DURABILITY OF CONCRETE MATERIALS FOR COMPONENTS OF HIGH RISE STRUCTURES

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Abstract

Globally, concrete is the most widely used construction material after water. Conventional concrete has traditionally been designed on the basis of 28 day compressive strength and may not meet the functional requirements of concrete structures like resistance to environmental & chemical attack, impermeability, shrinkage cracks, etc. This generally impacts the maintenance free service life of the structure. Normally in developing countries, concrete is specified in a prescriptive manner e.g. M-50. No other parameters for durability and performance are specified including the service life of the structure. As a result of this many times concrete meets the standard basic parameters but fails in meeting durability parameters or requirements. To counter the above requirements a shift to High Performance Concrete (HPC) is desirable. HPC should not be confused with High strength concrete. HPC is an engineered concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing and curing practices. It includes concrete that provides high strength, high early strength, ease in pumping and placement with or without vibration, resistance to segregation and bleeding, volume stability and resistance to shrinkage. It also enhances resistance to sulphate attack, alkali silica reaction, carbonation, chloride & corrosion induced disruption, low permeability and diffusion, high modulus of elasticity and lower creep coefficient, improved toughness, impact and abrasion resistance, enhanced resistance to freeze and thaw attack, higher durability and lower service life of structures. This article deals with the various durability aspects of High Performance Concrete in terms of mix design approach, testing & performance evaluation. As a case study this article emphasises on M80 free flow high performance concrete for shear columns & core walls and M40 temperature controlled concrete for raft foundations of high rise structures, which highlights the durability aspects holistically. The following criteria will be discussed in the article pertaining to ease of placement by using free flow or self-compacting concrete, Temperature controlled concrete for reducing core temperature and reducing the effect of thermal stresses on concrete and long term mechanical properties, which include Modulus of elasticity, drying shrinkage & creep in concrete.

Key Words: High performance concrete, Durability, Performance specifications, High strength free flow concrete, Temperature controlled concrete.

1. Introduction

Concrete is the most versatile material for construction in the world, after water. It is a material used in above ground, below ground, all types of waters, deep beneath the sea bed, in freezing zones and in all aggressive conditions where no other construction material has been found suitable. Concrete structures are built to function for an anticipated period of time with no demand for serious maintenance [1]. However, we have observed that concrete fails prematurely due to cracks, leaks, and spalls. Many a times the structure collapses before its anticipated service life leading to loss of life and property and also loss of reputation for all parties involved [2]. As of December-2016, Mumbai city alone has around 715 extremely dilapidated category buildings which have been served demolition notice by the municipal corporation[3]. These building are less than 50 years old and these structures have shown premature deterioration.

The durability of the reinforced concrete structures is affected by various factors, viz: Design Deficiencies, Environmental Conditions, Sulphate Attack, Chloride Attack, Corrosion of steel in concrete, Carbonation, Permeability, Leaching, Alkali- Aggregate reactions, Thermal damage, Plastic Shrinkage, Drying Shrinkage, failure Joints, Mechanical properties, Quality of Blending materials & Workmanship [4-5].

To enhance durability and increase the service life of concrete structures it is important to shift from the use of traditional concrete and adopt the use a High performance concrete which would meet the functional requirements of various structures [6]. There are several properties of High performance concrete and all the properties cannot be achieved at the same time. It should be designed with respect to the properties required in the type of structure under consideration.
2. High Performance Concrete

In the 1970's, in developing countries any concrete mixtures that showed 40 MPa or more compressive strength at 28 days were termed as high-strength concrete. In today's scenario, concrete of M60- M100 MPa and above, are being used in the construction of high-rise buildings and long-span bridges in many parts of the world.

American Concrete Institute (ACI) defines High Performance Concrete as a concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing, and curing practice.

High-performance concrete (HPC) is an engineered concrete which exceeds the properties and constructability of normal concrete. Normal and special materials are used to make these specially designed concretes which meets a combination of performance requirements. Special mixing, placing, and curing practices may be needed to produce and handle HPC. Extensive performance tests are usually required to demonstrate compliance with specific project needs.

High Performance Concrete is often confused with High Strength concrete. Though HPC may have a higher strength than normal concrete strength, it may not always be the primary requirement, e.g. a low strength concrete M-20 with very high durability and very low permeability is considered to have high performance properties.

Some of the properties of HPC include: ease of placement, compaction without segregation, high strength & high early strength, volume stability, high abrasion resistance, toughness and impact resistance, resistance to chemical attack, low permeability and diffusion, high modulus of elasticity, high resistance to frost and deicer scaling damage, high durability and long life in severe environments.

Concrete Materials for HPC

The durability of concrete is governed by its internal pore structure, porosity & permeability which depends on the raw materials used and its properties both in plastic and hardened stage. To achieve the desired properties of High Performance concrete mainly 3 aspects are to be considered; the hydrated cement paste needs to be strengthened, maximum particle size packing to be ensured and the transition zone needs to be further reinforced. The hydrated cement paste can be strengthened by increasing the quantity of Calcium Silicate Hydrate (C-S-H) gel through secondary hydration by using supplementary cementitious materials. These materials react with the soluble calcium hydroxide to form a crystalline C-S-H gel having lower gel porosity. Secondly, proper proportioning of aggregates and blending them with fine to ultrafine materials will ensure maximum particle size packing. For this purpose well graded aggregates manufactured in Vertical Shaft Impactor (VSI) crushers have to be used. Cement and supplementary cementitious materials like fly ash, Ultrafine fly ash, Granulated ground blast furnace slag (GGBS), ultrafine GGBS, Silica fumes, Metakolin, Rice husk ash, etc. will have to be used with a combination and predesigned proportion. Lastly, transition zone needs to be further reinforced by reducing the water/cementitious ratio in concrete. This can be achieved by using the fourth generation PCE (poly carbolic ethers) based admixtures. The materials used in HPC along with their properties have been given in Table 1.

| Materials       | Grade/Type                          | Specific gravity |
|-----------------|-------------------------------------|------------------|
| Cement          | UltraTech OPC53 confirming to IS-12269:2013 | 3.15             |
| Fly Ash         | Confirming to IS-3812:2013 Class F    | 2.2              |
| Ultrafine Fly Ash| Confirming to IS-3812:2013 Class F    | 2.2              |
| GGBS            | Confirming to IS 12089:1987 (R 2008)  | 2.9              |
| Ultrafine GGBS  | Confirming to IS 12089:1987 (R 2008)  | 2.9              |
| Silica fumes    | Confirming to IS-15388:2003          | 2.2              |
| Fine aggregates | As per IS 383-VSI crusher Zone-2     | 2.75             |
| Coarse aggregates| As per IS 383-VSI crusher 20/10 mm   | 2.85             |
| Admixture       | PCE based Confirming to IS-9103:1999 | 1.05             |

3. Case Study

As a part of our case study we will be emphasising on two properties of High performance concrete mainly High Strength free flow concrete and Temperature controlled concrete. We will be discussing two projects related to high rise residential towers in Mumbai, India where UltraTech Concrete has been successfully supplied from the commercial RMC plant, meeting the performance specifications of HPC as per the design criteria.

1. High Strength High flow M-80 grade concrete supplied to the columns and core walls of a 75 storied residential tower in Mumbai, India.
Temperature controlled M40 grade concrete supplied to the 3.5 meters deep raft foundation of a 55 storied Residential tower in Mumbai, India.

Fig. 1: Typical view of an RMC plant

Performance specification for High Strength High flow M-80 grade concrete for columns and core walls of a 75 storied residential tower in Mumbai.

**Properties of fresh concrete:**
- Flow of concrete minimum 500 mm after 3 hours, without initial segregation and bleeding. The same shall be tested in accordance to IS: 9103-1999 Annexure C.
- Placing temperature of concrete not more than 28°C
- Flyash not more than 35 % and GGBS not more than 70% Properties of hardened concrete:
- Minimum compressive strength of concrete cubes 88 MPa at 90 days, tested as per IS516
- Core temperature less than 70°C
- Differential temperature not more than 200°C
- RCPT as per ASTM C1202 & Water permeability as per DIN 1048 requirements of below 1500 coulombs & 25 mm respectively.

4. **Mix design approach**

Concrete supplied from Ultra Tech RMC confirms to the mix design guidelines as per IS 10262:2009 “Concrete mix proportioning-Guidelines”. The applicability of this standard has been specified for ordinary and standard concrete grades only (upto M-55 grade only). For the design of HPC determination of concrete rheology is the major factor in deciding quantity of cementitious materials. The various guidelines for durability in line with the requirements of IS456:2000 “Plain & reinforced concrete - Code of practice” are incorporated. The proportioning guidelines as per IS 10262:2009 for calculation the quantity of water and fine & coarse aggregates are used. Mix designs for M80 & M40 of Ultra Tech RMC are given in Table2.

| Grade of concrete | M80 | M40 |
|-------------------|-----|-----|
| Cement            | 300 | 190 |
| GGBS              | 240 | 200 |
| Fly Ash           | 65  | 150 |
| Ultrafine GGBS    | 45  | 0   |
| Water             | 150 | 125 |
| W/binder ratio    | 0.23| 0.23|
| Aggregate/binder ratio | 2.8 | 3.4 |
| Admixture dosage  | 1% (High PCE) | 1% (Mid PCE) |

Temperature controlled M40 grade concrete supplied to the 3.5 meters deep raft foundation of a 55 storied Residential tower in Mumbai, India.

**Properties of fresh concrete:**
- Slump of concrete minimum 150 mm after 3 hours, tested as per Is:1199
- Placing temperature of concrete not more than 28 °C Properties of hardened concrete:
- Minimum compressive strength of cubes 44 MPa at 56 days, tested as per IS:516
- Core temperature less than 700C
- Differential temperature not more than 200C
- RCPT tested as per ASTM C1202 & Water permeability as per DIN 1048 requirements of below 1500 coulombs & 25 mm respectively

Fig. 2 : Concrete mix design trails

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*Fig. 1: Typical view of an RMC plant*
5. Testing & evaluation

In wet/green stage:

The workability of concrete was evaluated by conducting flow test and slump test for M80 & M40 grade respectively. The flow of M-80 grade concrete was measured using a flow table as per the standard procedure of IS:1199-1959, the initial flow at the batching plant was between 700-750 mm without initial segregation and bleeding and flow measured after 3 hours or at placing point was between 500-550 mm. The slump of M-40 grade concrete was measured a slump cone as per the standard procedure of IS: 1199-1959, the initial slump at the plant was collapse and slump measured after 3 hours or at placing point was between 150-175 mm. The temperature of fresh concrete was between 20-27 °C depending upon the time of placing during the day and also the season of concrete placement.

In hardened stage:

The core temperature and temperature differentials were measured using thermocouples. The maximum core temperature recorded was 70 °C with a temperature differential of 200°C. The compressive strength of concrete was measured by casting standard 150 mm cubes as per IS: 516-1959 and testing at 3, 7, 28, 56 & 90 days for both the grade accordingly. The average strengths for M-80 were around 90 MPa at 90 days and that of M-40 were around 50 at 56 days. The concrete were also tested for durability parameters like RCPT which was around 900-1200 coulombs & waterpermeability 8-12 mm. The hardened concrete for M-80 was also tested for creep, modulus of elasticity & drying shrinkage to analyze the strain values considered in the design of the structure.

6. Major Challenges faced

The major challenge was to achieve the core temperature of both M-80 & M-40 grade of concrete less than 70° C. To achieve the desired compressive strength of concrete for M-80 & M-40 at 90 & 56 days respectively higher cement content was required which was resulting in an increase in the core temperature of concrete.

Though a combination of chilled water and ice flakes were used, it was a major challenge to maintain the placing temperature below 28 °C in peak Mumbai summers. Use of ice flakes was also resulting in lower batching efficiencies as the mixing time had to be increased 5 minutes, to ensure proper mixing.

For M-80 grade concrete the minimum flow at placing point had to be more than 500 mm as the pumping had to be done to a height of 150 meters for single stage pumping. For the floor height of more than 150 meters 2 stage pumping was used.

Managing heavy traffic issues in Mumbai, transportation of transit mixers in narrow crowded streets of Mumbai city, confined area for transit mixer movement at site, maintaining non-stop delivery of concrete to prevent setting of concrete in the pipelines and chocking of concrete pumps, maintaining the desired flow of concrete or slump at placing point for ease in pumping, etc. have been the major challenges in supplying of HPC from a commercial batching plant which is around 25-40 Kms away from the site.
7. Results & Discussions

The compressive strength of M-80 grade concrete was between 90-100 MPa at 90 days and that of M40 grade concrete was between 45-50 MPa at 56 days. The standard deviation of concrete was between 3.5 to 4 MPa, by maintaining good quality control right from raw material selection to final concrete placement.

As the depth of raft was 3.5 meters and least dimension of the core walls and shear columns were 3 meters, core temperature has been the major concern in addition to high strength. To control thermal shrinkage and achieve the desired compressive strength, the concrete has been designed to achieve the target mean strength at 90 days and 56 days for M-80 & M-40 respectively. The cement content in the mix had to be reduced and cementitious material content had to be increased to reduce the overall heat of hydration.

Considering the deteriorating effect of Mumbai’s coastal environmental conditions the durability parameters for RCPT were measured as per ASTM C-1202:1997 were well within limits (Actual values: 900-1200 coulombs). Also water permeability tested as per DIN 1048:1991 was below 25 mm (Actual values: 8-12 mm).

The use of cementitious materials like Fly Ash, GGBS, micro-fine GGBS & Silica fumes helps in achieving dense particle packing and eventually reduces permeability.

The hardened concrete for M-80 was also tested for creep, modulus of elasticity & drying shrinkage to analyze & compare the strain values considered in the design of the structure. As the exterior of the building has several architectural features and glass cladding these factors are of high importance in the service life of the structure.

8. Conclusions

This article provides an overview of high performance concrete for components of high rise structures, where both strength and durability is a necessity. In today’s world where buildings are being designed for a minimum service life of 100 years, strength of concrete alone is not the governing factor in design of concrete structures. Durability of concrete is of paramount importance, which directly reflects the service life of structures. Perhaps it is very easy to design a concrete for a particular strength criteria, however it is very difficult to produce a concrete with specified design or service life, particularly for an extended life time.

There is a major difference between high performance concrete & high strength concrete (HSC). HSC with higher permeability coefficient & high RCPT values would exhibit less durability when compared to a low strength concrete with low coefficient of permeability and low RCPT values. In this article we have discussed various aspects of HPC emphasizing on durability of concrete with performance specification like RCPT values less than 1500 coulombs & water permeability less than 25 mm. Over and above, the placing temperature of concrete has be below 280°C in order to achieve the maximum core temperature of 750°C with differential temperature between surface & core not exceeding 200°C. This kind of specification has resulted into high durability concrete for high rise towers discussed in the case study. Since considerable amount of supplementary cementitious materials like Fly Ash, GGBS, Silica Fumes have been incorporated in the concrete mix the strength of concrete is tested at 56 or 90 days instead of the regular 28 days testing, taking into account the secondary hydration process.

The overall mix design provided for M-80 & M-40 not only meets the strength criteria but also meets all the durability aspects like RCPT & permeability, though it is a challenging assignment.

Considering the overall benefits of HPC a paradigm shift is mandatory for all modern day concretes to move from prescriptive specification to performance ones.

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