



High Performance Concrete for Indian Nuclear Power Plants

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ABSTRACT: Inner containment dome of Reactor Building-II of Kaiga Project has been constructed using High Performance Concrete (HPC) of grade M-60 with microsilica and high range superplasticizers. This concrete was specially developed to cater to the design requirements of high compressive and tensile stresses coupled with workability, durability and impermeability. The structure was highly congested with reinforcement, prestressing cables and embedded parts, and concrete had to be placed at a height of 50 meters using concrete pumps and placers. This required a concrete mix of flowable consistency. A number of trials were carried out at Concrete Testing Laboratory of Kaiga Project to achieve the optimum mix proportions of the concrete. A few field trials were also conducted at the plant site to demonstrate the proper placement and compaction of concrete under field condition.

INTRODUCTION

High Performance Concrete (HPC) may be viewed as the concrete engineered to perform at or better than user's specification. There is no unique definition of HPC and it can be defined only with reference to the performance requirement of the intended use of the concrete. Therefore, in developing HPC for Indian Nuclear Power Plant (NPP) buildings and structures, the specific properties of concrete, which needs to be considered for the HPC, were first established¹. The mix design was also subjected to stringent field trials to examine its constructability.

Indian NPPs are based on pressurised heavy water reactor (PHWR). Major civil engineering buildings and structures of Indian NPP are reactor building, control building, service building, turbine building, spent fuel pool and building, stack, etc. The specific properties of HPC for the buildings and structures of Indian NPP encompass the requirements arising out of nuclear safety demand for civil engineering structures, design requirements (serviceability and strength), construction requirements and decommissioning.

Amongst all the major buildings and civil engineering structures of an NPP, the Inner Containment Structure (ICS) of Reactor Building is the most important one from the consideration of safety. It, alongwith other related system, provides the barrier between the reactor and the environment in the event of accident condition.

The specific properties which were considered in developing HPC for Indian NPP structure are summarized, from the above discussion, as high durability, moderate compressive and high tensile strength, high crack resistance and good impact resistance

characteristics, low permeability, low shrinkage, low heat of hydration, low creep and good workability. Therefore, the HPC for NPP structure has the following properties:

- Moderate compressive strength and high tensile strength
- Very high durability
- Low creep, shrinkage and heat of hydration.
- High workability with good rheology

Strategy adopted for the development of HPC mix, satisfying the above properties, for the IC Dome of Kaiga Project Unit-II and salient features of the mix design are presented in this paper.

STRATEGY OF DEVELOPMENT OF HPC

Concrete having above properties can be achieved by reducing the quantity of pore space and making pore size distribution more uniform. This is done by using mineral admixtures, which has properties of the pozzolana and also with or without filler attribute. Microsilica is used for this purpose to develop HPC for Indian NPP. Microsilica improves the strength of concrete by two mechanism; as a super pozzolana and as a filler^{2,3}. Various trials were carried out to arrive at the optimum mix proportions to achieve all the requirements of concrete. Concrete mix was designed to satisfy the following requirements.

- Characteristic compressive strength - 60 MPa
- Characteristic split tensile strength - 3.87 MPa
- Workability - 175 ± 25 mm
- Water permeability - penetration less than 25 mm

Mittal and Basu⁴ reported the mix design satisfying the above. Scope of the present paper is to describe how the mix design was developed at various stages. Total development work was carried out in three stages.

Stage 1: Preliminary trials to establish optimum quantity of cement, microsilica, admixture, sand etc. and to arrive at the candidate mix design.

Stage 2: Detailed trials on candidate mix to establish the properties of fresh and hardened concrete and statistical parameters.

Stage 3: Field trials on candidate mix to demonstrate that concrete can be placed and compacted under field conditions and for fine-tuning of the concrete mix.

SELECTION OF CONCRETE INGREDIENTS

For making high performance concrete, it is essential to select proper ingredients, evaluation of their properties and know-how about interaction of different materials for optimum usage. Mittal⁵ gave detail accounts of the ingredients used in developing the mix.

Cement: 43-grade cement was selected considering compressive strength at various ages, fineness, heat of hydration, alkali content, and compatibility with admixture.

Coarse Aggregate: 20 mm down crushed granite stones were used as coarse aggregates. Some important properties like crushing strength, durability, gradation, flakiness and elongation indices were given special consideration while selecting the aggregate for HPC. As the tensile strength of concrete was of prime importance, it is necessary to limit the quantity of flaky and elongated particles to 15% each for minimizing the weaker zone in concrete.

Fine Aggregate: River sand of 2.5 F.M. was used as fine aggregate. It was properly graded and washed at site to remove deleterious materials and chloride contamination.

Microsilica: Microsilica contains 85-95% of ultra fine solid, amorphous glassy microscopic spherical particles of silicon dioxide (SiO_2). Average particle size is 0.1 to 0.2 micron, which is similar to tobacco smoke and nearly 100 times smaller than cement grain. Specific surface of microsilica is 15-30 m^2/gm . The large surface area and high content of amorphous silicon dioxide gives microsilica super pozzolanic properties.

Admixture: High performance concrete has low water to binder ratio and ultra fine particles in the form of microsilica. Hence effective dispersion of cement and microsilica is necessary to achieve proper workability of the concrete without increasing the unit water content and cement content of mix. This has been achieved with the use of high range water reducing admixture; superplasticiser.

The optimum dose of admixture was evaluated by consistency test. At this dose it reduced water content of the mix by 35% and produced the concrete of flowable consistency. Retarder was also added to increase the setting time of concrete and improve the slump retention properties to avoid cold joints during construction.

Water: Potable water was found suitable for making HPC. The placement temperature of concrete has been restricted to below 23°C for reducing heat of hydration. This was achieved by replacing part of water with thin flakes of ice and pre-cooling of aggregates.

STAGE -1: TRIAL MIX

Mix design involves the proportioning of different ingredients of concrete in the optimum quantities based on their properties to achieve the concrete of specified strength, workability and durability. Target strength of the concrete is fixed based on the standard deviation. Considering good degree of Quality control⁹, which has been achieved in Kaiga Project Site in manufacturing concrete, standard deviation for compressive strength is assumed as 5.5 MPa and that for split tensile strength as 0.3 MPa. (Corresponding to approximately 7% coefficient of variation)

Target strength for compressive strength = $60 + 1.65 \times 5.5 = 69 \text{ MPa}$

Target strength for split tensile strength = $3.87 + 1.65 \times 0.3 = 4.37 \text{ MPa}$

As discussed earlier workability of the mix was a major consideration, various trials were carried out with cement content varying from 450 Kg/cum to 500 kg/cum and microsilica varying from 5 % to 15%; with a constant degree of slump at 175 mm; as shown in figure 1. From these trials it was established that 7.5% microsilica seems to be optimum for achieving the desired properties of concrete. Further trials were carried out using 7.5 % microsilica to establish strength versus water to cementitious ratio (W/Cm) curve for the same slump as shown in figure 2. From figure 2 it can be seen that for compressive strength requirement of

69 MPa, W/Cm ratio of 0.35 is sufficient. But based on the data available on split tensile strength, it was observed that this compressive strength level would not be sufficient to produce the concrete of desired split tensile strength. Hence W/Cm = 0.32 was selected considering high value of split tensile strength and low permeability of the concrete.

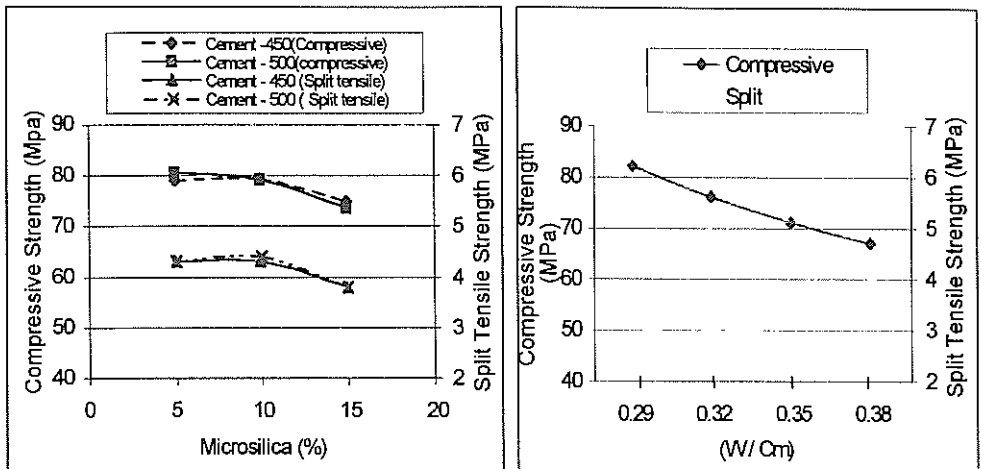


Figure 1 – Strength Vs Microsilica Figure 2 – Strength Vs W/Cm

Unit water content and sand percentage was derived considering the properties of coarse and fine aggregate, quantity of microsilica and admixture and workability of concrete. The candidate mix which was selected from the trial mixes for detail trial is;

Cement	: 475 Kg
Microsilica	: 35.6 kg
Water Ice	: 163 Kg
Coarse Aggregate	: 1092 kg
Fine Aggregate	: 659 Kg
Admixture	
<i>Superplasticizer</i>	: 8.0 Litre @ 2% by weight of cement
<i>Retarder</i>	: 0.4 Litre @ 0.1% by weight of cement
W\C	: 0.343
W\Cm	: 0.32

Air content for concrete mix with 20 mm down aggregate was assumed as 2%. Absolute volume method was used to determine the quantities of different ingredients. Preliminary trials were carried out to exactly determine unit water content, air content, sand percentage and workability of the concrete.

STAGE – 2: DETAIL TRIALS

Further trials were carried out to determine statistical parameters of compressive strength of cubes and cylinders, split tensile strength, and other properties of fresh and hardened concrete of the candidate mix. The salient properties of this mix determined from these trials are given below.

Properties of Fresh Concrete

Summary of the properties of fresh concrete of the candidate mix is given below in table 1.

Table-1: Test results of fresh concrete

Description of Test	Performance Standard	No. of samples	Average value	Requirement
Slump 0 min. (mm)	IS 1199	35	185	175± 25
30 min		35	130	125± 25
45 min		3	105	-
60 min		3	90	-
Air content (%)	IS 1199	35	0.95	2 %
Unit Weight (Kg/m ³)	IS 1199	35	2645	2425
Setting time (hrs:min)	IS 8142	3	6:20	-
Bleeding (%)	IS 9103	3	4.13	5% max.

Workability: Concrete mix was designed with initial slump of 175 ± 25 mm and observed values were well within this value. The slump after half an hour was 130 mm which was presumed to be suitable for site conditions.

Air Content and Unit Weight: Mix was designed assuming air content of 2 % for 20 mm aggregates concrete. It was observed that average air content of the mix was 0.95 %. This was due to the detrainment of air by the admixtures used. This reduction in air content has resulted in increased unit weight of concrete.

Normally, it is mistaken that the microsilica increases the density of the concrete. Microsilica only helps in proper distribution of hydration products and improvement of fine pore structure, resulting in the stronger and less permeable concrete, keeping the total porosity of concrete unchanged.

Setting Time: Through various trials, it was observed that use of microsilica slightly reduces the setting time of concrete. For proper placement and compaction of concrete at site without formation of cold joints, it was felt that the concrete should have an initial setting time of around 6 hrs. The Superplasticizer used was of Type F. Retarder was also added along with Superplasticizer in suitable dosage to achieve above setting time. The initial setting time and final setting time of the mix are 4 hours and 8 hours respectively.

Bleeding: Use of microsilica significantly reduces the bleeding of concrete due to large surface area of microsilica, there is very little free water left in the concrete mix for bleeding. The use of microsilica has resulted in uniform and cohesive concrete.

Properties of Hardened concrete

Summary of the properties of hardened concrete of the candidate mix is given below in table-2.

Table-2: Test Results of Hardened Concrete

Description of Test	Performance Standard	No. of samples	Avg. value	S.D.	C.V. (%)	Calculated Characteristic strength	Requirements
Cube compressive strength, 28 days (MPa)	IS 516	35	75.9	3.86	5.08	69.5	Min 60
Cylinder compressive strength, 28 days (MPa)	IS 516	35	61.2	3.64	5.94	55.2	Min 48
Split tensile Strength, 28 days (MPa)	IS 5816	35	4.36	0.26	5.86	3.94	Min 3.87
Flexural Strength, 28 days (MPa)	IS 516	2	5.83	-	-	-	-
Modulus of Elasticity, 28 days (MPa)	IS 516	2	4.41×10^4				
Water permeability	DIN 1048	2	Water penetration-Nil				
Note: S.D. = Standard Deviation (Mpa) C.V. = Coefficient of Variation							

Cube Compressive Strength: The average 28 days cube compressive strength achieved was 76 MPa with a standard deviation of 3.86 MPa and coefficient variation 5.08 %. With this the calculated characteristic compressive strength works out to 69.5 MPa which is much higher than the requirement of 60 MPa. Moving average chart of cube compressive strength is given in figure 3 and development of strength with age is given in figure 4.

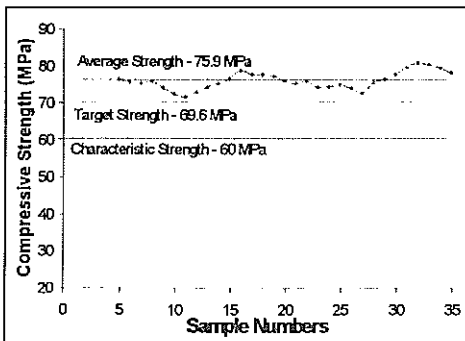


Figure 3 – Moving Average Chart for Cube Compressive Strength

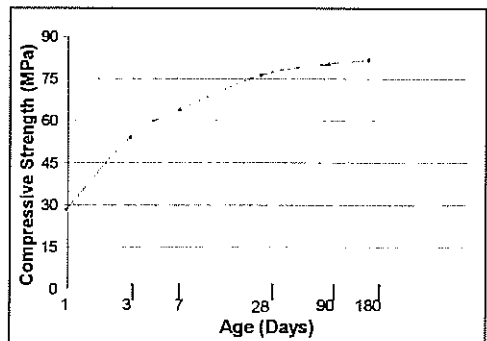


Figure 4 – Development of Strength with Age

Split tensile strength: Average split tensile strength achieved was 4.36 MPa with a standard deviation of 0.26 MPa. With this, the calculated characteristic split tensile strength works out to 3.94 MPa, which is marginally higher than the requirement of 3.87 MPa. Due to this, although compressive strength obtained was much higher than the requirement; W/Cm ratio could not be altered.

Flexural Strength: Flexural strength achieved was 5.83 MPa which is very close to the value calculated by the expression $0.7\sqrt{f_{ck}}$

Modulus of elasticity: Modulus of elasticity achieved was 4.407×10^4 MPa which is very close to the value calculated by expression $5700\sqrt{f_{ck}}$

Permeability: Tests for water permeability were carried out as per the test procedure given in DIN 1048. Water penetration was found to be practically nil in all samples.

STAGE – 3: FIELD TRIALS

After designing the concrete mix and establishing various parameters of fresh and hardened concrete in the laboratory by trial studies, a number of field mockups were done to demonstrate that concrete could be properly placed and compacted under field conditions⁶.

The concrete was pumped to a height of 50 m to check its pumpability characteristics. Wet sieve analysis of concrete samples before and after pumping ensured identical proportions. Concrete samples were also taken after pumping to the dome height and cured under field conditions to determine insitu strength. Average insitu compressive and tensile strength was 74 MPa and 4.34 MPa respectively which is comparable to laboratory values as given in table - 2.

During pumpability trials it was observed that for easy pumping and placement of concrete, slump at pumping point shall be minimum 120 to 140 mm and best results were obtained when it was around 175 mm. Hence it was decided to redose the admixture at site incase slump drops below 140 mm. It was confirmed through trials that redosing of admixture does not affect strength and other properties of concrete.

For these mockup studies, a portion of ring beam and a portion of dome near steam generator openings was selected, the latter being the most difficult portion for concreting in the whole structure. These mockups were simulated to site conditions (i.e. reinforcement, prestressing cables, embedments etc.) and were carried out using the actual construction equipments, which were proposed to be used in the actual construction. Through concrete cores were drilled at several locations to verify proper placement and compaction of concrete even in the congested areas.

CONCLUSION

Development of HPC in three stages has resulted in arriving at the optimum mix proportions, determining the properties of fresh and hardened concrete and also establishing the concrete mix under field conditions. Actual concreting work of Inner containment dome of Reactor Building -2 of Kaiga Atomic Power Project commenced on 6/1/98 and completed on 18/3/98.

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