Are existing IS codes suitable for engineering of HVFAC?

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Tracing back the history of the development of concrete, compressive strength was being considered as the most important parameter to classify this material since its inception. Even, in order to produce durable concrete, grade of concrete was generally increased, based on the perception that there was a direct relation between the strength of concrete and durability. It has been realised with experience that strength is not the only important parameter, other attributes such as durability and workability of concrete are also important for successful engineering of concrete structures. There are a number of cases of premature failure of concrete structures due to inadequate durability though concrete strength was high. This has led to the concept of developing high performance concrete (HPC). HPC is a concrete which is engineered to satisfy the criteria proposed to overcome the limitations of control concrete or normal strength concrete (NSC), in order to meet the requirements specific to its intended use. High volume fly ash concrete (HVFAC) is a type of HPC in which fly ash is used in higher quantity as supplementary cementitious material partially replacing Ordinary Portland Cement (OPC).

Concrete, be it NSC or HVFAC, is principally a three phase composite material consisting of a binding media within which particles or fragments of aggregates are embedded[1]. These three phases are bulk hydrated cement paste (HCP), aggregates and transition zone between bulk HCP and aggregate. The transition zone, also HCP but of inferior quality than that of bulk HCP, is the weakest phase from strength as well as durability point of view. It mainly consists of bulk quantity of calcium hydroxide crystal, voids, pores, microcracks, and water is present in plenty in this phase of microstructure. Improved properties of any concrete composite is achieved by modifying the microstructure, particularly that of transition zone by using chemical or mineral admixtures having pozzolanic characteristics. The mechanism which leads to the desired modification of the microstructure has three components[2],

(i) reaction mechanism among ingredients,

(ii) physical process, and

(iii) curing.

Reaction mechanism is basically related to chemical reaction among ingredients and related physical phenomena. Physical process, deals with different construction activities — production of fresh concrete, transportation and placement. Curing maintains the satisfactory condition so that reaction mechanism can be completed to a desirable state by preventing moisture loss and maintaining appropriate temperature during the process of hydration.

Fly ash is a fine-grained pozzolanic material, generally spherical in shape. Scanning electron microscope (SEM) images reveal that fly ash consists of either solid and/or hollow spheres. It is most probably the best mineral admixture to be used as supplementary cementitious material in concrete. In HVFAC, cement replacement level by fly ash is 50 percent or more and water-binder (cement plus fly ash) ratio is not more than 0.4.

From the consideration of reaction mechanism, the reactive silica of fly ash produces C-S-H gel after reacting with CH crystal generated from the primary hydration of OPC. In addition, unhydrated fly ash particles act as filler material in the microstructure. Such pozzolanic action causes improved microstructure of concrete composite, especially in transition zone by eliminating CH crystals, reducing voids and refining both grains and pores. All these result in concrete of higher performance (better rheology, strength and durability), preservation of resources (saving in limestone, coal and energy used in the production of OPC clinker). The material, HVFAC, is also environmental friendly as it is a highly productive and effective method of disposing fly ash in eco-friendly way and also reduce greenhouse gas emissions associated with manufacturing of OPC. In view of this, fly ash is also considered as resource material for sustainable development of a country like India[3].

Characterisation of materials to ensure proper quality of ingredient and their appropriate proportioning in the mix has strong impact on the reaction mechanism in developing HVFAC mix. Physical process, such as mixing method (manufacturing process), transportation and placement result in creating conducive conditions for reaction mechanism to take place appropriately for imparting the desired attributes of the mix. HVFAC mix needs to be cured adequately. Another important aspect is acceptance criteria. All these activities related to construction using HVFAC should be undertaken following well established specifications which are generally based on the codes and practice of the country. Are Indian Standard (IS) codes good enough for prescribing the requisite specification for engineering concrete structures using HVFAC? The objective of the present article is to assess the suitability of the existing IS codes having a bearing on fly ash concrete, especially HVFAC.

The ingredients for HVFAC are binder (OPC and fly ash), aggregates (coarse and fine), and water along with superplasticiser. Relevant IS codes of practice for specification of aggregates, water and superplasticiser have been successfully used over a long period for proportioning and producing acceptable concrete mixes without mineral admixtures. These standards were also successfully used in the recent past in developing high performance concrete incorporating silica fume and high reactivity metakaolin[4,5]. Transportation and placement of any concrete mix is related to rheology and workability of the mix. Mix proportioning has great influence on these two attributes of concrete mix at fresh state. Time for striking of shuttering is dependent on the strength gain of the mix after placement, which is again dependent on the mix proportion. In view of this, only those IS codes relevant to characterisation of fly ash, proportioning of HVFAC mixes and its acceptance criteria, mixing method and curing are deliberated below in the light of the findings of experimental studies presented in literature[3,6,7,8,9,10].

Characterisation of fly ash

As per IS 3812 : 2003 , the generic name of the waste product due to burning of coal or lignite in the boiler of a thermal power plant is pulverised fuel ash (PFA)[11,12]. PFA can be fly ash, bottom ash, pond ash or mound ash. 'Fly Ash' is the pulverised fuel ash extracted from the flue gases by any suitable process like cyclone separation or electrostatic precipitation. PFA collected from the bottom of boilers by any suitable process is termed as 'Bottom Ash'. The terminology 'Pond Ash' is used when fly ash or bottom ash or both mixed in any proportion is conveyed in the form of water slurry is deposited in pond or lagoon. When fly ash or bottom ash or mixture of these in any proportion is conveyed or carried in dry form and deposited dry, it is known as 'Mound Ash'. Use of fly ash as mineral admixture in structural concrete is acceptable as per IS 456[13]. However, the second revision of IS 3812 : 2003 encourages use of any type of PFA, in concrete provided it satisfies the requirements of the code[11,12]. Otherwise, the ash is to be processed.

IS 3812 : 2003 categorises fly ash into two types, namely, siliceous fly ash *(SFA)* having reactive calcium oxide content less than 10 percent and calcareous fly ash (CFA) having reactive calcium oxide content generally between 10 percent to 25 percent[11,12]. SFA type of fly ash is more suitable for HVFAC. ASTM C618-03 defines fly ash as finely divided residue resulting from the combustion of ground and powdered coal and transported by flue gas[14]. ASTM C 618-03 categorises fly ash into two classes; class F and class C, which are equivalent to SFA and CFA, respectively of IS 3812 : 2003. Canadian code also defines fly ash in a similar way as that of ASTM C618-03.

Results presented in reference 3 indicate that Indian fly ash possesses all the requisite characteristics needed for producing HVFAC of acceptable quality. The independent work of Fournier *et al* and Sivasundaram confirms this[6,7]. Bureau of Indian Standards (BIS) has published the specifications of pulverised fuel ash, IS 3812 : 2003 in two parts,

- Part-1: for use as pozzolana in cement, cement mortar and concrete
- Part-II: for use as admixture in cement mortar and concrete.

Both the parts of the code define fly ash as a special class of PFA. This code can be adopted for characterisation depending on its use as pozzolana or mineral admixture. However, the terminologies, pozzolana and mineral admixture, are sometimes ambiguously used as synonymous to each other. It is important to clearly understand the difference between these two types of usage, as there exist certain variations in specification given in the two parts of IS 3812 : 2003.

As per ASTM C125-02, admixture is a material other than water, aggregates, hydraulic cementitious material, and fibre reinforcement that is used as an ingredient of a cementitious mix to modify its freshly mixed, setting or hardened properties and which is added to the batch before or during its mixing[15]. Chemical admixtures like superplasticiser are water-soluble. The term mineral admixture has been used to refer to different types of water insoluble, finely divided materials such as pozzolanic materials, cementitious materials and aggregate. These materials are not similar and it is not correct to group them under a single term. The name of the specific material should be used; for example, use 'pozzolan' as is appropriate. Pozzolan is siliceous or siliceous and aluminous material, which itself possesses little or no cementitious value but will, in finely divided form and in the presence of moisture, chemically react with calcium hydroxide at ordinary temperatures to form compounds possessing cementious properties.

Mineral admixtures may be reactive or inactive in terms of cement hydration. Pozzolans or cementitious materials are reactive mineral admixtures, while finely divided aggregates are inactive. IS 3812 : 2003 allows the use of fly ash in concrete both as pozzolana (Part-I) and mineral admixture (Part-II). Both the parts of IS 3812 : 2003 specify detailed requirements on physical and chemical characteristics of fly ash. Amongst these, two requirements, the one on loss of ignition and the other one on the fineness are important. Requirement on LOI has significant bearing on durability, higher LOI could impede durability. Therefore, strict adherence to the requirement of LOI (5 percent) is very important. Fineness has influence on improving strength and also durability.

IS 3812 : 2003 specifies 34 percent retention of particles coarser than 45 µ in case of fly ash used as pozzolanic material (Part-I) and 50 percent retention for its use as mineral admixture (Part-II). Additionally, the standard also specifies the average fineness requirement as 320 m^2/kg for the use as pozzolana (Part – I) and 200 m^2/kg for admixture. Contribution of particles coarser than 45 µ to secondary hydration by means of pozzolanic reaction is not significant. Their incorporation in concrete mix may be viewed as replacement of sand. Therefore, particle size of 45 µ or less is more important for pozzolanic action than the average fineness of fly ash. ASTM C618-03 and Japanese code JISA 6201-99 do not specify the requirement on average fineness[13,16]. This requirement should be deleted from IS 3812 : 2003, otherwise it may create confusion.

Mix proportioning

There is a school of thought which subscribes to the view that IS codes do not allow more than 35 percent of fly ash in concrete. No IS code limits the quantity of fly ash to be used either as pozzolana or mineral admixture for replacement of OPC in proportioning the mix for structural concrete. However, IS 1489 (Part I) : 1991 specifies 35 percent as the upper limit of fly ash for blended cement, (Portland pozzolanic cement)[17]. The confusion might have originated from the footnote of *Table* 5 of IS 456[13]. The first footnote of the table states,

> "Cement content prescribed in this table is irrespective of the grades of cement and it is inclusive of additions mentioned in 5.2. The additions such as fly ash or ground granulated blast furnace slag may be taken into account in the concrete composition with respect to the cement content and water – cement ratio if the suitability is established and as long as the maximum amounts taken into account do not exceed the limit of pozzolana and slag specified in IS 1489 (Part-I) and IS 455, respectively" [17].

Intent of the footnote is only related to determination of the minimum cement content, maximum water-cement ratio and minimum grade of concrete for different exposures with normal weight aggregates of 20 mm nominal maximum size. As per this footnote, contribution of fly ash should not be taken more than 35 percent of the total cement content (binder: OPC + fly ash) in calculating the minimum cement content when CRL by fly ash is more than 35 percent. For example, in case of severe exposure condition, minimum grade of concrete and corresponding minimum cement content specified in *Table* 5, IS 456 is M30 and 320 kg/m^3, respectively[13]. If HVFAC mix is to be proportioned with CRL of 50 percent by fly ash, then binder (OPC + fly ash) content of 377.00 kg/m^3 is required to satisfy the minimum requirement of 320 kg/m^3 cement (OPC: 0.5 x 377.00 + fly ash: 0.35 x 377.0).

Another important aspect associated with mix proportioning is fixation of target strength. In this context, clause 4.9.2.2 of IS 456 specifies the following[15]:

> "The mix shall be designed to produce the grade of concrete having the required workability and characteristic strength not less than appropriate values given in *Table* 2. The target mean strength of concrete mix should be equal to the characteristic strength plus 1.65 times the standard deviation".[13]

Requirement of the first part is related to the acceptance criteria and needs to be adhered to for all types of concrete mix whether it is produced by hand mixing or through highly mechanised batching plant having high-speed mixer. The second part is desirable if hand mixing or other means is resorted to for production of concrete where higher uncertainties exist in achieving at site the same properties as determined at laboratory from trial mixes. But, this requirement is completely unnecessary when batching plant with high-speed mixer at site or ready mix concrete (RMC) is used. Canadian code A23.1-04 does not specify such requirements[18]. Experience shows concrete mix produced by high-speed mixer exhibit better properties than that of trial mixes conducted at laboratory. Application of this clause, irrespective of production mode would result in unnecessary use of higher quantity of OPC, which is not conducive for sustainable development of a country like India. The requirement of target strength shall not be considered as mandatory; mandatory requirement is the acceptance criteria.

HVFAC concrete shall always be produced in plant using mechanised mixer having weight batcher and not by hand mixing. The target strength for proportioning HVFAC need not be equal to the characteristic strength plus 1.65 times standard deviation. HVFAC is not expected to be economical for mix leaner than M30 and the target strength, if necessary for convenience of developing mix proportion, could be conservatively set at the value of 1.2 times the characteristic strength.

Mixing method

Manufacturing process of concrete mix involves stages of mixing (single stage or multistage) and agitation time in each stage. There are no IS codes which specify guidelines on the mixing method for concrete and hardly any published specification is available on this subject. However, research work indicates that mixing method has influence on the properties of concrete mixes including HVFAC mix[19]. Therefore, selection of appropriate mixing method is important for optimal utilisation of HVFAC.

The acceptance criteria of any concrete mix is specified in terms of 28 days cube compressive strength, refer *Table* 11 of IS 456. It is seen from the results mentioned in references and those results published in different literature that gain in strength and reduction in rapid chloride permeability test (RCPT) value of fly ash concrete from the age of 28 days to 56 days and beyond are substantial[3,6,7,8,9,10]. Moreover, no structure or structural component is subject to designed service condition at the age of 28 days. Therefore, acceptance criteria based on 28 days would lead to non-utilisation of all advantages of HVFAC. It is suggested to define the acceptance criteria based on 56 days properties or more. Canadian code A23.1-04 has already specified such acceptance criteria[18]. However, every care is to be taken to ensure that the mix gains requisite strength to withstand the effect of construction activities after the minimum period necessary for curing, that is, 14 days or after stripping of shuttering, whichever is earlier.

Curing

HVFAC mix has low w/b ratio that causes less bleeding resulting in potential risk of plastic shrinkage cracks if curing is not started as early as possible. This calls for initial curing, which should be started immediately after placing of concrete. No IS codes covers specification of initial curing and reference – 20 addresses initial curing of silica fume incorporated HPC in detail. Approaches suggested there have been found suitable for HVFAC. Covering surfaces with impervious sheet or applying curing compounds as in the case for concrete pavements are efficient methods for initial curing. After final setting of concrete, water curing should be commenced. Specification of IS 456 is sufficient for this purpose[13].

Conclusion

Based on the above discusion, following conclusions can be drawn.

(i) Existing IS codes are suitable for characterisation of concrete ingredients for HVFAC. Major observations on IS 3812 (Part - I and II) : 2003 specifications for characterisation of fly ash are,

(a) The standard specifies suitable requirements for characterisation of fly ash. Requirement mentioned about average fineness is not necessary and may be deleted.

(b) Most important requirement for characterisation of fly ash is to restrain the LOI to 5 percent.

(ii) IS codes impose limitation of 35 percent on the maximum usage of fly ash in Portland pozzolana cement but there exists no limitation on the quantity of fly ash in concrete mix, if it is mixed separately in site batching.

(iii) HVFAC should be produced in mechanised batching plant or RMC plant under necessary quality control. Target strength for developing HVFAC or any concrete mix produced by mechanised mixer need not be fixed at characteristic strength plus 1.65 times standard deviation. A conservative estimate of target strength is 1.2 times the characteristic strength for mix not leaner than grade M30.

(iv) From the point of view of economy, HVFAC should be characterised for 56-day strength. However, the mix should have required strength for construction purpose after the minimum period required for curing, that is, 14 days.

(v) Neither IS code nor codes of any other country provides guidelines on mixing method of HVFAC. Published work on this subject suggests mixing method has influence on the performance of HVFAC and other types of concrete mixes.

(vi) HVFAC should be cured in two stages. Initial curing is dry curing for which no specification is available in any IS code. However, specification of IS 456 on wet curing is adequate.

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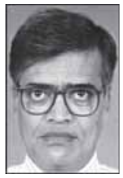

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