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Research Article

Evaluation of coal based bottom ash as an alternative to fine aggregate in concrete: recommendations for specifications of bottom ash and its concrete mix design

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Abstract

Present study is an attempt to develop recommendations for specifications of bottom ash and concrete mix design guidelines by carrying out studies on bottom ash samples collected from 10 thermal power plants across India. Bottom ash samples were evaluated for physical and chemical properties. Composite fine aggregates were prepared by replacing 10-50% of conventional fine aggregate with bottom ash. 70 concrete mix trials were carried out using composite fine aggregates and mixes were evaluated for fresh, hardened and durability properties. Study indicated that maximum replacement of conventional fine aggregate with bottom ash for preparation of OPC based concrete shall not exceed 50% by weight of total fine aggregate and fineness modulus of resultant composite fine aggregate for use in concrete as fine aggregate shall be at least 1.35. The compressive strength of concrete at 28 days for all trials using composite fine aggregates were comparable with compressive strength of control concrete made with 100% conventional fine aggregates. The carbonation depth of control concrete were 6.6 mm to 9.5 mm and for concrete with composite fine aggregates, carbonation depths were 5.5 to 11.0 mm. The RCPT results of all mixes (including control mixes) shows that all mixes are lying in same class of penetrability. The electrical resistivity values of control concrete mixes were 7.1 to 6.1 k-ohm-cm and for concrete with composite fine it was 6.7 to 8.58 k-ohm-cm. Based on the results; recommendations were derived for specification of coal based bottom ash for its utilisation as an alternative to conventional fine aggregate in concrete along with guidelines for concrete mix design.

1. Introduction

One of the major components of concrete matrix are aggregates, as they generally occupy more than seventy percent of entire volume of concrete. Natural fine aggregates used in concrete are generally obtained by mining river sand from its bed. As consumption of concrete is increasing exponentially, particularly in developing country like India, it leads to the rapid rise in mining of river sand which leads to ecological problems alongside creating an impact on aquifer of river bed [1]. Therefore, aggressively growing construction industry requires an urgent sustainable alternative to conventional sand. In coal based thermal power plants, bottom ash has to be dumped in an open area nearby power plant, which pollutes the natural water bodies and also reduces the available productive land. The physical properties, chemical properties and the particle gradation of bottom ash are quite similar to that of fine aggregate. Therefore, in past decade, several studies related to physical and chemical evaluation of bottom ash as an aggregate and its

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effect on mechanical and durability perfromance of concrete has been carried out to investigate the possibility of using bottom ash as an alternative to conventional sand in concrete which has shown encouraging results [1-7]. Bottom ash majorly consists of fused coarser coal ash particles. Bottom ash particles are well graded, have rough texture and are comparatively more irregular, porous and lighter in comparison to conventional sand [2-4]. The size range of bottom ash particles vary from fine aggregate to gravel. Aforementioned properties of bottom ash make it an attractive alternative to natural sand. Cheriaf et al [7] based on morphological study of bottom ash using scanning electronic microscope found that bottom ash is very different as compared to fly ash particles with respect to its shape and surface characteristics. Seals et al [4] evaluated different characteristics of bottom ash from West and reported that density for bottom ash samples varied from 11.6 to 18.4 kN/m^3 (standard Proctor density) and optimum moisture content were observed to vary from 12 to 34 [4]. Coarser size of bottom ash along with its surface characteristics like fused, glassy texture makes it an ideal alternative for natural fine aggregates. However, utilization of bottom ash in concrete as fine aggregate is limited due to several technical challenges such as variation in characteristics of bottom ash, water requirement and its contribution in cements hydration [5].

Using bottom ash instead of sand leads to increase in water demand to attain the similar level of workability of concrete in its fresh state because of higher water absorption, irregular shape as well as porous nature of bottom ash particles [6 -10]. Therefore, in case of concrete incorporating bottom ash as replacement of fine aggregate, amount of extra water added to the mix, which just fills up the void and does not participate in lubrication needs to be taken into account [11–13]. Effective water to binder ratio in concrete needs to be appropriately adjusted to take into consideration, the porous nature of bottom ash particles [14]. Kadam et al [15] concluded from their study that with the increase in proportion of bottom ash as fine aggregate, the concrete mix becomes more cohesive resulting in lower workability. Singh and Siddique concluded that with increase in bottom ash proportion in concrete mix causes increase in amount of irregular and porous particles in the mix, which subsequently leads to increase in inter-particles friction [2]. However, some researchers have also found contradicting results [16-17]. Bai et al [18] observed that with increase in coal bottom ash, ball bearing effect increases, leading to better workability. However, most of the researchers have accepted that increasing the percentage level of coal based bottom ash as fine aggregate in concrete leads to increase in water demand to produce a workable concrete mix [19].

Studies carried out in past reveal that porosity of interfacial transition zone (ITZ) between aggregate particles and hydrated cement matrix gets increased with increase in bottom ash proportion in mix and it further leads to accumulation of free water nearby bottom ash particles [2]. Increased porosity and local w/c ratio of ITZ have detrimental effects on mechanical characteristics of concrete, particularly its compressive strength. Past research studies with focus on pozzolanic reactivity of bottom ash conclude that in spite of its relatively low pozzolanic activities it can be utilized to produce durable concrete [20-21]. Ksaibati [22] evaluated the feasibility of coal bottom ash utilisation as a complete aggregate substitution. Samples were prepared using bottom ash from three different sources and results indicated that the optimum asphalt content was higher in the mixture containing bottom ash with similar performance of the bottom ash mix compared control mixture during service period. The coal based bottom ash contains high amount of SiO_2, Al_2O_3, and Fe_2O_3 that enhances pozzolanic effects, mix interlock, and mechanical properties of concrete [23]. Even though pozzolanic potential of bottom ash is less due to its grain size [24], its lower pozzolanic nature does not prove to be any limiting factor for its potential to be utilized as replacement of conventional fine aggregate. On the contrary, any level of contribution due to the pozzolanic action of bottom ash particles improves the hardened as well as long term durability performance of concrete because of densification of cement matrix with secondary C-S-H formation [25]. Aggarwal et al [26] carried out research experiments on development of concrete mixes by using coal based bottom ash as 40% replacement of conventional fine aggregate (by weight) and found that up to 40% replacement level, mechanical properties like compressive and flexural strength are comparable or higher than control concrete. Arumugam et al [27] carried out lab experiments on preparation of concrete mixes by replacing as much as 60% of conventional fine aggregate with bottom ash and concluded that compressive strength of concrete mixes was higher in comparison to control concrete (without bottom ash), only up to 20% replacement of fine aggregate with bottom ash. Studies conducted by Raju et al [28] on concrete mixes prepared by replacement of up to 30% fine aggregate (by weight) with coal based bottom ash. Enhancement in mechanical properties of concrete mixes such as compressive, flexural and split tensile strength was observed only up to 20% replacement level. Above mentioned studies reveal that it is possible to incorporate and utilize coal based bottom ash as a partial replacement of conventional fine aggregate in cement concrete. Past studies have established the beneficial environmental impact of bottom ash utilisation in concrete as compared to conventional concrete [29-30]. Studies have proved bottom ash as a green and sustainable material that could decrease harmful environmental impact and promote sustainability in concrete production [31-32].

Research Significance:

Bureau of Indian Standards has permitted the use of manufactured aggregates in concrete through IS: 383-2016 [37]. It specifies that coal based bottom ash can be used as to replace conventional sand up to 25% in lean concrete only. However, the standard does not allow the use of coal based bottom ash in plain concrete and reinforced concrete. All across the globe, research studies on application of bottom ash as fine aggregate in concrete have been carried out at replacement levels varying from 10 to 100%. However, for wide use of bottom ash in construction as fine aggregate there is need for development of specification for conformance criteria in terms of physical and chemical parameters, so that end user can evaluate the bottom ash as per recommended specifications for use in concrete. Along with specifications, mix design guidelines and recommendations needs to be formulated for design of concrete mixes using coal based bottom ash as partial replacement of conventional sand in concrete. Present study focuses on development of specification for use of bottom ash as fine aggregate in concrete as well as formulation of guidelines for mix design of concrete mixes using bottom ash as part replacement of conventional fine aggregate.

2. Experimental Plan

Based on previous study conducted by Ojha et al [34-36], on feasibility study on possible utilisation of coal based bottom ash as replacement of conventional sand in concrete, it was concluded that up to 50% replacement of conventional sand with coal based bottom ash is viable in designed concrete mixes without affecting durability performance of concrete. The above recommendation was based on the bottom ash collected from only two sources. To formulate the specifications, in present study bottom ash samples were collected from 10 thermal power plants spread across various regions of India and those samples were characterized for their respective physical and chemical properties. Based on characterization results, specifications of bottom ash will be derived, for its use as a part replacement of conventional fine aggregate. Present study also covers studies on concrete mixes prepared using 21 selected composite fine aggregate (covering bottom ashes from all the sources). All the concrete mixes were evaluated for initial slump, air content, wet density and compressive strength. Durability studies were also carried out on selected concrete mixes. Based on aforementioned studies, mix design guidelines and recommendations were formulated for use of bottom ash as part replacement of conventional fine aggregate in concrete.

3. Characterization of bottom ash samples

3.1. Physical characterization

Bottom ash samples collected from 10 thermal power plants were evaluated for their different physical characteristics such as sieve analysis, water absorption, specific gravity, material finer than 75 microns and soundness as per relevant parts of IS 2386. Sieve analysis of bottom ash samples were carried out and fineness modulus was determined and compared with fineness modulus of zone of fine aggregate as specified in IS 383:2016 and the results are given in Table 1.

Table 1. Sieve analysis results (gradation) of bottom ash samples

IS Sieve Size	Percentage Passing (%) Plant No.									
	1	2	3	4	5	6	7	8	9	10
10 mm	100	100	100	100	100	100	100	99	100	98
4.75 mm	98	100	100	94	100	100	97	97	100	94
2.36 mm	96	100	99	87	100	99	95	95	100	88
1.18 mm	94	99	98	80	100	95	91	93	100	80
600 µm	87	93	96	68	99	86	83	89	100	69
300 µm	74	68	81	41	93	62	62	76	98	44
150 µm	37	25	27	15	38	20	28	36	86	15
Fineness Modulus	1.14	1.15	1	2.15	0.67	1.38	1.44	1.15	0.16	2.12
Zone as per IS:383-2016	Finer than ZoneIV	Finer than ZoneIV	Finer than ZoneIV	ZoneIII	Finer than ZoneIV	Finer than ZoneIV	Finer than ZoneIV	Finer than ZoneIV	Finer than ZoneIV	Zone III

Individual grading of all bottom ash indicates that all the bottom ash samples are finer than Zone 4 except bottom ash from plant-4 and plant-10. Fineness modulus of bottom ashes are in the range of 0.16 to 2.15. It is observed that fineness modulus of plant-9 was lowest i.e. 0.16 and that of plant-4 was highest i.e. 2.15. The results of other physical properties of bottom ash samples are given in Table 2 below.

Values of specific gravity of all samples are varying from 1.7 to 2.05 and are observed to be less than the conventional fine aggregate, whose specific gravity values are in the range of 2.6 to 2.9. In case of water absorption (tested as per IS 2386), it was observed that apart from plant-6 and plant-7, water absorption values of other bottom ash samples are in the range of 0.49 to 1.82 and are comparable with conventional fine aggregate. In case of accelerated mortar bar results (conducted as per ASTM 1260), expansion of mortar bars made using bottom ash samples as fine aggregate less than maximum limit (i.e. 0.1 %) as per ASTM C 1260. Therefore, samples of bottom ash from all sources are innocuous in nature. In order to decide specifications for physical characteristics of bottom ash as a replacement to conventional fine aggregate in concrete, requirement in terms of fineness modulus, water absorption, material finer than 75 microns and soundness has been considered to evaluate the bottom ash samples collected from 10 thermal power plants across India by studying its fresh, hardened and durability properties in concrete. Low value of fineness modulus of bottom ash will create issues with fresh concrete properties such as water demand, workability and ratio of coarse to fine aggregate. Limit on water absorption of bottom ash as a fine aggregate is critical as higher water absorption can lead to higher slump loss and issues with workability of concrete.

Table 2. Results of Physical properties of Bottom Ash Sample

Test Carried out	Source of Bottom Ash Plant No.									
	1	2	3	4	5	6	7	8	9	10
Specific gravity	1.86	1.73	1.75	1.72	2.05	1.7	1.73	1.83	1.98	1.79
Water absorption %	0.64	1.69	1.36	1.23	0.49	6.89	5.19	1.82	1.43	1.52
Material finer than 75 µm % (wet sieving)	5.47	1.67	7.3	3.17	4.53	8.63	8.07	8.43	64.33	2.83
Soundness Na_2SO_4,%	2.53	3.42	1.2	6.15	2.76	3.01	1.37	0.85	0.40	2.09
Organic impurities %	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Clay Lumps %	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil	Nil
Accelerated Mortar Bar ASTM C1260 %	0.04	0.03	0.04	0.02	0.05	0.04	0.05	0.03	0.07	0.06

Limit on material finer than 75 microns is critical as higher value will lead to more water demand and higher dosage of admixture to achieve similar fresh, mechanical and durability performance of concrete as in case of conventional fine aggregate. Higher value of materials finer than 75 microns can affect the compressive strength of concrete negatively. In order to avoid the expansion issues in concrete, the soundless limit are very important and higher soundness value can affect durability properties of concrete due to excessive change in volume of concrete. Based on the Physical characterization of bottom ash samples, it can be inferred that since very low value of fineness modulus of bottom ash will create issues with fresh concrete properties such as water demand, workability, ratio of coarse to fine aggregate, Minimum Fineness modulus of bottom ash has been kept at 1. Maximum value of water absorption of bottom ash to be used in concrete has been kept 2% as same is mentioned in Indian Standard IS: 383-2016 for conventional aggregate to be used in concrete. Maximum value of material finer than 75µ has been 8.63%, therefore requirements for material finer than 75µ has been kept at maximum 12%. Maximum value of Soundness of bottom ash by Na2SO4 has been observed 6.15%, therefore maximum limit of 10% has been considered. Similarly, maximum limit of soundness with MgSO4 has been kept at 15%. Currently Indian standard, IS: 383-2016 permits conventional fine aggregate with limit of soundness with 10% and 15% for Na2SO4 and MgSO4 respectively. All the results were well below this limit and same limit as conventional fine aggregate has been kept for bottom as replacement as fine aggregate.

3.2 Chemical Characterization of Bottom Ash

Bottom ash samples from 10 thermal power plants were evaluated for their different chemical properties such as loss on Ignition, major constituents and minor constituents, total alkali content as Na_2O equivalent, chloride content and total Sulphur as S to establish the specifications of bottom ash. The results of chemical characterization of bottom ash samples have been tabulated in Table-3 below.

Table 3. Characterization of Bottom Ash Samples

Parameters	Source of Bottom Ash Plant No.									
	1	2	3	4	5	6	7	8	9	10
Loss on Ignition %	0.28	0.28	0.78	0.82	0.12	0.19	0.67	2.72	0.41	1.21
SiO_2 %	61.29	62.37	65.80	66.20	61.95	63.98	65.30	61.05	62.08	66.38
Fe_2O_3 %	8.64	8.06	3.88	4.10	12.63	6.21	4.06	5.86	5.52	4.03
Al_2O_3 %	23.45	22.91	23.89	21.03	19.01	24.48	25.80	24.93	26.65	20.47
CaO %	2.02	2.15	1.02	3.54	1.88	1.05	1.25	1.20	2.21	4.16
MgO %	0.61	0.62	0.92	1.00	0.92	1.44	1.15	1.91	1.27	1.78
Total Sulphur (as S) %	0.33	0.27	0.24	1.50	0.39	0.10	0.10	0.12	0.08	0.17
$Na_2O_{equi.}$ %	0.84	1.03	0.88	0.89	0.95	0.69	0.66	1.01	0.73	0.93
Cl %	0.014	0.008	0.010	0.006	0.011	0.011	0.011	0.030	0.010	0.011
SO_3 %	0.06	0.05	0.09	0.11	0.06	0.93	0.13	0.18	0.14	0.22
TiO_2 %	1.94	1.67	1.80	1.46	1.70	0.34	0.36	0.35	0.36	0.28
Cr^{+3} %	0.013	0.012	0.013	0.013	0.013	0.047	0.041	0.041	0.053	0.044

Keeping in view that bottom ash is a man-made material produced from thermal power plants and composition of coal and manufacturing process can have impact on the chemical characteristics of bottom ash which can subsequently affect the fresh, hardened and durability properties of concrete, when bottom ash is used as fine aggregate. The fine aggregates may contain different chemical constituents that react with coarse aggregate or cement paste matrix and form cracks on concrete surface which affects mechanical and durability perfromance. Therefore, the aggregates must be tested to ensure that such kinds of particles are not present in aggregates. Inorder, to have uniformity in quality of bottom ash as a fine aggregate and its consistent performance in concrete, limits on loss on Ignition, SiO_2 content, MgO content, SO_3 content, acid soluble chloride content, total chloride content and total alkali content as Na_2O equivalent has been considered, Maximum value of loss on ignition was observed 2.72%, therefore requirement for loss on ignition has been kept at maximum 3%. Minimum value of SiO_2 was observed 61.05%, therefore requirement for SiO_2 has been kept Minimum 50%. Maximum value of MgO was observed 1.91%, therefore requirement for MgO has been kept at maximum 3%. Maximum value of SO_3 was observed 0.93%, therefore requirement for SO_3 has been kept at maximum 2%. Maximum value of acid soluble chloride was observed 0.03%, therefore requirement for acid soluble chloride has been kept at maximum 0.04%. Maximum value of Total Chloride was observed 0.048%, therefore requirement for total chloride has been kept at maximum 0.05%. Maximum value of total alkalies as Na_2O equivalent was observed 1.03, therefore requirement for total alkalies as Na_2O equivalent has been kept Maximum 1.5% and this does not have any impact on alkali silica reaction as expansion values in accelerated mortar bar test are within permissible limit.

3.3. Study of Size and Grading of Composite Fine Aggregate for Preparation of Guidelines for Mix Design

In order to effectively utilize bottom ash as fine aggregate in concrete, it is imperative to study the grading and size distribution of bottom ash, as this will affect the fresh concrete properties such as water demand, ratio of coarse aggregate to fine aggregate, workability, air content wet density etc. There were total 10 sources of bottom ash in which Bottom ash from Plant-9 and Plant-1 were not considered in study for formulation of guidelines for concrete mix design as the bottom ash from Plant-9 was very fine and fineness modulus is comparable with that of coarse fly ash. Whereas, Plant-1 has been shut down permanently. In this study, bottom ash samples from 8 sources (i.e. except Plant-1 and Plant-9) were mixed with fine aggregate from natural source of Zone- II & III and crushed sand of Zone-I, II & III as part replacement of 10%, 20%, 30%, 40% and 50%. Total 200 composite fine aggregate (8 sources of Bottom Ash × 5 Source of fine aggregate × 5 different percentage replacement) were worked out theoretically.

Table 4. Composition of 21 composite fine aggregates selected for further study

Sl. No.	Fineness Modulus	Fineness Modulus Range	Bottom Ash Source	Percentage Replacement	Fine Aggregate Source
CFA-1	1.33	1.33-1.69	Plant-5	50%	Natural Sand Zone-III
CFA-2	1.47		Plant-3	50%	Natural Sand Zone-III
CFA-3	1.55		Plant-8	50%	Natural Sand Zone-III
CFA-4	1.67		Plant-6	50%	Natural Sand Zone-III
CFA-5	1.68		Plant-2	50%	Crushed Sand Zone-III
CFA-6	1.68		Plant-5	40%	Crushed Sand Zone-II
CFA-7	1.71	1.7-1.89	Plant-2	30%	Natural Sand Zone-III
CFA-8	1.7		Plant-7	50%	Natural Sand Zone-III
CFA-9	1.78		Plant-8	40%	Crushed Sand Zone-III
CFA-10	1.8		Plant-5	40%	Natural Sand Zone-II
CFA-11	1.84		Plant-3	30%	Crushed Sand Zone-III
CFA-12	1.97	1.9-2.09	Plant-7	40%	Crushed Sand Zone-II
CFA-13	1.99		Plant-10	20%	Natural Sand Zone-III
CFA-14	2.05		Plant-4	50%	Natural Sand Zone-III
CFA-15	2.06		Plant-3	20%	Crushed Sand Zone-II
CFA-16	2.16	2.1-2.49	Plant-10	50%	Crushed Sand Zone-III
CFA-17	2.25		Plant-8	20%	Natural Sand Zone-II
CFA-18	2.38		Plant-5	30%	Crushed Sand Zone-I
CFA-19	2.41		Plant-4	30%	Natural Sand Zone-II
CFA-20	2.76	2.5-3.01	Plant-6	20%	Crushed Sand Zone-I
CFA-21	2.61		Plant-10	50%	Crushed Sand Zone-I

Grading of all 200 composite fine aggregates have been calculated mathematically based on weightage average. Fineness modulus values of all the composite fine aggregates are in the range of 1.33 to 3.01 and has been further categorized in 5 different ranges of fineness modulus (i.e. 1.33-1.69, 1.70- 1.89, 1.90-2.09, 2.1-2.49, 2.50- 3.01) on the basis fineness modulus of all zone of sands as mentioned in above table. A matrix was prepared for 200 composite fine aggregate in 5 different ranges. Out of total 200, Composite Fine Aggregate (CFA), 21 composite fine aggregates were selected on the basis of their fineness modulus, criticality and were also selected in such a manner that Bottom ash from all the 8 sources and all types of fine aggregates of different zones are covered for the further studies on concrete mix design. Composite Fine Aggregates (CFA) selected for further study were selected in such a way that they cover different ranges of fineness modulus, different proportions of replacement (i.e. 20, 30, 40 and 50%) and bottom ash samples from all possible sources. Composition of Composite Fine Aggregates (CFA) selected for further study has been tabulated below in table 4.

The actual sieve analysis was carried out for the selected 21 composite fine aggregates from all ranges as mentioned above. The sample of bottom ash was mixed with the fine aggregate as per the percentage of part replacement as mentioned for their respective composite fine aggregates and the fineness modulus was determined experimentally. The fineness modulus of experimentally determined values and mathematically calculated values of all the 21 composite mixes were found to be comparable and were within the deviation of +10%. Sieve analysis along with fineness modulus of aforementioned composite fine aggregates has been tabulated below in Table 5.

Table 5. Sieve analysis results of selected composite fine aggregate

Sieve Size	CFA-1	CFA-2	CFA-3	CFA-4	CFA-5	CFA-6	CFA-7
				% Passing			
10 mm	100	100	100	100	100	100	100
4.75 mm	100	100	100	100	100	100	100
2.36 mm	100	100	95	100	96	95	100
1.18 mm	97	96	96	94	85	80	95
600 µm	88	88	84	84	74	72	86
300 µm	61	55	54	48	56	58	35
150 µm	22	18	23	16	24	29	14
Fineness Modulus	1.32	1.49	1.48	1.58	1.65	1.66	1.70
Sieve Size	CFA-8	CFA-9	CFA-10	CFA-11	CFA-12	CFA-13	CFA-14
				% Passing			
10 mm	100	100	100	100	100	100	100
4.75 mm	100	98	99	99	98	98	98
2.36 mm	99	92	91	92	93	98	95
1.18 mm	92	78	90	84	76	96	88
600 µm	83	74	74	72	60	76	75
300 µm	47	56	46	53	52	33	36
150 µm	18	25	20	23	30	8	12
Fineness Modulus	1.61	1.77	1.8	1.77	1.91	1.91	1.96
Sieve Size	CFA-15	CFA-16	CFA-17	CFA-18	CFA-19	CFA-20	CFA-21
				% Passing			
10 mm	100	100	100	100	100	100	99
4.75 mm	100	98	95	100	94	100	98
2.36 mm	92	86	94	88	92	81	85
1.18 mm	74	79	88	62	84	62	69
600 µm	61	65	66	55	58	44	46
300 µm	44	45	30	44	27	32	31
150 µm	31	19	14	23	12	12	16
Fineness Modulus	1.98	2.08	2.13	2.28	2.33	2.59	2.56

4. Concrete Mix Trials and Determination of Properties of Concrete Mixes in Fresh State and Their Compressive Strength for Formulation of Concrete Mix Design Guidelines

As per guidelines given in IS 10262:2019 [37] for the concrete mix design, concrete mix trials were conducted to determine the parameters required for formulation of guidelines i.e. air content in fresh concrete; water required for workability of fresh concrete for slump 25 mm- 50 mm; additional percentage of water required for every 25 mm increase in slump; estimation of proportion of coarse aggregate (i.e. volume of coarse aggregate per unit volume of total aggregate). Concrete mix trials were conducted at different water content and different ratios of coarse to fine aggregate to determine the aforementioned parameters. Concrete mix trials were conducted using OPC-43 and 21 number of selected composite fine aggregates at water to binder ratio of 0.5 and for maximum aggregate size of 20 mm. All the mixes were cast without any chemical admixture. Coarse and fine aggregate conforming to IS 383:2016 [33] and OPC-43 grade cement conforming to IS 269:2015 [38] were used for conducting trials and preparation of concrete mixes. The target compressive strength for the mixes designed with composite fine aggregate and control mixes were 31.62 MPa which corresponds to M25 grade concrete mix design. Total 70 concrete mix trials with OPC-43 grade cement using 21 composite fine aggregate were conducted and properties of concrete in fresh state such as air content, wet density and workability in terms of slump were determined. Mixes were also evaluated for compressive strength at 28 days. Several trials were conducted to determine the volume of coarse aggregate per unit volume of total aggregates. Details of all concrete mix trials along with their fresh properties and compressive strength at 7 and 28 days have been tabulated in table 6.

Table 6. Details of trials conducted using composite fine aggregates, fresh properties and compressive strength of trial mixes

Sl. no	Composite fine aggregate	% of bottom ash in composite fine aggregate	Ratio of coarse and fine aggregate	Water kg/m³	Slump mm	Air Content %	Wet Density kg/m³	Comp. Strength	
								7 Days MPa	28 Days MPa
1	CFA-1	50%	(70:30)	186	25	1.8	2430	27.35	33
2	CFA-1	50%	(72:28)	186	25	1.6	2400	27.57	36.08
3	CFA-1	50%	(72:28)	194	45	1.4	2428	23.94	31.92
4	CFA-1	50%	(74:26)	194	70	1.2	2391	23.86	32.06
5	CFA-2	50%	(68:32)	194	20	1.8	2381	27.36	34.78
6	CFA-2	50%	(70:30)	194	25	1.4	2405	26.74	33.65
7	CFA-2	50%	(70:30)	202	60	1.2	2389	24.89	32.5
8	CFA-3	50%	(68:32)	194	25	1.3	2417	25.09	32.9
9	CFA-3	50%	(70:30)	194	35	1.3	2443	24.31	32.6
10	CFA-3	50%	(72:28)	194	40	1.3	2396	25.27	34.59
11	CFA-4	50%	(68:32)	194	30	1.7	2438	22.35	33.76
12	CFA-4	50%	(70:30)	194	30	1.5	2470	24.59	34.7
13	CFA-4	50%	(72:38)	194	50	1.3	2430	24.88	35.1
14	CFA-4	50%	(72:38)	202	75	1.5	2466	22.96	33.9
15	CFA-5	50%	(68:32)	194	10	1.9	2415	27.84	35.43
16	CFA-5	50%	(70:30)	194	10	2.0	2400	26.99	34.78
17	CFA-5	50%	(70:30)	204	30	1.9	2396	24.8	35.34
18	CFA-6	40%	(68:32)	194	20	1.5	2437	25.61	35.7
19	CFA-6	40%	(68:32)	202	40	1.5	2419	24.03	34.76
20	CFA-6	40%	(70:30)	202	45	1.2	2410	28.95	35.78
21	CFA-6	40%	(72:28)	202	45	1.0	2425	25.04	34.5
22	CFA-7	30%	(68:32)	194	40	1.2	2453	28.82	35.65
23	CFA-7	30%	(70:30)	194	50	1.5	2471	29.37	36.89
24	CFA-7	30%	(72:28)	194	50	1.7	2462	26.23	34.76
25	CFA-8	50%	(68:32)	194	20	1.5	2442	27.52	34.65
26	CFA-8	50%	(70:30)	194	20	1.5	2469	29.2	35.98
27	CFA-8	50%	(70:30)	202	45	1.4	2427	24.33	34.65
8	CFA-9	40%	(68:32)	194	35	1.8	2404	22.05	33.76
29	CFA-9	40%	(70:30)	194	45	1.6	2396	23.68	33.89
30	CFA-9	40%	(72:28)	194	45	1.9	2384	24.44	35.87
31	CFA-10	40%	(68:32)	194	40	1.5	2393	26.39	35.78
32	CFA-10	40%	(70:30)	194	50	1.5	2426	27.5	35.2
33	CFA-10	40%	(72:28)	194	45	1.5	2412	26.77	34.97

34	CFA-11	30%	(68:32)	194	35	1.7	2453	28.71	34.54
35	CFA-11	30%	(70:30)	194	45	1.2	2468	28.93	35.65
36	CFA-11	30%	(70:30)	202	75	1.1	2441	24.16	34.90
37	CFA-12	40%	(66:34)	194	10	Mix was not cohesive and was not evaluated further			
38	CFA-12	40%	(66:34)	202	25	1.7	2439	26.95	34.7
39	CFA-12	40%	(68:32)	194	25	1.3	2376	24.74	31.87
40	CFA-13	20%	(68:32)	194	25	1.5	2390	26.39	33.43
41	CFA-13	20%	(68:32)	202	35	1.3	2376	24.74	31.87
42	CFA-13	20%	(70:30)	194	20	1.3	2419	27.28	34.8
43	CFA-14	50%	(66:34)	194	40	2.1	2480	27.11	35.89
44	CFA-14	50%	(68:32)	194	40	1.6	2473	27.39	35.5
45	CFA-14	50%	(68:32)	202	60	1.3	2448	26.82	34.6
46	CFA-14	50%	(70:30)	194	50	1.5	2436	29.06	36.1
47	CFA-15	20%	(64:36)	194	30	1.6	2482	24.53	34.87
48	CFA-15	20%	(66:34)	194	30	1.2	2492	26.02	35.76
49	CFA-15	20%	(68:32)	194	35	1.2	2504	24.69	34.7
50	CFA-15	20%	(68:32)	202	50	1.7	2468	22.03	33.85
51	CFA-16	50%	(62:38)	194	10	1.2	2430	28.31	35.6
52	CFA-16	50%	(62:38)	204	70	1.0	2449	24.04	32.8
53	CFA-16	50%	(68:32)	194	45	1.6	2428	22.64	31.6
54	CFA-16	50%	(70:30)	194	90	1.2	2433	22.5	31.9
55	CFA-16	50%	(72:28)	194	95	1.2	2420	25.68	33.76
56	CFA-17	20%	(66:34)	194	40	1.4	2452	26.5	33.52
57	CFA-17	20%	(68:32)	194	60	1.6	2443	26.62	32.90
58	CFA-17	20%	(70:30)	194	80	1.4	2429	26.23	32.97
59	CFA-18	30%	(64:36)	194	40	1.5	2459	26.62	35.7
60	CFA-18	30%	(66:34)	194	50	1.5	2411	28.71	36.76
61	CFA-18	30%	(66:34)	202	80	1.0	2426	28.06	35.98
62	CFA-18	30%	(68:32)	194	40	1.6	2390	27.33	34.76
63	CFA-19	30%	(64:36)	194	50	1.6	2387	24.87	33.32
64	CFA-19	30%	(66:34)	194	50	1.9	2425	26.37	34.7
65	CFA-20	20%	(62:38)	194	45	1.4	2371	29.06	35.8
66	CFA-20	20%	(64:36)	194	55	1.4	2369	30.01	36.12
67	CFA-20	20%	(64:36)	202	90	1.3	2405	28.43	35.56
68	CFA-21	50%	(64:36)	194	50	1.5	2493	27.56	35.89
69	CFA-21	50%	(62:38)	186	10	Mix was not cohesive and was not evaluated further			
70	CFA-21	50%	(62:38)	194	40	1.8	2461	30.89	40.04
71	Control-1	100%	(70:30)	194	75	1.9	2385	32.89	38.25
72	Control-2	100%	(68:32)	209	65	1.6	2421	31.79	37.65

For concrete mixes using composite fine aggregates lying in the fineness modulus range of 1.33-1.69, it was observed that for concrete mix having volume of coarse aggregate per unit volume of total aggregate of 0.72 and water content at 194 kg, the mix was cohesive and desired slump was achieved (i.e. 25 mm- 50 mm) without chemical admixture. Due to very low fineness modulus, the composite fine aggregate percentage was kept low and after further reducing the composite fine aggregate the mix was not found cohesive. For concrete mixes using composite fine aggregates lying in the fineness modulus range of 1.70-1.89, it was observed that for concrete mix having volume of coarse aggregate per unit volume of total aggregate of 0.70 and water content at 194 kg, the mix was cohesive and the desired slump (i.e. 25 mm- 50 mm) was achieved without chemical admixture. For concrete mixes using composite fine aggregates lying in the fineness modulus range of 1.9-2.09, it was observed that for concrete mixes at volume of coarse aggregate per unit volume of total aggregate of 0.68 and water content at 194 kg, the mix was cohesive and required slump (i.e. 25 mm- 50 mm) was achieved. Similarly, for concrete mixes using composite fine aggregates lying in the fineness modulus range of 2.1-2.49, volume of coarse aggregate per unit volume of total aggregate of 0.66 and water content of 194 kg per cum has been finalized to achieve the slump value of 25 mm- 50 mm. Similarly, for concrete mixes using composite fine aggregates lying in the fineness modulus range of 2.5- 3.01, volume of coarse aggregate per unit volume of total aggregate of 0.64 has been finalized as the fineness modulus of composite fine aggregate is comparable to coarser range of Zone-II and finer range of Zone-I. Along with above, in general for all concrete mix trials using different composite fine aggregates, it was observed that air content of all the mixes were varying from 1.0% to 2.0%. Majority of the values were lying near 1.5%. Therefore, air content of 1.5% shall be considered for the design mix of concrete mix incorporating bottom ash as part replacement of conventional fine aggregates. It was observed that at 194 kg of water per cubic meter of concrete, desired slump (i.e. 25 to 50 mm) was achieved without any chemical admixture. To achieve additional 25 mm slump above 50 mm, additional 4% of water shall be added as per Indian Standard IS: 10262-2019 procedure. The compressive strength of concrete mixes at 28 days of all the trials using composite fine aggregates (containing bottom ash) were comparable with the compressive strength of control concrete mixes made with 100% conventional fine aggregates i.e. natural and crushed sand. Based on above trials the volume of coarse aggregate per unit volume of total aggregate for different ranges of fineness modulus of composite fine aggregate at water to cement ratio of 0.50 and nominal maximum size of aggregate as 20 mm for which the mixes were observed to be cohesive have been tabulated in table 7 for design mix of concrete.

Table 7. Volume of coarse aggregate per unit volume of total aggregate for water-cement ratio of 0.50 and nominal maximum size of aggregate of 20 mm

Fineness Modulus of composite fine aggregate	1.33-1.69	1.7-1.89	1.9-2.09	2.1-2.49	2.5-3.01
Volume of Coarse Aggregate per Unit Volume of total Aggregate	0.72	0.70	0.68	0.66	0.64

5. Studies on Durability Properties of Selected Concrete Mixes

Out of total 70 mixes using OPC-43 cement, 8 concrete mixes were selected for further studies on long term durability related properties of concrete as mentioned below:

- Pore structure using MIP
- Accelerated Carbonation Test at 28 days as per ISO 1920- Part-12
- Rapid Chloride Permeability Test (RCPT) as per ASTM C 1202
- Electrical resistivity of concrete by four-point Wenner Probe method

The mixes were selected keeping in view the fineness modulus of composite fine aggregate to cover the fineness modulus range from 1.33 to 2.25 and the replacement percentage of composite fine aggregate of bottom ash between 20 to 50 percent. This was done to cover that upper, lower and middle range of fineness modulus and replacement percentage of composite fine aggregate and also to cover the maximum number of sources into consideration. Two concrete mixes containing 100% conventional fine aggregates (one concrete mix with 100% natural sand and one concrete mix with 100% crushed sand) were selected to act as control concrete mixes. Further, 6 experimental concrete mixes prepared using composite fine aggregates having different proportions of bottom ash from different sources) were selected. Out of six experimental mix, two mixes had composite fine aggregate containing 20% bottom ash, one mix had composite fine aggregate containing 30% bottom ash and three mixes had composite fine aggregate containing 50% bottom ash as part replacement of conventional fine aggregate.

5.1 Pore Structure Using Mercury Intrusion Porosity (MIP)

Mortar sample extracted from hardened concrete was evaluated for porosity percentage, total pore volume, average pore diameter and median pore diameter using Mercury

Intrusion Porosimeter (MIP) equipment. Mercury was intruded into the sample at pressure of 350 MPa for measurement of aforementioned parameters related to pore structure and test results have been tabulated below in table 8 and test setup used for evaluation of parameters associated to pore structure has been shown in figure 1.

Table 8. Pore structure parameters of mixes using Mercury Intrusion Porosity

Mix	Fineness modulus of fine aggregate	Source of Bottom ash	% of bottom ash in fine aggregate	Type of conventional Fine aggregate	Porosity of Mortar using MIP	Total Pore Volume (mm^3/g)	Average pore diameter (nm)	Median pore diameter (nm)
Mix-1	1.96	-	0%	Natural Sand Zone-3	9.38	45.03	24.39	48.90
Mix-2	2.21	-	0%	Crushed Sand Zone 3	15.93	78.09	26.36	66.05
Mix-3	1.33	Plant-5	50%	Natural Sand Zone 3	14.16	67.69	48.48	221.30
Mix-4	1.68	Plant-2	50%	Crushed Sand Zone 3	12.86	60.68	67.59	165.16
Mix-5	1.7	Plant-7	50%	Natural Sand Zone 3	11.50	51.99	61.34	254.06
Mix-6	1.84	Plant-3	30%	Crushed Sand Zone 3	10.49	50.46	35.33	61.09
Mix-7	1.99	Plant-10	20%	Natural Sand Zone 3	10.58	49.53	52.91	112.02
Mix-8	2.25	Plant-8	20%	Natural Sand Zone 2	7.16	18.72	37.40	147.20

Fig. 1 Test setup for evaluation of pore structure

Fig. 2 Accelerated Carbonation Test

Porosity of control sample (without Bottom ash) was 9.38% to 15.93 %. Whereas, for concrete samples containing composite fine aggregate, porosity values are varying from 7.16 to 14.16%. Total pore volume of control samples (without bottom ash) are 45.03 mm^3/g to 78.09 mm^3/g. Whereas for concrete samples containing composite fine aggregate values of total pore volume varies from 18.72 to 67.69 mm^3/g which is comparable to control concrete.

The average pore diameter of control samples (without bottom ash) are 24.39 nm to 26.36 nm. Whereas, for concrete samples containing composite fine aggregate values of average pore diameter varies from 35.33 to 67.59 nm. Again, the median pore diameter of control samples (without bottom ash) are 48.90 to 66.05 nm. Whereas, for concrete samples containing composite fine aggregate values of average pore diameter varies from 66.09 to 254.06 nm. The results of porosity and total pore volume are in the similar range but wide variation between the average pore diameter and median pore diameter results of concrete with conventional aggregate and composite fine aggregate is seen. With the replacement of bottom ash as a fine aggregate the nucleation sites sometimes gets formed in the cement hydration products and intrusion of mercury in composite fine aggregate though is same, pore diameters are different.

5.2. Carbonation Chamber Used for Accelerated Carbonation Test

Accelerated carbonation test on selected concrete mixes was conducted as per adopted as per ISO 1920 part 12. Concrete specimens (dimension 100 × 100 × 500 mm) were cast and cured in water at temperature of 27 ± 2 °C for 28 days and then conditioned under controlled laboratory environment for 14 days at temperature of 27 ± 2 °C and relative humidity of 65 ± 5 % [39-41]. Carbonation depth of concrete specimen after 70 days of carbonation has been tabulated in table 9 Carbonation chamber used for accelerated carbonation of concrete specimen has been shown in figure 2. The carbonation depth of control concrete samples (without bottom ash) are observed to be 6.6 mm and 9.5 mm. Whereas, for the concrete mixes made with composite fine aggregates, carbonation depths are in the range of 5.5 to 11.0 mm. This suggest that, the carbonation depth values of concrete mixes made with composite aggregate (bottom ash as part replacement of conventional fine aggregate) and control concrete mixes (without bottom ash) are similar and comparable as the range is around 5 to 11 mm for both types of fine aggregate.

5.3. Rapid Chloride Penetrability Test

This test is used to evaluate any material against the chloride ion penetration. RCPT test was carried out as per procedure laid down in ASTM C 1202. This test was carried out on saturated 50 mm thick concrete disc of 100 mm diameter extracted from cylindrical concrete specimen having 100 mm diameter and 200 mm length. The total charge passed (in coulombs) through samples of all the concrete mixes at the age of 28 days is given in table 9 and is related to the chloride ion penetrability class according to the criteria given in ASTM C1202. The RCPT results of all the mixes (including control mixes) shows that all mixes are lying in the same class of penetrability (i.e. 2000- 4000 coulombs, Moderate degree of penetrability). Therefore, performance of concrete mixes prepared with composite fine aggregate against chloride ion penetration is similar and comparable with the control concrete mixes (without bottom ash).

5.4. Electrical Resistivity of Concrete

Electrical resistivity testing of concrete slabs (300 × 300 × 100 mm) was conducted using four-point Wenner probe resistivity meter which is used for in-situ measurement of electrical resistivity in concrete [42-44]. Resistivity meter permits a rapid and non-destructive measurement of the quality of concrete with respect to its resistivity. Test results of concrete resistivity for concrete mixes are given in table 9. The electrical resistivity values of control concrete mixes are 7.1 and 6.1 k-ohm-cm. Whereas concrete mixes with composite fine aggregate are in the range of 6.7 to 8.58 k-ohm-cm. This suggest that, the electrical resistivity values of concrete mixes made with composite aggregate (bottom ash as part replacement of conventional fine aggregate) and control concrete mixes (without bottom ash) are almost similar and comparable.

Table 9. Accelerated carbonation depth, RCPT and electrical resistivity of selected concrete mixes

Mix	Fineness Modulus of fine aggregate	Bottom ash Source	% Replacement of fine aggregate using bottom ash	Conventional Fine aggregate (Type)	RCPT (Coulombs) After 28 days	Electrical Resistivity (k-Ω-cm) After 28 days	Accelerated Carbonation depth (mm) After 70 days of carbonation
Mix-1	1.96	-	0%	Natural Sand Zone-3	3575	7.1	6.5
Mix-2	2.21	-	0%	Crushed Sand Zone 3	3670	6.1	9.5
Mix-3	1.33	Plant-5	50%	Natural Sand-Zone 3	3446	7.5	10.0
Mix-4	1.68	Plant-2	50%	Crushed Sand-Zone 3	2873	8.58	6.2
Mix-5	1.7	Plant-7	50%	Natural Sand-Zone 3	2874	7.3	6.5
Mix-6	1.84	Plant-3	30%	Crushed Sand-Zone 3	2284	7.5	5.5
Mix-7	1.99	Plant-10	20%	Natural Sand-Zone 3	3194	6.7	11.0
Mix-8	2.25	Plant-8	20%	Natural Sand-Zone 2	3686	7.2	11.0

6. Conclusion and Recommendations

Based on the detailed study done and literature reviewed to develop recommendations for specifications of bottom ash and concrete mix design guidelines by carrying out studies on bottom ash samples collected from 10 thermal power plants across India, the following conclusions and recommendations are drawn:

Based upon the Physical characterization of bottom ash samples, minimum fineness modulus of bottom ash has been kept at 1 as low value of fineness modulus of bottom ash creates issues with fresh concrete properties such as water demand, workability and ratio of course to fine aggregate. Maximum value of water absorption of bottom ash to be used in concrete has been kept 2%. Maximum value of material finer than 75µ has been 8.63%, therefore requirements for material finer than 75µ has been kept at maximum 12%. Maximum value of Soundness of bottom ash by Na_2SO_4 has been observed 6.15%, therefore maximum limit of 10% has been considered. Similarly, maximum limit of soundness with $MgSO_4$ has been kept at 15%. Based upon the chemical characterization of bottom ash samples, maximum value of loss on ignition was observed to be 2.72%, therefore requirement for loss on ignition has been kept at maximum 3%. Minimum value of SiO_2 was observed 61.05%, therefore requirement for SiO_2 has been kept Minimum 50%. Maximum value of MgO was observed 1.91%, therefore requirement for MgO has been kept at maximum 3%. Maximum value of SO_3 was observed 0.93%, therefore requirement for SO_3 has been kept at maximum 2%. Maximum value of acid soluble chloride was observed 0.03%, therefore requirement for acid soluble chloride has been kept at maximum 0.04%. Maximum value of Total Chloride was observed 0.048%, therefore requirement for total chloride has been kept at maximum 0.05%. Maximum value of total alkalies as Na_2O equivalent was observed 1.03, therefore requirement for total alkalies as Na_2O equivalent has been kept Maximum 1.5%. Based upon findings and conclusions on physical and chemical characteristics of bottom ash to be used in concrete as part replacement of fine aggregate, recommendations for specification of physical and chemical characteristics of bottom ash are given below in Table 10 & Table 11.

Table 10. Recommendations for Specification for physical characteristics of bottom ash

Physical Parameter	Requirement
Material finer than 75µ, % Max	12
Fineness Modulus of Bottom Ash, Min and Max	1 and 4
Water absorption Max	2
Soundness (Na_2SO_4), % Max	10
Soundness ($MgSO_4$), % Max	15

Table 11. Recommendations for Specifications for chemical characteristics of bottom ash

Chemical Parameter	Requirement
Loss on Ignition, % Max	3
SiO_2, % Min	50
MgO, % Max	3
SO_3 , % Max	2
SiO_2+Al_2O_3+Fe_2O_3, % Min	60
Acid Soluble Chloride, % Max	0.04
Total Chloride, %, Max	0.05
Total Alkalies as Na_2O equivalent, % Max	1.5

Composite fine aggregate recommended for use in concrete is a mixture of fine aggregate (i.e. natural/ crushed sand) and bottom ash. Conventional fine aggregate is partly replaced with bottom ash in different percentage by weight to make composite fine aggregate of required fineness modulus. Based on the aforementioned trials, recommendations for composite fine aggregate are that composite fine aggregate shall be a mixture of conventional fine aggregate (i.e. natural/crushed sand) and coal based bottom ash. Maximum replacement of conventional fine aggregate with coal based bottom ash for preparation of OPC based cement concrete shall not exceed 50% by weight of total fine aggregate. Sieve analysis of conventional fine aggregate and coal based bottom ash shall be done and fineness modulus of both shall be determined. Conventional fine aggregate shall be replaced by bottom ash in such proportion (not exceeding the permissible limit of 50 %) that fineness modulus of the resultant composite fine aggregate for use in concrete as fine aggregate shall be at least 1.35. The specific gravity of composite fine aggregate (as prepared by the procedure given above) shall be determined mathematically as well as experimentally as per IS 2386.

Based on the aforementioned trials on 70 different concrete mixes, rrecommendations for concrete mix design using coal based bottom ash as part replacement of conventional sand are that value of entrapped air supposed to be in case of non-air entrained concrete having 20 mm maximum size of aggregate (MSA), shall be taken as 1.50%. In case of availability of experimental site data (at least five air content values for similar mix), actual air content values can be used during concrete mix proportioning. The quantity of water for one cubic meter concrete having MSA 20 mm shall be kept as 194 kg/m^3. Aforementioned amount of water has been suggested for concrete mixes made using angular coarse aggregate, having initial slump value of 25 to 50 mm. The amount of water may be tentatively reduced by 10 kg, in case the aggregates are sub-angular in nature, by 15 kg in case of aggregates made up of gravel along with some quantity of crushed particles and approximately by 20 kg in case the aggregates are rounded gravel to generate similar degree of workability as mentioned in Indian Standard IS: 10262-2019. For each increase or decrease in slump value of around 25 mm, recommended value of water may either be appropriately increased or decreased by approximately 4 percent or it may be established by carrying out appropriate trials. Volume of coarse aggregate per unit volume of total aggregate for concrete mix at w/c of 0.50 and 20 mm MSA shall be 0.72, 0.70, 0.68, 0.66 and 0.64 for composite aggregate having fineness modulus of 1.33-1.69, 1.7-1.89, 1.9-2.09, 2.1-2.49 and 2.5-3.01 respectively as tabulated above in table 7. These suggested proportions may be duly adjusted for concrete mixes prepared at water-cement ratios other than 0.50. The aforementioned proportion of coarse aggregates shall be increased at rate of 0.01, for every decrease in w/c by 0.05 and decreased at rate of 0.01 for every increase in w/c by 0.05. Other mix design parameters, such as maximum water-cement ratio, target mean strength, selection of water cement ratio along with other calculations shall be as per IS 10262: 2019.

References

[1] Ojha PN, Singh B, Kaura P, Singh A. Lightweight geopolymer fly ash sand: an alternative to fine aggregate for concrete production. Research on Engineering Structures and Materials, 2021; 7(3): 375-392. https://doi.org/10.17515/resm2021.257ma0205

[2] Muthusamy K, Rasid MH, Jokhio GA, Mokhtar Albshir Budiea A, Hussin MW, J Mirza. Coal bottom ash as sand replacement in concrete: A review. Construction and Building Materials, 2020; 236:117507. https://doi.org/10.1016/j.conbuildmat.2019.117507

[3] Singh M, R Siddique. Effect of coal bottom ash as partial replacement of sand on properties of concrete. Resour. Conserv. Recycl, 2013; 72:20-32. https://doi.org/10.1016/j.resconrec.2012.12.006

[4] Singh N, Shehnazdeep B. Reviewing the role of coal bottom ash as an alternative of cement. Construction and Building Materials, 2020; 233:117276. https://doi.org/10.1016/j.conbuildmat.2019.117276

[5] Seals RK, Moulton LK, Ruth BE, Bottom ash: An Engineering Material. JSMFD, American Society of Civil Engineers, 1972; 98 (SM4): 311-325. https://doi.org/10.1061/JSFEAQ.0001741

[6] Andrade LB, Rocha JC, Cheriaf M. Aspects of moisture kinetics of coal bottom ash in concrete. Cement and Concrete Research, 2007; 37:231-241. https://doi.org/10.1016/j.cemconres.2006.11.001

[7] Ghafoori N, Bucholc L. Investigation of Lignite-Based Bottom Ash for Structural Concrete, ASCE J. Mater. Civ. Eng., 1996: 8:128-137. https://doi.org/10.1061/(ASCE)0899-1561(1996)8:3(128)

[8] Andrade LB, Rocha JC, Cheriaf M. Evaluation of concrete incorporating bottom ash as a natural aggregates replacement, Waste Manage., 2007;27(9):1190- 1199. https://doi.org/10.1016/j.wasman.2006.07.020

[9] Weber S, Reinhardt HW. A new generation of high-performance concrete: concrete with autogenous curing", Adv. Cem Mater., 1997; 6(2): 59-68. https://doi.org/10.1016/S1065-7355(97)00009-6

[10] Barbare N, Shukla A, Bose A. Uptake and loss of water in cenosphere-concrete composite material, Cement and Concrete Research, 2003; 33(10):1681-1686. https://doi.org/10.1016/S0008-8846(03)00148-0

[11] Kasemchaisiri R, S Tangtermsirikul. A method to determine water retainability of porous fine aggregate for design and quality control of fresh concrete, Construction and Building Materials, 2007;21(6):1322-1334. https://doi.org/10.1016/j.conbuildmat.2006.01.009

[12] Ghafoori N, Bucholc J. Investigation of lignite-based bottom ash for structural concrete", Journal of materials in Civil Engineering, 1996; 8(3):128-137. https://doi.org/10.1061/(ASCE)0899-1561(1996)8:3(128)
[13] Ghafoori N, Bucholc J. Properties of high-calcium dry bottom ash concrete, ACI Materials Journal, 1997; 94(2):90-101. https://doi.org/10.14359/289
[14] Chengzhi Z, Aiqin W, Mingshu T, Xiaoyu L. The filling role of pozzolanic material, Cement and Concrete Research, 1996; 26(6):943-947. https://doi.org/10.1016/0008-8846(96)00064-6
[15] Andrade LB, Rocha JC, Cheriaf M. Influence of coal bottom ash as fine aggregate on fresh properties of concrete, Construction and Building Materials, 2009; 23:609-614. https://doi.org/10.1016/j.conbuildmat.2008.05.003
[16] Kadam MP, Patil YD. Effect of sieved coal bottom ash as a sand replacement on properties of cement concrete, Magazine of Concrete Research, 2015; 67(5): 227- 234. https://doi.org/10.1680/macr.14.00179
[17] Kou SC, Poon CS, Properties of concrete prepared with crushed fine stone, furnace bottom ash and fine recycled aggregate as fine aggregates, Construction and Building Materials, 2009;23:2877-2886. https://doi.org/10.1016/j.conbuildmat.2009.02.009
[18] Gooi S, Mousa AA, Kong D. A critical review and gap analysis on the use of coal bottom ash as a substitute constituent in concrete. J. Clean. Prod. 2020: 268:121752. https://doi.org/10.1016/j.jclepro.2020.121752
[19] Bai Y, Darcy F, Basheer PAM. Strength and drying shrinkage properties of concrete containing furnace bottom ash as fine aggregate, Construction and Building Materials, 2005;19:691-697. https://doi.org/10.1016/j.conbuildmat.2005.02.021
[20] Nikbin IM, Saman RR, Allahyari H, Damadi M. A comprehensive analytical study on mechanical properties of concrete containing waste bottom ash as natural aggregate replacement", Construction and Building Materials, 2016; 121:746-759. https://doi.org/10.1016/j.conbuildmat.2016.06.078
[21] Singh M, Siddique R. Compressive strength, drying shrinkage and chemical resistance of concrete incorporating coal bottom ash as partial or total replacement of sand, Construction and Building Materials, 2014; 68:39-48. https://doi.org/10.1016/j.conbuildmat.2014.06.034
[22] Lee HK, Kim HK, Hwang EA. Utilization of power plant bottom ash as aggregates in fiber-reinforced cellular concrete, Waste Management, 2010;30:274-284. https://doi.org/10.1016/j.wasman.2009.09.043
[23] Ksaibati K, Stephen J. Utilization of Bottom Ash in Asphalt Mixes; No. MCP Report No. 99-104A. Department of Civil & Architectural Engineering, University of Wyoming: Laramie, USA; 1999.
[24] Singh N, Mithulraj M, Arya S. Utilization of coal bottom ash in recycled concrete aggregates based self-compacting concrete blended with metakaolin. Resour. Conserv. Recycl. 2019; 144:240-251. https://doi.org/10.1016/j.resconrec.2019.01.044
[25] Andrade, LB. Methodology of assessment to use of bottom ash of thermoelectric power plants as aggregate in concrete, M.Sc. Thesis, Department of Civil Engineering, Federal University of Santa Catarina, Santa Catarina, Brazil; 2004.
[26] Singh, B, Ojha PN, Trivedi A, Patel, V, Arora VV. Development Of Empirical Equations For Prediction Of Flexural And Split Tensile Strength For Normal And High Strength Concrete With Granite And Calc-Granulite Aggregate, Indian Concrete Journal, 2021: 95 (11): 36-46.
[27] Aggarwal P, Aggarwal Y, Gupta SM. Effect of Bottom Ash as replacement of fine aggregate in concrete, Asian Journal of Civil Engineering (Building and Housing), 2007; 8 (1):49-62.
[28] Arumugam K, Ilangovan R, Manohar JD, A study on characterization and use of pond ash as fine aggregate in concrete, International Journal of Civil and Structural Engineering, 2011;2 (2):466.

[29] Raju R, Paul MM, Aboobacker KA, Strength performance of concrete using bottom ash as fine aggregate", Int. J. Research Eng. Technol., 2014: 2:111-119.
[30] Jamora JB, Gudia Sel, Go AW, Giduquio MB, Loretero ME. Potential CO2 reduction and cost evaluation in use and transport of coal ash as cement replacement: A case in the Philippines. Waste Manag. 2020; 103:137-145. https://doi.org/10.1016/j.wasman.2019.12.026
[31] Ankur N, Singh N. Performance of cement mortars and concretes containing coal bottom ash: A comprehensive review, Renew. Sustain. Energy Rev. 2021; 149: 111361. https://doi.org/10.1016/j.rser.2021.111361
[32] Inayat A, Inayat M, Shahbaz M, Sulaiman SA, Raza M, Yusup S. Parametric analysis and optimization for the catalytic air gasification of palm kernel shell using coal bottom ash as catalyst, Renew. Energy 2020; 145:671-681. https://doi.org/10.1016/j.renene.2019.06.104
[33] IS 383. Coarse and Fine Aggregate for Concrete-Specification", Bureau of Indian Standards-New Delhi, India; 2016.
[34] Ojha PN, Trivedi A, Singh B, Singh A. Evaluation of mechanical and durability properties of concrete made with Indian bottom ash as replacement of fine aggregate, Journal of Asian Concrete Federation, 2020;6 (2):50-65. https://doi.org/10.18702/acf.2020.12.6.2.50
[35] Ojha PN, Singh B, Kaura P, Satyakam R. Ash Utilization Strategy in India-A Way Forward, In Advances in Sustainable Materials and Resilient Infrastructure, Springer, Singapore, 2022;145-157. https://doi.org/10.1007/978-981-16-9744-9_10
[36] Ojha PN, Kaura P, Kumar S, Jain H, Singh B, Mittal P. Design of low carbon high performance concrete incorporating ultrafine materials, Sustainable Structures & Materials, An International Journal, 2022; 5(1):1-12.
[37] IS 10262. Concrete Mix Proportioning - Guidelines", Bureau of Indian Standards- New Delhi, India; 2019.
[38] IS 269. Ordinary Portland Cement- Specifications", Bureau of Indian Standards-New Delhi, India; 2015.
[39] Arora VV, Singh B, Patel V. Durability and corrosion studies in prestressed concrete made with blended cement, Asian Concrete Federation Journal, 2019;5 (1):15-24. https://doi.org/10.18702/acf.2019.06.30.15
[40] Ojha PN, Trivedi A, Singh B, KNS Adarsh, Patel V, Gupta RK. High performance fiber reinforced concrete-for repair in spillways of concrete dams. Research on Engineering Structures and Materials, 2021; 7(4):505-522. https://doi.org/10.17515/resm2021.252ma0128
[41] Ojha PN, Singh B, Singh P, Singh A, Mandre MK. Study on effect of fly ash and limestone powder on compressive strength of roller compacted concrete for dam construction, Journal of Asian Concrete Federation, 2022;8 (1):37-50. https://doi.org/10.18702/acf.2022.6.8.1.37
[42] Ojha PN, Singh B, Singh A, Patel V, Arora VV, Experimental study on creep and shrinkage behaviour of high strength concrete for application in high rise buildings, Indian Concrete Journal, 2021; 95:2:30-42.
[43] Arora VV, Singh B, Patel V. Durability and corrosion studies in prestressed concrete made with blended cement. Journal of Asian Concrete Federation, 2019:5(1):15-24. https://doi.org/10.18702/acf.2019.06.30.15
[44] Arora VV, Singh B, Yadav L. Flexural and fatigue behavior of prestressed concrete beams made with Portland pozzolana cement. Journal of Asian Concrete Federation, 2016:2(1):15-23. https://doi.org/10.18702/acf.2016.06.2.1.15