Influence of Curing Practices and Environment on Compressive Strength Development of High Strength Concrete

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Abstract: The paper presents the impact of practicing curing techniques on the compressive strength evolution of ternary blended high strength concrete under local prevailing environmental conditions. Initially the control mix was designed using the guidelines of IS: 10262:2009, whose compressive strength at 28 days is greater than 70 MPa. Later mechanical properties of high strength concrete after incorporating the alternative binder materials was evaluated. For all mixtures water to cement ratio was kept as 0.25. For the purpose of improving the mechanical properties of control mix and to achieve the economy slag, fly ash, quartz powder and silica fume were incorporated in the mix as partial substitution of cement. Total replacement with supplementary binders was kept at 20% by its weight of cement. Among all the combinations, silica fume and slag combination performed well in respect to the hardened properties. Subsequently, the same mix was considered in order to study the influence of practicing curing methods. From the results it was concluded that although type of curing regime on strength development both in indoor and outdoor environment at early ages was not considerable but at the later ages the effect was considerable. Compressive strength of specimens subjected to sprinkling, burlap and plastic cover curing in outdoor environment are significantly affected than the corresponding specimens in indoor environment.

Key words: Cement, Fly ash, Slag, Curing, Indoor, Outdoor, Silica fume

1. Introduction

Several benefits associated with the high strength in terms of improved mechanical properties, faster construction times, and reduced dead loads and economic benefits its usage now days it is becoming prominent. Increasing cement content beyond certain limit causes shrinkage and cracking problems resulting from higher thermal strains are the most common problems. Several techniques were employed in technique literature to minimize the autogenous shrinkage and cracking such as usage of fibers, replacing normal aggregate with saturated surface dry light weight aggregates [2, 3, 4]. However partial replacement cement by supplementary cementitious materials is one such alternative. Reduction in workability and strength of high strength concrete (HSC) due to the utilization of cementitious materials like blast furnace slag, fly ash can be effectively balanced by combining them with silica fume along with the use of superplasticizers [20, 21]. Earlier investigations revealed that use of 15% of natural pozzolana and 15% of silica fume combinations leads to very high compressive and tensile strengths of mortar and concrete rather than their individual usages [22]. Partial replacement of cement with blast furnace slag and silica fume by 15%
of weight improved the rupture, tensile and compressive strengths of HSC [18]. From the experimental investigation on the incorporation silica fume as partial replacement of 15% cement by weight culminated in enormous enhancement of split tensile, flexural and compressive strengths in addition to the modulus of elasticity of high strength concrete [1]. Enhanced mechanical properties of High strength concrete were observed when 2% by weight of cement is replaced with nano-silica. Improved durability characteristics such as better resistance towards chloride penetration, water absorption are also noticed when nano-silica is included [9]. From the point of view of enhancing the flexural, compressive and split tensile strengths an optimum replacement of cement was found to be 20% when fly ash was used as supplementary binder [6]. Use of 20 to 35% ultra-fine fly ash by weight cement enhanced resistance to chloride ion permeation in high strength concrete and non-evaporable water content in the cement paste [7, 8].

Curing Duration, the temperature allowed and the curing regime applied will have significant bearing on the development of compressive strength and durability of high-performance concrete [25, 26]. Vital role of curing in the compressive strength evolution of high strength concrete is highlighted in previous studies along with ill-effects of self-desiccation [21]. It was reported that the distribution of micro-cracks in high strength concrete is highly influenced by curing regime although the prior one did not have much influence on the permeability, compressive and tensile strengths [19]. Steam curing application on high strength slag concrete accelerates initial strengths and reduces the shrinkage but later stage strengths are relatively less than the standard water curing. High resistance to Carbonation, sulfate and free thaw resistance are also noticed when high strength concrete was subjected to standard curing [23]. The role of elevated curing temperatures on the strength properties of ordinary Portland cement concrete (OPC) and pulverized fuel fly ash (PFA) concrete were studied and results indicated that it is advantageous for pulverized fuel fly ash concrete but not in case of OPC due to induced thermal stresses [2]. The necessity of enlightening construction practitioners about the effectiveness of practicing curing methods was highlighted in the previous studies particularly in hot climates. Severe influence of hot environments on accelerated moisture evaporation and uneven distribution of hydration products was also examined [5]. The influence of low curing temperatures on ordinary and high performance concrete were compared and reported that the influence is low in later case due to less pores and low freezing temperature of mineral salts in the water in the capillary pores [12]. Inclusion of 1 to 2% nano-CaCO3 by weight of cementitious content resulted in smaller orientation index of CH and enhancement in the strength of HSC both at low and standard curing temperatures [24]. Partial replacement of cement by high reactive metakaolin enhanced the mechanical properties self-consolidated concrete at all ages under accelerated and standard curing regimes. The optimum temperature for accelerated curing was kept at 80°C [10, 11]. The present investigation is intended to examine the role of prevailing environmental conditions and curing practices available in the local regions on the strength evolution of High strength concrete(HSC). To achieve economy the HSC mixes were prepared using auxiliary binder materials namely slag, fly ash, quartz powder and silica fume. Optimum mix was selected among those combinations and the influence of curing practices was studied under local temperatures both in door and out door.

2. Materials and Mix Proportions

2.1 Cement and other alternative binder materials
53 grade OPC in accordance to IS 12269-1987 [17] was used in this experimental investigation. Silica fume, slag, Fly ash and quartz powder combinations were used as the partial replacement of OPC. The specific gravity and fineness of cementitious materials are provided in Table 1. Chemical composition of cement and other binding materials is shown in Table 2. Fly ash (FA) sample was collected at NTPC Visakhapatnam, A.P, India. Other supplementary materials namely quartz powder, silica fume, and slag are collected from nearby available sources. Fly ash and slag particles size lies in the range of 37 μm to 45 μm.
and 53 μm to 75 μm respectively. The particle size of quartz powder and silica fume ranges between 75 μm to 90 μm and 90 μm to 150 μm respectively.

**Table 1. Specific gravity and fineness of cementitious materials**

| Binder Material | Specific gravity | Specific surface (m²/kg) |
|-----------------|-----------------|--------------------------|
| Cement          | 3.12            | 300                      |
| Fly Ash         | 2.21            | 360                      |
| GGBS            | 2.89            | 315                      |
| Silica          | 2.3             | -                        |
| Quartz          | 2.5             | -                        |

**Table 2. Chemical configuration of binder materials**

| Oxides      | OPC | Fly Ash | GGBS | Silica Fume | Quartz powder |
|-------------|-----|---------|------|-------------|---------------|
| CaO         | 60.45| 1.41    | 34.61| 1.65        | -             |
| SiO₂        | 21.74| 58.13   | 34.4 | 91.7        | 97            |
| Mgo         | 3.38 | 0.71    | 8.83 | 1.78        | -             |
| Al₂O₃       | 6.61 | 32.55   | 16.3 | 1.1         | 0.4           |
| Fe₂O₃       | 3.71 | 4.044   | 0.68 | 0.92        | 0.07          |
| Na₂O        | 0.15 | 0.17    | 0.22 | -           | 0.15          |
| K₂O         | 0.2  | 0.96    | 0.63 | -           | 0.1           |
| SO₃         | 0.5  | 0.12    | 1.44 | 0.86        |               |

**2.2 Aggregates**

River sand obtained at local sources was used as fine aggregate whose fineness modulus and specific gravity is 2.39 and 2.65 respectively. Coarse aggregate with nominal size of 10 mm and specific gravity of 2.68 was used.

**2.3 Super-plasticizer**

For better workability of HSC mix CONPLAST WL a superplasticizer, having a specific gravity of 1.2 was added.

**2.4 Mix proportions**

Trial tests were conducted based on the guidelines of IS: 10262:2019 [16] method of mix design in order to fix the mixture proportions with the aim of obtaining targeted compressive strength and workability. OPC alone used for preparing control mix, for the other mixes blend of silica fume (SF), slag (S), fly ash (FA), and quartzite powder (QP) are used as a partial replacement of cement. For control mix the water to binder ratio and the slump were kept as 0.25 and 25 mm respectively. Table 3, denotes the mixture proportions of all the mixtures prepared. The control mix was designated as OPC as it does not contain any other cementitious materials and uses OPC alone. Combined weight of auxiliary cementitious materials was
kept as 20% by weight of cement. Mixes wherein fly ash and slag along with silica fume combinations as partial replacement were designated as C + FA + SF and C + S + SF respectively. The individual percentage replacements of cement by silica fume and slag (or) fly ash was 4 and 16% by weight of cement. Mix with blend of OPC, slag, silica fume (3%) and quartz powder (1%) is denoted as C + S + SF + QP. Addition of cementitious materials resulted in the reduction of the slump of concrete. Reduction of the slump may be ascribed to the reduced particle size since portion of water is adsorped onto the surface of finer particles.

Table 3. Mixture proportions (kg/m$^3$) of concrete

| Mix ID     | Cement (kg/m$^3$) | Fly ash | Slag | Silica fumes | Quartz powder | Coarse aggregate | Fine aggregate | Water | Slump (mm) |
|------------|-------------------|---------|------|--------------|---------------|------------------|----------------|-------|------------|
| OPC        | 600               |         |      |              |               | 1020             | 714            | 150   | 30         |
| C+FA+SF    | 480               | 96      | 24   |              |               | 1020             | 714            | 150   | 25         |
| C+S+SF     | 480               | 96      | 24   |              |               | 1020             | 714            | 150   | 27         |
| C+S+QP+SF  | 480               | 96      | 18   | 6            |               | 1020             | 714            | 150   | 23         |

3. Mixing Procedure and Specimen Preparation

A measured amount of the binder components, namely cement, fly ash, slag, silica fume (or) quartzite powder, was added to the mixer. Initially, the binder components were blended in dry condition. The fine and coarse aggregates were then added and mixed for yet another two to three minutes. At this point, super-plasticizer and potable water are added, and mixing continues for another two minutes. Cubes of 150 mm and 150X300 mm cylindrical moulds (IS: 10086-2008 [15]) were casted following suitable compaction. Moulds were then allowed to vibrate for 30 to 45 seconds. The specimens were then left alone for 24 hours. Similarly, prismatic moulds with dimensions of 100100500 mm (IS: 516-1959 [13]) were casted.

4. Curing

Moulded specimens kept for determining the mechanical properties were demoulded after 24 hours of air curing at room temperature. Specimens intended for evaluating curing regime influence of on compressive strength, were placed in the respective indoor or outdoor environment and allowed for setting. According to the selected method of curing, three of specimen faces were covered and the top-as-cast face was kept open and cured twice a day for a period of two weeks. Compressive strength of specimens was determined at 1, 3, 7, 14, 28 and 90 days of curing period. Curing procedures employed in this investigation and the designations of the specimens subjected to specific curing regime were outlined in Table 4.

Table 4. Description of the curing regimes used

| Specimen designation | Indoor Environment | Outdoor Environment |
|----------------------|--------------------|---------------------|
|                      | Process of curing application | Process of curing application |

4
NC_ID | Air curing in Indoors | NC_OD | Air cured in Outdoors
--- | --- | --- | ---
SC_ID | Sprinkling twice daily for two weeks without cover in Indoors | SC_OD | Sprinkling twice daily for two weeks without cover in Outdoors
BC_ID | Sprinkling twice daily for two weeks with burlap covers on three faces in Indoors | BC_OD | Sprinkling twice daily for two weeks with burlap covers on three faces in Outdoors
PC_ID | Sprinkling twice daily for two weeks with plastic covers on three faces in Indoors | PC_OD | Sprinkling twice daily for two weeks with burlap covers on three faces in Outdoors
OC_ID | Oven cured for 24 hours at 80°C and left for air curing without covers in Indoors | OC_OD | Oven cured for 24 hours at 80°C and left for air curing without covers in Outdoors

Specimens after air curing for 24 hours in indoor and outdoor are later cured by conventional process of immersing in water till the day of testing and these specimens are designated as IC_ID and IC_OD respectively. Average Indoor temperature during the curing period was noted as 28°C. Average temperature of the outdoor environment over a period of 28 days was found to be 37°C.

5. Testing Procedures
Compressive strength of specimens was evaluated in accordance to the stipulated procedures mentioned in IS: 516-1959 [13]. The split tensile and flexural strength tests were carried out at above mentioned curing periods to evaluate the strength progression of specimens in accordance with IS: 5816-1999 [14] and IS: 516-1959 [13] respectively. The test setup and the alignment of samples is as shown in Figure 1.

![Compressive strength test setup](image1.png)
![Split tensile strength test setup](image2.png)
![Flexural strength test setup](image3.png)

(a) Compressive strength test setup  (b) Split tensile strength test setup  (c) Flexural strength test setup

*Figure 1. Concrete samples arrangement for testing*

6. Experimental Results and Discussions

6.1 Compressive strength
Compressive strength for the casted cubical specimens was evaluated at the age of 3, 7, 14 and 28 days. Figure 2 denotes the compressive strength evolution of four concrete mixes. The compressive strength variation for the control mix at 3, 7 and 14 days of curing is 44, 64 and 87% of its 28 days strength.
Figure 2. Compressive strength progression of mixes with age of concrete

This trend shows that strength progression in high strength concrete is similar to strength evolution of normal concrete. Use of fly ash and silica fume results in better compressive strength than while using OPC due to refined micro structure caused due to the finer particle size of fly ash and slag. The rate of increments in the strength at 3, 7, 14 and 28 days, when 20% of OPC was replaced with fly ash and silica fume were found to be 17, 10, 5 and 6% respectively compared to control concrete. At 3, 7, 14 and 28 days of curing period, the percentage increase in the compressive strength of concrete were found to be 24, 11, 12 and 12% respectively, while 20% of cement is replaced with the slag and silica fume combination.

6.2 Split Tensile Strength

Figure 3. shows tensile strength development in case of high strength concrete (HSC) at the age of 3, 7, 14 and 28 days. Percentage increment in tensile strength of HSC was found to be 25, 15, 10 and 7 respectively while combination of silica fume and slag are used as 20% replacement. When silica fume and fly ash are used as partial replacement split tensile strength of HSC the percentage improvement in the strength was found to be 18, 12, 5 and 3 at 3, 7, 14, 28 days curing periods respectively. No significant improvements in tensile strength was observed when quartz powder, silica fume and slag combination was utilized as a partial replacement except at the very early curing periods.
Figure 3. Tensile strength progression of mixes with age of concrete

6.3 Flexural Strength

*Figure 4 shows the flexural strength results of various concrete mixes.* There was no significant change in the flexural strength development mainly at later ages of curing periods, when alternative binder combinations namely quartz powder, silica fume and slag are used as partial replacement of OPC. The percentage improvement in the flexural strength was 22, 10, 4 and 7 %, when silica fume and fly ash were used as partial replacement. Among all the above mixes the combination of OPC, silica fume and slag is found to be exhibiting better mechanical properties. Therefore, this specific mix was selected for studying the influence of curing practices on the compressive strength of HSC [27].
6.4 Weight loss in HSC Samples under different Curing Practices

Figure 5 and 6 shows weight loss of HSC specimens cured in indoor and outdoor environments. As expected the weight loss of specimens cured in outdoor environment was relatively higher than those cured in indoor environment.

It was observed that similar trends of weight loss can be observed for all specimens cured in outdoor environment regardless of curing regime applied. Weight loss of HSC specimen cured in indoor environment was more sensitive to the type of curing regime adopted. Weight loss of specimens in indoor environment is following the hierarchy mentioned below: OC, NC, SC, PC, BC and lastly IC. It can be understood that weight loss is inversely proportional to the water retaining capacity of surrounding media of curing in indoor environment. In case of outdoor environment the weight loss of specimens exposed to sprinkling, burlap and plastic curing is relatively less compared to the weight loss in oven and no curing conditions particularly at later ages of curing. This may be due to the continuous evaporation of moisture in the later specimens.
Figure 6. % Weight loss of HSC specimens cured in Outdoor Environment

6.5 Compressive strength of HSC Samples under different Curing Practices

Figure 7 depicts that in indoor environment at early age of curing the development of compressive strength of HSC specimens cured under sprinkling method, burlap and plastic covers is almost similar to the strength development of the specimens in conventional curing (or) immersion curing (IC). Beyond 7 days curing period the compressive strength of the conventional curing specimens is considerably higher than those specimens cured by sprinkling, burlap and plastic covers. However the compressive strength of cured by burlap covers is slightly higher than the specimens cured by plastic covers and sprinkling. This might be due to the relatively more water retaining capacity of burlap cover which enabled moisture to be available for further hydration process. It is evident from the Figure 7 that beyond 28 days curing period no significant increase in the compressive strength of HSC specimens cured by sprinkling, plastic and burlap covers, but in case of specimens cured by conventional process, a significant increment was observed in the compressive strength. The reason for this may be attributed to continuing hydration process beyond 28 days also.

Figure 8 illustrates for the same indoor environment, the compressive strength development of HSC specimens subjected to oven and air curing in comparison to those specimens with the standard water immersion curing. It can be noted that at the early curing periods the specimens under oven curing exhibits slightly higher compressive strengths than even water cured specimens. Beyond 7 days curing period the increment in the compressive strength of specimens in no curing and oven curing is not significant when compared to the strength development of specimens cured in standard water curing. This may be due to the accelerated hydration process under prevailing initial high temperatures and on the other hand in water cured specimens continuous improvement in strength implies a steady hydration process during curing period.

Figure 9 shows the strength development of outdoor environment specimens cured by sprinkling, burlap, and plastic covers in comparison with the specimens cured in water immersion. There is no significant variation in the strength development of SC, PC and BC specimens up 3 days curing period.
After 7 days the strength development of SC cured specimens was relatively lower than that of the PC and SC cured specimens. The relative merit of using covers which results in minimizing the evaporation losses can be noticed in this connection. On the other hand the strength evolution of PC and BC cured follows similar trends of course. BC cured specimens have slightly higher values than BC cured specimens.
Figure 9. Compressive Strength of specimens cured in Outdoor Environment

Figure 10 shows the strength development of air and oven cured specimens in outdoor in comparison with the specimens cured in conventional process (or) subjected water immersion curing. It can be noticed that specimens which are exposed to air curing exhibited low compressive strength. Oven cured specimens which exhibited relatively higher strengths in the beginning does not show much improvement in the compressive strength of HSC at later ages. This might be due to the reason that significant completion of hydration process in the beginning at high temperature.

Figure 10. Compressive Strength of Oven and No curing specimens cured in Outdoor Environment
Conclusions

- High strength concrete of strength up to 70 MPa was achieved using the guidelines of IS 10262:2007. It was noticed that use of 1% super-plasticizer along with 20% replacement of cement by mineral admixtures results in enhanced mechanical properties without much influence on workability.
- Improved early strength development resulting from the use of mineral admixtures will aid faster construction since the form work can be removed at early ages.
- Replacing 20% of the OPC in the HSC mix with silica fume and slag mixture led in higher compressive, flexural, and split tensile strengths as compared to a fly ash and silica fume mixture. Inclusion of quartzite powder has no discernible effect on hardened characteristics.
- Although loss in weight of specimens is relatively higher in outdoor environment, specimens cured in indoor environment more distinctive to type of curing regime adopted.
- Specimens under air and oven curing indoor exhibited relatively better strengths than in outdoor environment. This indicates presence of moisture in HSC helps in continuous strength evolution.
- Compressive strength of specimens in outdoor specimens subjected to sprinkling, plastic and burlap cover curing was significantly affected than the respective specimens in indoor environment specifically at later ages of curing.

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