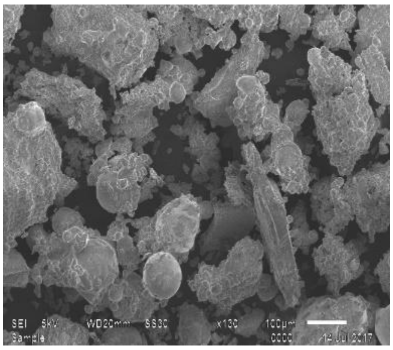

Fig. 5 – SEM image of BY2- bottom ash (fraction between 4.75 mm and 75 µm)

Table 5 – Phases and their relative abundance in BY and BY2 samples

Phase	Chemical Formula	Relative Abundance	
		BY	BY-2
Quartz	SiO2	Predominant	Predominant
Mullite	$Al_6Si_2O_{13}$	Major	Major
Tridymite	SiO_2	Major	Major
Hematite	Fe_2O_3	Minor	Minor

Table 6 – Test results of cement sample (OPC-43 Grade)

Sl. No.	Properties	Test results	Limits as per IS 269:2015
(A) Physical analysis:			
1	Blain's fineness, m^2/kg	309	225.0 (min.)
2	Setting time, minutes Initial & final	155 & 215	30.0 (min.) & 600.0 (max.)
3	Compressive strength, N/mm^2 3 days 7 days 28 days	 32 43 54.5	 23.0 (min.) 33.0 (min.) 43.0 (min.)
4	Soundness Autoclave, % Le Chatelier Exp. (mm)	 0.06 2.0	 0.8 (max.) 10.0 (max.)
(B) Chemical analysis:			
1	Loss of ignition (LOI) % by mass	2.91	5.0 (max.)
2	Silica (SiO_2) % by mass	20.00	--
3	Iron oxide (Fe_2O_3) % by mass	4.08	--
4	Aluminum oxide (Al_2O_3) % by mass	4.81	--
5	Calcium oxide (CaO) % by mass	60.15	--
6	Magnesium oxide (MgO) % by mass	4.50	6.0 (max.)
7	Sulphate (SO_3) % by mass	1.89	3.5 (max.)
8	Alkalies: Na_2O & K_2O %	0.45 & 0.55	--
9	Chloride content % by mass	0.028	0.1
10	Insoluble residue % by mass	1.76	5.0

Table 7 – Physical test results of coarse aggregates (10 mm & 20 mm) samples

Sl. No.	Test Carried out	Result Obtained		Permissible Limits as Per IS: 383-2016
		CA 10 mm	CA 20 mm	
1	Specific gravity	2.73	2.75	--
2	Water absorption (%)	0.3	0.3	--
3	Crushing value %	27	26	30 (For wearing surface)
4	Impact value %	20	19	30 (For wearing surface)
5	Flakiness index %	4.8	6.2	(40%) Combined limit for flakiness and elongation index
6	Elongation index %	10.5	19.2	
8	Deleterious materials % (except coal & lignite)	0.15	0.2	2

4 Evaluation of fresh, hardened and durability properties of concrete

Preparation, casting and testing of concrete mixes was carried out as per relevant IS/ASTM/DIN/ISO methods to determine the engineering properties of various concrete mixes. Fresh concrete properties such as slump, air content, wet density and initial & final setting time of concrete (as per IS: 1199) along with compressive strength (as per IS: 516) at 3, 7, 28, and 56 days and cylindrical compressive strength as per ASTM C39 at 28 days were evaluated for all the 32 mixes. Hardened concrete properties such as flexural strength (as per IS:

Table 8 – Sieve analysis of coarse aggregates (10 mm & 20 mm)

IS sieve size (mm)	CA 10 mm		CA 20 mm	
	% passing	As per Table 7 (Clause 6.1 & 6.2) IS 383-2016	% passing	As per Table 7 (Clause 6.1 & 6.2) IS 383-2016
40	100	100	100	100
20	100	100	95	85-100
12.5	100	100	-	-
10	86	85-100	2	0-20
4.75	5	0-20	0	0-5
2.36	0	0-5	0	-

Table 9 – Physical test results of fine aggregate (natural & crushed) sample

Sl No.	Test Carried out	Result obtained		Permissible Limits as Per IS: 383-2016	
		Natural	Crushed	Natural	Crushed
1	Specific gravity	2.64	2.73	--	--
2	Water absorption, %	0.4	0.6	--	--
3	Material finer than 75-micron, IS Sieve %	0.2	5.9	3	15

Table 10 – Sieve analysis of fine aggregate (crushed) sample

Sieve Size	Percentage passing		Percentage passing for Grading Zone III as per IS 383:2016 Table 9
	Natural	Crushed	
10 mm	100	100	100
4.75 mm	100	100	90-100
2.36 mm	100	90	85-100
1.18 mm	97	78	75-100
600 micron	74	62	60-79
300 micron	25	38	12-40
150 micron	5	19	0-10 (but for crushed stone sands, the permissible limit on 150 micro IS Sieve is increased to 20 %)
Zone as per IS: 383-2016	Zone III		

516), static modulus of elasticity (as per IS: 516) along with drying shrinkage (as per IS: 1199) and moisture movement (as per IS: 1199) were evaluated at the age of 28 days for 5 selected experimental mixes and 2 control mixes. Evaluation of durability properties of concrete such as pH value, water permeability (as per DIN 1048), volume of permeable voids, water absorption (as per ASTM C 1585), rapid chloride penetration test (as per ASTM C 1202), electrical resistivity using four-point Wenner probe, air permeability and accelerated carbonation test (as per ISO 1920 Part 12) were carried out for 5 selected experimental mixes and 2 control mixes.

The concrete mix trials have been carried out using OPC-43 grade cement, natural fine aggregate (sand), crushed fine aggregate (sand) at w/c 0.4 and 0.65 and using bottom ash samples in different proportions. There are four control mixes i.e,, M1, M6, M11 and M15 having 100% Fine Aggregate (Crushed/Natural) with w/c 0.4 and 0.65. Study was conducted on two fractions of bottom ash BY (As such) and BY2 (between 4.75 mm and 75 µm). 14 Nos. out of 28 Nos. concrete mix trials conducted on bottom ash (As such) and 14 no's conducted on bottom ash (between 4.75 mm and 75µm). In concrete mixes, fine aggregate is being replaced with each fraction of bottom ash by 25%, 50%, 75%, and 100% respectively. The concrete mixes were designed for the workability range of 90 – 120 mm slump. Mix-proportions and test results of 32 concrete mixes are given in Tables 11 and 12, respectively.

4.1 Evaluation of fresh concrete properties and compressive strength of hardened concrete

32 mixes were prepared and analyzed for different fresh properties of concrete along with compressive strength at different ages. Mix proportions and fresh concrete properties along with compressive strength results for all the mixes are given in Tables 11 and 12, respectively. Comparison of 28-day compressive strength for all the mixes has been shown in figure 6. Observations related to experimental mixes

Table 11 – Mix design details of all the mixes

Mix	Bottom ash (% replacement of fine aggregate)	Dosage of Admixture (% by weight of cement)	Cement (kg/m^3)	Water (kg/m^3)	Fine aggregate (kg/m^3) (Type)	Bottom Ash (kg/m^3)	Coarse Aggregate (kg/m^3)	
							10 mm	20 mm
M1	0	0.2 (PCE based)	425	170	739 (crushed)	0	464	696
M2	25 (BY)	0.3 (PCE based)	425	170	554 (crushed)	139	464	696
M3	50 (BY)	0.8 (PCE based)	425	170	370 (crushed)	282	463	695
M4	75 (BY)	1.2 (PCE based)	425	170	171 (crushed)	390	487	731
M5	100 (BY)	1.0 (PCE based)	425	170	0	503	492	739
M6	0	0	300	195	814 (crushed)	0	451	677
M7	25 (BY)	0.5 (Naptha based)	300	195	609 (crushed)	155	450	670
M8	50 (BY)	1.2 (Naptha based)	300	195	405 (crushed)	309	449	674
M9	75 (BY)	0.6 (PCE based)	300	195	202 (crushed)	464	450	675
M10	100 (BY)	1.0 (PCE based)	300	195	0	616	448	673
M11	0	0.2 (PCE based)	425	170	697 (Natural)	0	472	708
M12	25 (BY)	0.3 (PCE based)	425	170	508 (Natural)	134	479	719
M13	50 (BY)	0.6 (PCE based)	425	170	338 (Natural)	267	478	717
M14	75 (BY)	1.0 (PCE based)	425	170	160 (Natural)	377	492	739
M15	0	0.5 (Naptha based)	300	195	748 (Natural)	0	466	699
M16	25 (BY)	1.0 (Naptha based)	300	195	560 (Natural)	147	465	698
M17	50 (BY)	2.0 (Naptha based)	300	195	372 (Natural)	293	463	695
M18	75 (BY)	0.5 (PCE based)	300	195	168 (Natural)	398	497	745
M19	25 (BY-2)	0.2 (PCE based)	425	170	554 (crushed)	139	464	696
M20	50 (BY-2)	0.6 (PCE based)	425	170	359 (crushed)	271	471	706
M21	75 (BY-2)	1.0 (PCE based)	425	170	170 (crushed)	384	485	727
M22	100 (BY-2)	1.0 (PCE based)	425	170	0	498	492	739
M23	25 (BY-2)	0	300	195	610 (crushed)	154	451	677
M24	50 (BY-2)	1.0 (Naptha based)	300	195	396 (crushed)	299	457	686
M25	75 (BY-2)	2.0 (Naptha based)	300	195	192 (crushed)	436	464	695
M26	100 (BY-2)	1.0 (Naptha based)	300	195	0	554	481	721
M27	25 (BY-2)	0.3 (PCE based)	425	170	522 (Natural)	136	472	707
M28	50 (BY-2)	0.6 (PCE based)	425	170	329 (Natural)	257	486	729
M29	75 (BY-2)	0.9 (PCE based)	425	170	155 (Natural)	363	500	750
M30	25 (BY-2)	0.6 (Naptha based)	300	195	561 (Natural)	146	466	699
M31	50 (BY-2)	1.5 (Naptha based)	300	195	354 (Natural)	276	480	720
M32	75 (BY-2)	0.7 (PCE based)	300	195	178 (Natural)	416	481	722

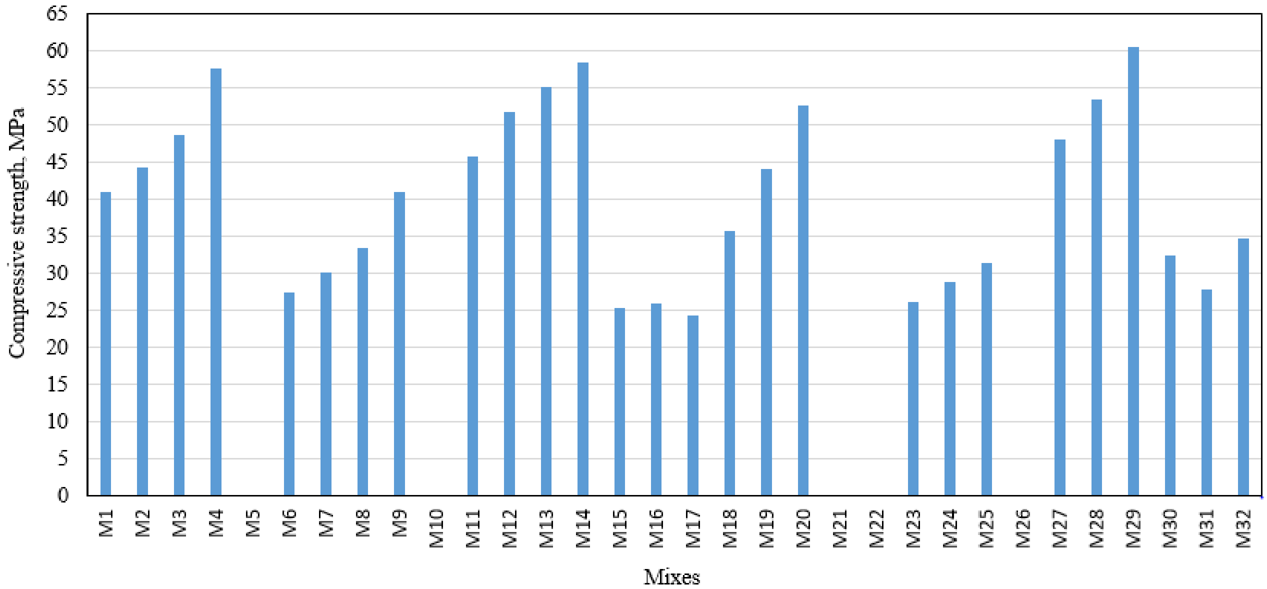

Fig. 6 – Comparison of 28-day compressive strength results for all the mixes

Table 12 – Fresh concrete properties and compressive strength of hardened concrete of all the mixes

Mix	Slump (mm)	Air content (%)	Wet Density (kg/m^3)	Setting time (minutes)		Cube Compressive Strength (MPa)				Cylindrical Compressive Strength (MPa) as per ASTM C39	Standard Deviation for compressive strength at 28 days age for six specimen for each mix
				Initial	Final	3 Day	7 Day	28 Day	56 Day	28 Day	
M1	100	0.8	2542	380	560	32.65	39.52	40.99	42.20	33.59	1.85
M2	100	1.2	2530	440	550	38.56	37.77	44.36	47.99	35.77	2.04
M3	120	0.8	2489	470	610	46.05	46.35	48.66	54.88	39.24	1.84
M4	110	1.3	2425	510	690	35.15	42.35	57.71	60.81	48.49	1.65
M5	Zero	Properties were not evaluated									
M6	110	1.9	2498	420	610	16.94	19.65	27.49	27.66	21.65	1.88
M7	110	1.3	2525	450	580	20.58	22.55	30.11	33.42	24.09	1.79
M8	110	1.4	2471	480	640	22.79	25.47	33.47	37.79	26.78	1.68
M9	100	1.3	2423	520	660	26.30	28.97	40.99	46.70	34.16	1.54
M10	Zero	Properties were not evaluated									
M11	100	1.9	2447	420	620	39.99	40.36	45.76	46.64	37.20	1.89
M12	110	1.8	2495	450	640	39.30	47.24	51.80	52.78	43.53	1.99
M13	100	1.5	2477	470	670	41.82	45.30	55.19	57.01	46.77	2.01
M14	90	1.3	2427	480	710	38.60	41.71	58.49	65.96	49.56	1.84
M15	100	1.7	2435	510	750	15.69	21.18	25.31	27.25	19.93	1.69
M16	110	1.5	2427	540	770	15.94	21.94	25.91	28.56	21.06	1.74
M17	90	1.2	2394	580	800	15.91	17.75	24.38	25.93	19.50	2.01
M18	120	1.0	2403	620	830	24.58	27.07	35.79	38.97	29.09	1.99
M19	100	1.4	2587	450	560	36.25	40.58	44.13	47.74	36.78	2.06
M20	110	1.3	2409	480	640	43.20	48.36	52.59	55.05	44.19	1.85
M21	Zero	Properties were not evaluated									
M22	Zero	Properties were not evaluated									
M23	100	1.2	2447	460	565	16.31	21.88	26.11	29.80	20.39	1.96
M24	110	1.0	2409	490	610	20.64	24.59	28.83	32.94	22.70	1.85
M25	120	0.8	2370	530	640	18.35	23.83	31.30	31.99	25.04	1.79
M26	Zero	Properties were not evaluated									
M27	100	1.4	2519	470	660	42.32	44.96	48.14	50.49	39.13	1.84
M28	120	1.1	2489	490	690	44.35	50.45	53.54	56.96	45.37	2.01
M29	110	1.2	2462	500	710	43.10	49.19	60.62	63.49	50.94	2.34
M30	100	1.7	2439	560	790	23.26	26.36	32.35	35.22	26.09	1.89
M31	110	1.4	2409	600	830	20.67	22.44	27.77	30.49	21.87	2.22
M32	120	1.0	2400	630	850	27.60	30.03	34.66	37.11	27.08	1.67

(containing bottom ash) of similar type along with their corresponding control mixes has been discussed individually under sections 4.1.1 to 4.1.8.

4.1.1 Mix using bottom ash BY (As such), w/c 0.4 and crushed fine sand

Concrete trial mixes were carried out at w/c ratio of 0.4 using crushed fine aggregate and Bottom Ash BY (as such) sample. The crushed fine aggregate has been replaced in four concrete mixes (i.e.,, M2, M3, M4, and M5) by 25%, 50%, 75%, and 100%, respectively, with bottom ash BY. Mix proportions and fresh concrete properties along with compressive strength results for all the mixes are given in Tables 11 and 12, respectively, where M1 is control mix using crushed fine aggregate at w/c 0.4.

The study indicates that with increase in percentage of bottom ash in the concrete mix to maintain given workability in the range of 90 – 120 mm, the chemical admixture dosage increases. When the crushed fine aggregate is replaced by 100%, the workability could not be achieved despite using 1% PC based admixture/super-plasticizer (M5) and therefore its concrete properties were not evaluated further. Wet Density results for M2 (25% replacement), M3 (50% replacement) and M4 (75% replacement) are comparable with that of control mix (M1). Compressive strength results for M2 (25% replacement), M3 (50% replacement) and M4 (75% replacement) are higher than that of M1 (control mix) at 3, 7, 28, and 56 days.

4.1.2 Mix using bottom ash BY (As such), w/c 0.65 and crushed fine sand

Concrete trial mixes were carried out at w/c of 0.65 using crushed fine aggregate and bottom ash BY (as such) sample. The crushed fine aggregate has been replaced in four concrete mixes (i.e.,, M7, M8, M9, and M10) by 25%, 50%, 75%, and 100%, respectively, with bottom ash BY. Mix proportions and fresh concrete properties along with compressive strength results for all the mixes are given in Tables 11 and 12, respectively, where M6 is control mix using crushed fine aggregate at w/c 0.65. The study indicates that with increase in percentage of bottom ash in the concrete mix to maintain given workability in the range of 90 – 120 mm, the chemical admixture dosage increases. When the crushed fine aggregate is replaced by 100%, the workability could not be achieved despite using 1% PC based admixture/super-plasticizer (M10) and therefore its concrete properties were not evaluated further. Wet Density results for M7 (25% replacement), M8 (50% replacement) and M9 (75% replacement) are comparable with that of control mix (M6). Compressive strength results for M7 (25% replacement), M8 (50% replacement) and M9 (75% replacement) are higher than that of M6 (control mix) at 3, 7, 28, and 56 days.

4.1.3 Mix using bottom ash BY (As such), w/c 0.4 and natural fine sand

Concrete trial mixes were carried out at w/c ratio of 0.40 using natural fine aggregate and bottom ash BY (As such) sample. The natural fine aggregate has been replaced in four concrete mixes (i.e.,, M12, M13, M14, and M5) by 25%, 50%, 75%, and 100%, respectively, with bottom ash. Mix proportions and fresh concrete properties along with compressive strength results for all the mixes are given in Tables 11 and 12, respectively, where M11 is control mix using natural fine aggregate at w/c 0.40. The study indicates that with increase in percentage of bottom ash in the concrete mix to maintain given workability in the range of 90 – 120 mm, the chemical admixture dosage increases. When the natural fine aggregate is replaced by 100%, the workability could not be achieved despite using 1% PC based admixture/super-plasticizer (M5) and therefore its concrete properties were not evaluated further. Wet density results for M12 (25% replacement), M13 (50% replacement) and M14 (75% replacement) are comparable with that of control mix (M11). Compressive strength results for M12 (25% replacement), M13 (50% replacement) and M14 (75% replacement) are higher than that of M11 (control mix) at 3, 7, 28, and 56 days.

4.1.4 Mix using bottom ash BY (As such), w/c 0.65 and natural fine sand

Concrete trial mixes were carried out at w/c of 0.65 using natural fine aggregate and bottom ash BY (As such) sample. The natural fine aggregate has been replaced in four concrete mixes (i.e.,, M16, M17, M18, and M10) by 25%, 50%, 75%, and 100%, respectively, with bottom ash. Mix proportions and fresh concrete properties along with compressive strength results for all the mixes are given in Tables 11 and 12, respectively, where M15 is control mix using natural fine aggregate at w/c 0.65. The study indicates that with increase in percentage of bottom ash in the concrete mix to maintain given workability in the range of 90 – 120 mm, the chemical admixture dosage increases. When the natural fine aggregate is replaced by 100%, the workability could not be achieved despite using 1% PC based admixture/super-plasticizer (M10) and therefore its concrete properties were not evaluated further. Wet Density results for M16 (25% replacement), M17 (50% replacement) and M18 (75% replacement) are comparable with that of control mix (M15). Compressive strength results for M16 (25% replacement), M17 (50% replacement) and M18 (75% replacement) are higher than that of M15 (control mix) at 3,7,28 & 56 days.

4.1.5 Mix using bottom ash BY-2 (fraction between 4.75 mm and 75 µm), w/c 0.40 and crushed fine sand

Concrete trial mixes were carried out at w/c ratio of 0.40 using crushed fine aggregate and Bottom Ash BY-2 (fraction between 4.75mm & 75µm) sample. The crushed fine aggregate has been replaced in four mixes (i.e., M19, M20, M21 & M22) by 25%, 50%, 75% & 100% respectively with Bottom Ash. Mix proportions and fresh concrete properties along with compressive strength results for all the mixes are given in Tables 11 and 12, respectively, where M1 is Control Mix using Crushed Fine Aggregate at w/c of 0.40. The study indicates that with increase in percentage of Bottom Ash in the concrete mix to maintain given workability in the range of 90-120mm, the chemical admixture dosage increases. When the Crushed Fine Aggregate is replaced by 75% & 100%, the workability could not be achieved despite using 1% PC based admixture/super-plasticizer (M21 & M22) and therefore their concrete properties were not evaluated further. Wet Density results for M19 (25% replacement) and M20 (50% replacement) are comparable with that of control mix (M1). Compressive strength results for M19 (25% replacement) and M20 (50% replacement) are higher than that of M1 (control mix) at 3, 7, 28, and 56 days.

4.1.6 Mix using bottom ash BY-2 (fraction between 4.75mm & 75µm), w/c=0.65 and crushed fine sand

Concrete trial mixes were carried out at w/c ratio of 0.65 using crushed fine aggregate and Bottom Ash BY-2 (fraction between 4.75mm & 75µm) sample. The crushed fine aggregate has been replaced in four concrete mixes (i.e., M23, M24, M25, and M26) by 25%, 50%, 75% & 100% respectively with Bottom Ash. Mix proportions and fresh concrete properties along with compressive strength results for all the mixes are given in Tables 11 and 12 respectively, where M6 is Control Mix using Crushed Fine Aggregate at W/C ratio 0.65. The study indicates that with increase in percentage of Bottom Ash in the concrete mix to maintain given workability in the range of 90-120mm, the chemical admixture dosage increases. When the Crushed Fine Aggregate is replaced by 100%, the workability could not be achieved despite using 1% PC based admixture/super-plasticizer (M26) and therefore its concrete properties were not evaluated further. Wet Density results for M23 (25% replacement), M24 (50% replacement) and M25 (75% replacement) are comparable with that of control mix (M6). Compressive strength results for M23 (25% replacement), M24 (50% replacement) and M25 (75% replacement) are higher than that of M6 (control mix) at 3, 7, 28, and 56 days.

4.1.7 Mix using bottom ash BY-2 (fraction between 4.75 mm and 75 µm), w/c 0.40 and natural fine sand

Concrete trial mixes were carried out at w/c ratio of 0.40 using natural fine aggregate and Bottom Ash BY-2 (fraction between 4.75mm & 75µm) sample. The natural fine aggregate has been replaced in four concrete mixes (i.e., M27, M28, M29 & M22) by 25%, 50%, 75% & 100% respectively with Bottom Ash. Mix proportions and fresh concrete properties along with compressive strength results for all the mixes are given in Tables 11 and 12, respectively, where M11 is Control Mix using Natural Fine Aggregate at W/C ratio 0.40. The study indicates that with increase in percentage of Bottom Ash in the concrete mix to maintain given workability in the range of 90-120mm, the chemical admixture dosage increases. When the Natural Fine Aggregate is replaced by 100%, the workability could not be achieved despite using 1% PC based admixture/super-plasticizer (M22) and therefore its concrete properties were not evaluated further. Wet Density results for M27 (25% replacement), M28 (50% replacement) and M29 (75% replacement) are comparable with that of control mix M11. Compressive strength results for M27 (25% replacement), M28 (50% replacement) and M29 (75% replacement) are higher than that of M11 (control mix) at 3, 7, 28, and 56 days.

4.1.8 Mix using bottom ash BY-2 (fraction between 4.75 mm and 75 µm), w/c 0.65 and natural fine sand

Concrete trial mixes were carried out at w/c ratio of 0.65 using natural fine aggregate and Bottom Ash BY-2 (fraction between 4.75 mm and 75 µm) sample. The natural fine aggregate has been replaced in four concrete mixes (i.e., M30, M31, M32 & M26) by 25%, 50%, 75% & 100% respectively with Bottom Ash. Mix proportions and fresh concrete properties along with compressive strength results for all the mixes are given in Tables 11 and 12 respectively, where M15 is control mix using natural fine aggregate at w/c 0.65. The study indicates that with increase in percentage of bottom ash in the concrete mix to maintain given workability in the range of 90-120mm, the chemical admixture dosage increases. When the Natural Fine Aggregate is replaced by 100%, the workability could not be achieved despite using 1% PC based admixture/super-plasticizer (M26) and therefore its concrete properties were not evaluated further. Wet Density results for M30 (25% replacement), M31 (50% replacement) and M32 (75% replacement) are comparable with that of control mix M15. Compressive strength results for M30 (25% replacement), M31 (50% replacement) and M32 (75% replacement) are higher than that of M15 (control mix) at 3, 7, 28, and 56 days.

4.2 Evaluation of hardened concrete and durability properties in selected mixes

On analysis of fresh concrete properties (workability, air content and wet density) and compressive strength results for all the concrete mixes, it was observed that the mixes incorporating crushed sand showed less strength as compared to mixes having natural sand. Also, the admixture dosage requirement is higher in case of crushed sand mixes than that of mixes with natural sand.

Studies on other hardened concrete properties and durability studies of concrete were carried out on selected mixes. Five mixes (M3, M4, M8, M9 & M24) incorporating bottom ash replacing crushed sand and two control mixes (M1 & M6 with crushed sand at w/c 0.4 and 0.65, respectively) were selected for the same. Comparison of flexural strength, MOE, RCPT and accelerated carbonation test results has been shown in Figures 7 to 10.

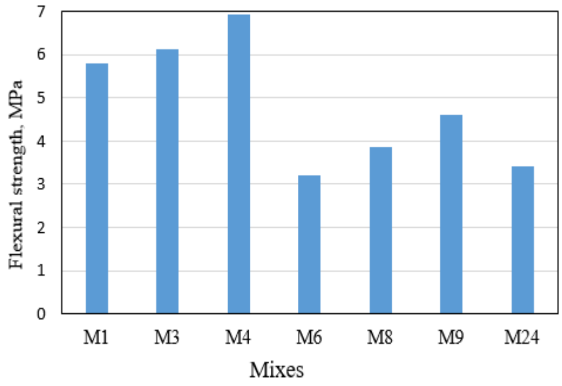

Fig. 7 – Comparison of 28-day flexural strength results for selected mixes

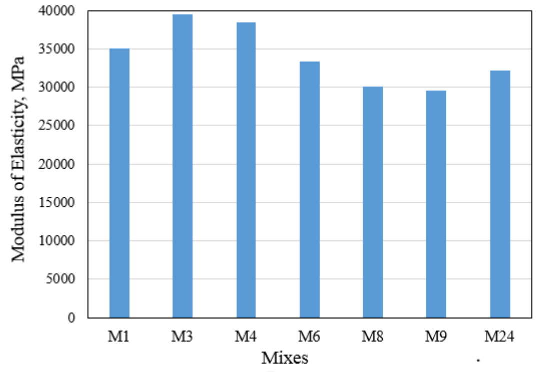

Fig. 8 – Comparison of 28-day modulus of elasticity results for selected mixes

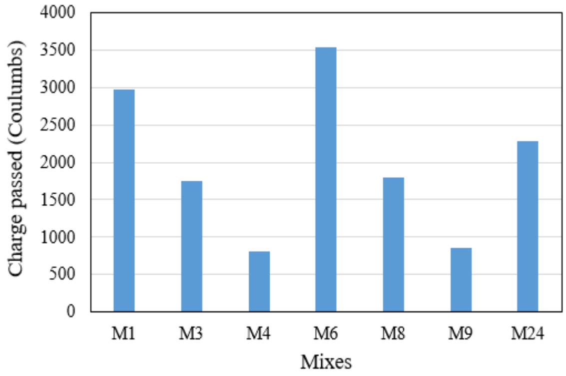

Fig. 9 – Comparison of 28-day RCPT results for selected mixes

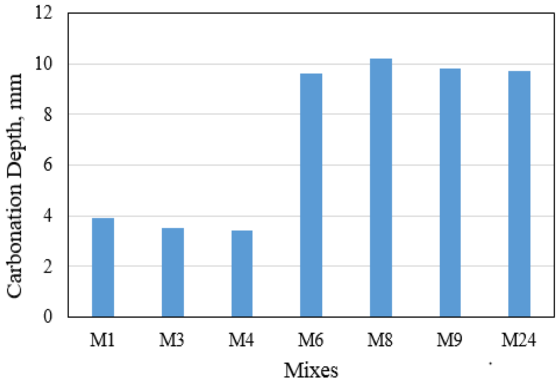

Fig. 10 – Comparison of carbonation depth results for selected mixes

Table 13 – Hardened and durability properties of selected concrete mixes (Part-I)

Mix	Bottom Ash (% replacement of fine aggregate	Test results at the age of 28 days						
		Compressive strength (MPa)	Flexural strength (MPa)	Modulus of elasticity (MPa)	Drying shrinkage (%)	Moisture movement (%)	pH value	Water permeability (mm)
M1	0	40.99	5.80	35055	0.0159	0.0177	12.83	8.33
M3	50 (BY)	48.66	6.13	39468	0.0150	0.0165	12.61	6.00
M4	75 (BY)	57.71	6.94	38512	0.0162	0.0175	12.75	3.33
M6	0	27.49	3.20	33322	0.0169	0.0186	12.63	26.0
M8	50 (BY)	33.47	3.85	30100	0.0165	0.0179	12.35	18.0
M9	75 (BY)	40.99	4.62	29636	0.0158	0.0174	12.40	13.0
M24	50 (BY-2)	28.83	3.42	32128	0.0160	0.0175	12.45	24.5

Table 14 – Hardened and durability properties of selected concrete mixes (Part-II)

Mix	Bottom Ash (% replacement of fine aggregate)	Test results at the age of 28 days						Accelerated carbonation test (mm)
		RCPT (Coulumbs)	Volume of permeable voids (%)	Sorptivity index (%)		Electrical resistivity kOhm.cm	Air permeability ($\times 10^{-16}$ m^2)	
				Initial mm/sqrt (sec)	Secondary mm/sqrt (sec)			
M1	0	2973	6.88	0.004	0.0010	12.8	0.044	3.9
M3	50 (BY)	1754	6.25	0.003	0.0005	17.2	0.030	3.5
M4	75 (BY)	806.7	5.84	0.002	0.0003	25.0	0.018	3.4
M6	0	3531	9.61	0.004	0.0010	21.2	0.090	9.6
M8	50 (BY)	1796	9.82	0.006	0.0015	35.2	0.065	10.2
M9	75 (BY)	859	8.19	0.002	0.0008	41.9	0.054	9.8
M24	50 (BY-2)	2291	8.99	0.004	0.0006	25.2	0.080	9.7

4.2.1 Mix using bottom ash BY (as such), w/c 0.40 and crushed fine sand

Concrete trial mixes were carried out at w/c ratio of 0.40 using Crushed Fine Aggregate and Bottom Ash BY (As such) sample. The crushed fine aggregate was replaced by 0%, 50% & 75% of Bottom Ash (As such) sample (M1, M3 & M4). The results of hardened and durability properties of concrete are given in Tables 13 and 14, where M1 is control mix using crushed fine aggregate at w/c 0.40. The study indicates that the test results of compressive strength, flexural strength and static modulus of elasticity are either comparable or higher at 50% & 75% replacement of crushed sand by bottom ash in comparison to control mix (M1). Drying shrinkage and moisture movement test results of mixes (M3 and M4) at 50% and 75% replacement of crushed sand by bottom ash are comparable to that of control mix (M1). Ph value for mixes (M3 and M4) at 50% and 75% replacement of crushed sand by bottom ash is comparable with that of control mix (M1). Water permeability, volume of permeable voids, air permeability, RCPT and initial and secondary sorptivity values are lower in case of mixes (M3 and M4) at 50% and 75% replacement of crushed sand by bottom ash with that of control mix (M1). Electrical resistivity is higher in case of mixes (M3 and M4) at 50% and 75% replacement of crushed sand by bottom ash with that of control mix (M1). Carbonation depth results measured by accelerated carbonation test are lower in case of mixes (M3 and M4) at 50% and 75% replacement of crushed sand by bottom ash with that of control mix (M1).

4.2.2 Mix using bottom ash BY (as such), w/c 0.65 and crushed fine sand

Concrete trial mixes were carried out at w/c ratio of 0.65 using crushed fine aggregate and Bottom Ash BY (As such) sample. The crushed fine aggregate was replaced by 0%, 50%, and 75% of Bottom Ash BY (As such) sample (M6, M8 & M9). The results of hardened and durability properties of concrete are given in Tables 13 and 14, where M6 is control mix using crushed fine aggregate at w/c ratio of 0.65. The study indicates that the test results of compressive strength, flexural strength and static modulus of elasticity are either comparable or higher for mixes (M8 and M9) at 50% and 75% replacement of crushed sand by bottom ash in comparison to control mix (M6). Drying shrinkage and moisture movement test results of mixes (M8 and M9) at 50% and 75% replacement of crushed sand by bottom ash are comparable to that of control mix (M6). Ph value for mixes (M8 and M9) at 50% and 75% replacement of crushed sand by bottom ash is comparable with that of control mix (M6). Water permeability, volume of permeable voids, air permeability, RCPT and initial and secondary sorptivity values are lower in case of mixes (M8 and M9) at 50% and 75% replacement of crushed sand by bottom ash with that of control mix (M6). Electrical resistivity is higher in case of mixes (M8 and M9) at 50% and 75% replacement of crushed sand by bottom ash with that of control mix (M6). Carbonation depth results measured by accelerated carbonation test are lower in case of mixes at (M8 and M9) 50% and 75% replacement of crushed sand by bottom ash with that of control mix (M6).

4.2.3 Mix using Bottom Ash BY-2 (fraction between 4.75 mm and 75 µm), w/c 0.65 and crushed fine sand

Concrete trial mix were carried out at w/c of 0.65 using crushed fine aggregate and Bottom Ash BY-2 (fraction between 4.75 mm and 75 µm) sample. The crushed fine aggregate was replaced by 0% and 50% of Bottom Ash BY-2 (fraction between 4.7 5mm and 75 µm) sample (M6 and M24). The results of hardened and durability properties of concrete are given in Tables 13 and 14, where M6 is control mix using crushed fine aggregate at w/c of 0.65. The study indicates that the test results of compressive strength, flexural strength and static modulus of elasticity are higher for mix (M24) at 50% replacement of crushed sand by bottom ash in comparison to control mix (M6). Drying shrinkage and moisture movement test results of mix (M24) at 50% replacement of crushed sand by bottom ash are comparable to that of control mix (M6). Ph value for mix (M24) at 50% replacement of crushed sand by bottom ash is comparable with that of control mix (M6). Water permeability, volume of permeable voids, air permeability, RCPT and initial and secondary sorptivity values are either lower or comparable in case of mix (M24) at 50% replacement of crushed sand by bottom ash with that of control mix (M6). Electrical resistivity is higher in case of mix (M24) at 50% replacement of crushed sand by bottom ash with that of control mix (M6). Carbonation depth results measured by accelerated carbonation test are lower in case of mix (M24) at 50% replacement of crushed sand by bottom ash with that of control mix (M6).

5 Conclusions

Based on the test results and discussion of characterization of bottom ash, fresh concrete, hardened concrete and durability properties of concrete mixes following are the conclusions:

(1) With addition of Bottom Ash, there is increase in admixture dosage in concrete mixes for maintaining the same workability as compared to

control mixes. However, at more than 50% replacement of Bottom Ash, it does not give a workable mix even at the higher admixture dosage than the permissible limits.

(2) Strength of the mixes made with Bottom Ash 'as such' is more than the mixes made with Bottom Ash 'fraction between 4.75 mm and 75µm'. However, for both the fractions i.e., 'as such' and 'fraction between 4.75 mm and 75µm' of Bottom Ash, their behavior in fresh, hardened and durability properties of concrete is comparable. Presence of material finer than 75µm is beneficial in concrete mixes in terms of pore refinement and pozzolanic reactivity, which results in development of higher compressive strength of concrete as compared to control mix. Therefore, use of "as such" fraction of bottom ash as replacement to fine aggregate in concrete is technically logical.

(3) Air content in all fresh concrete mixes is less than 2%. In all the mixes, with replacement of fine aggregate with Bottom Ash, the wet density of fresh concrete decreases as the specific gravity of Bottom Ash is less than that of fine aggregate. In all the mixes, with replacement of fine aggregate with Bottom Ash, setting time got marginally delayed. However, as seen in the hardened concrete results, it does not affect the strength development.

(4) With addition of Bottom Ash in the mixes made using bottom ash as a replacement to natural and crushed sand, strength parameters such as compressive strength and flexural strength increases for both the fractions as compared with that of control mixes. Static Modulus of Elasticity, drying shrinkage, moisture movement, pH of concrete and accelerated carbonation test results are comparable for both the fractions of Bottom Ash as compared with control mix.

(5) Water permeability, Volume of permeable voids, RCPT and Air permeability are lower for both the sources and both the fractions of Bottom Ash as compared with control mix due to pore refinement in hardened concrete. Electrical Resistivity is higher for both the sources and both the fractions of Bottom Ash as compared with control mix which shows higher resistance to corrosion.

(6) Since the replacement of fine aggregate with Bottom Ash is more than replacement of cementitious material with fly ash in concrete, the total quantity of alkali may be higher. Therefore, a study needs to be conducted to verify the potential alkali-aggregate reaction in such a concrete system. Presence of higher alkali may affect the setting time of concrete. It is observed that in all the mixes, with replacement of fine aggregate with Bottom Ash, setting time of concrete gets marginally delayed. However, as seen in the hardened concrete results, it does not affect the strength development.

References

1. Central Electricity Authority, http://www.cea.nic.in/
2. Abubakar, A. U.; and Baharudin, K. S. (2012) "Properties of concrete using Tanjung bin power plant coal bottom ash and fly ash," International Journal of Sustainable Construction Engineering & Technology, vol. 3, no. 2, pp.56-69.
3. Kasemchaisiri, R.; and Tangtermsirikul, S. (2008) "Properties of self compacting concrete incorporating bottom ash as a partial replacement of fine aggregate", Science Asia Research Article, vol. 34 pp. 087-095.
4. Rafieizonooz, M.; Mirza, J.; Salim, M. R.; Hussin, M. W.; and Khankhaje, E. (2016) "Investigation of coal bottom ash and fly ash in concrete as replacement for sand and cement," Construction and Building Materials, vol. 116, pp. 15-24.
5. Kim, H. K.; Jang, J. G.; Choi, Y. C. and Lee, H. K. (2014) "Improved chloride resistance of high strength concrete amended with coal bottom ash for internal curing," Construction and Building Materials, vol. 71, pp. 334-343.
6. Singh, M.; and Siddique, R. (2014) "Strength Properties and microstructural properties of concrete containing coal bottom ash as partial replacement of sand," Construction and Building Materials, vol. 68, pp. 39-48.
7. Andrade, L. B.; Rocha, J. C. and Cheriaf, M. (2009) "Influence of coal bottom ash as fine aggregate on fresh properties of concrete," Construction and Building Materials, vol. 23, no. 2, pp. 609-614.
8. Aggarwal, P.; Aggarwal, Y.; and Gupta, S. M. (2007) "Effect of Bottom Ash as replacement of fine aggregate in concrete," Asian Journal of Civil Engineering (Building and Housing), vol. 8, no. 1, pp. 49-62.
9. Kadam, M. P.; and Patil, Y. D. (2013) "Effect of coal bottom ash as sand replacement on the properties of concrete on different w/c ratio," International Journal of Advanced Technology in Civil Engineering, vol. 2, no. 1, pp. 45-50.
10. Arumugam, K.; Ilangovan, R.; and Manohar, J. D. (2011) "A study on characterization and use of pond ash as fine aggregate in concrete," International Journal of Civil & Structural Engineering, vol. 2, no. 2., pp. 466-474.

11. Raju R.; Paul M. M.; and Abubaker K. A. (2014) “Strength Performance of concrete using Bottom Ash as fine aggregate,” International Journal of Research in Engineering and Technology, vol. 2, no. 9, pp. 111-122.