Optimization and Experimental investigation of High-Performance concrete

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Abstract. This study presents to determine the optimum values of the design parameters in High-Performance Concrete (HPC). Three design parameters considered for this study, such as Binder/aggregate, Superplasticizers. An orthogonal array was formed with the help of design parameters; optimization was done using the Taguchi method. The mechanical properties were studied in different specimens with different fiber ratios. When the HPC has very high in compressive strength, at the same time, brittleness of the concrete also high. There is a need to improve the ductile of the high-performance concrete. Due to fiber added to the mix, it enhances the strength of the concrete. Fibers are used in concrete to control the concreting, better toughness. Fiber pullout and fiber debonding are two toughening mechanisms provided by the fibers in concrete. Microstructure Study was conducted by using SEM images; it gives the interaction between the materials in concrete. The experimental and microstructure models were compared in this study for M80 concrete.

1. Introduction
Concrete is an extensively used construction material, where it should withstand a maximum number of cyclic loads in the structures. Concrete generally contains several deficiencies like pores and internal cracks, etc. Failure in Brittle materials occurs suddenly without any indication [1]. Steel fibers have been added in the high performance concrete to avoid sudden failure in the structural components. These steel fibers help to bridge the crack from sudden failure. Steel fibers are of different types, but among them, hook end steel fibers are more suitable for the bridging of the crack is done with the help of hook end structure of steel fibers. While any failure occurs, this hook end steel fiber gets interlocked and helps from the failure of the structure. The increase in the bearing capacity under flexural loading since the addition of fiber strongly depends on the ratio between fiber reinforced concrete (FRC) toughness and reinforcement ratio [2]. Fiber-reinforced concrete (FRC) can alter the collapse mode of beam moving the failure from crushing of concrete to steel rupture. The behavior of beams containing through shaped fiber was superior to those beams containing the other two types of fiber viz straight and crimped fibers at 1% and 1.5% volume fraction.

For specific engineering applications, there are certain physical, mechanical properties to be considered [3]. Fracture toughness is one such property that is to be tested. There are several tests used to determine fracture toughness, among them the most often used method is using notched specimen

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as one of them is V-notch or U-notch. It will be impacted from behind the notch displacement test under a three-point beam bending test with microscopic thin cracks present in the specimens before application of load [4].

2. Taguchi approach
The purpose of this study is to incorporate parameters that usually has an impact on the strength characteristics of a high-performance concrete infused with different fiber ratios [5]. Further, the number of experiments is also minimized due to this study. The selected method for this optimization process is the Taguchi method with orthogonal array [6]. L9, to execute three parameters at once. The parameters are selected based upon there influence over the compressive strength of high-performance concrete. The parameters considered are binder/aggregate content, superplasticizer, and water/binder ratio, where all these parameters have a significant impact on the compressive strength of high-performance concrete. The levels of variations of the considered variables are shown in Table 1. The variables and levels which are determined for the orthogonal array are shown in Table 2. Once the mixing is done, high-performance concrete is allowed to initially set aside for 24 hours before the demoulding takes place. The hardened sample is then cured for 28 days in a freshwater tank. The temperature of curing is between 27°C to 32°C. The completely cured high-performance concrete specimens are then subjected to compressive strength tests to determine their compressive strength on 3rd day, 7th day, and 28th day consecutively. The specimen cast for the compressive strength test is 100 mm x 100 mm x 100mm cube specimens.

| Parameters          | Unit | Level 1 | Level 2 | Level 3 | Level 4 |
|---------------------|------|---------|---------|---------|---------|
| Binder/aggregate    | -    | 0.322   | 0.36    | 0.45    | 0.45    |
| Super plasticizers  | kg/m³| 6       | 6.9     | 7.1     | 7.7     |
| W/B Ratio           | -    | 0.3     | 0.27    | 0.28    | 0.22    |

| Table 2. Orthogonal Array. |
|---------------------------|
| Experimental Number | Binder/Aggregate | Superplasticizers | W/B Ratio | CA/FA |
|-----------------------|------------------|-------------------|-----------|-------|
| HPC1                  | 1                | 2                 | 1         | 2     |
| HPC2                  | 2                | 2                 | 1         | 3     |
| HPC3                  | 3                | 1                 | 2         | 4     |
| HPC4                  | 1                | 3                 | 1         | 2     |
| HPC5                  | 2                | 3                 | 3         | 3     |
| HPC6                  | 4                | 4                 | 3         | 3     |
| HPC7                  | 3                | 4                 | 4         | 1     |
| HPC8                  | 4                | 3                 | 4         | 1     |
| HPC9                  | 3                | 1                 | 2         | 4     |
3. Material Characterization
In This Study OPC grade, 53 was used along with Coarse aggregate of 12.5mm passing through and 10 mm retained was used. M-sand has used; the gradation of M-sand was done; it comes under zone II.

| S.No | Material                  | Properties       | Result | Standard values          | References         |
|------|---------------------------|------------------|--------|--------------------------|--------------------|
| 1    | Cement (OPC 53Grade)      | Specific gravity | 3.12   | 3.1 to 3.25              | IS 12269-2013      |
|      |                           | Initial setting time | 34 min | Min. of 30 min          | IS 12269-2013      |
|      |                           | Final setting time | 522 min | Max. of 600 min          | IS 12269-2013      |
| 2    | Coarse aggregate M sand (Zone II) | Specific gravity | 2.87   | 2.5 to 3.0              | IS 383-2016        |
| 3    | M sand                    | Specific gravity | 2.73   | 2.5 to 2.9              | IS 383-2016        |
| 4    | Silica fume               | Specific gravity | 2.2    | 2.2 to 2.3              | ACI 226-1988       |

Silica fume and Superplasticizer was intended for applications where extended workability and retardation are required. The main advantages of using superplasticizers are increased retardation controls the heat of hydration and yields high ultimate strength, arrest bleeding, and segregation due to the presence of in-built VMA [7]. Micro silica also used in this study.

4. Experimental investigation
A concrete grade of M80 was taken for this study. For these various materials. Mix design was done as per ACI. The values of silica fume were taken as 10% of the cementitious material, and the superplasticizer was 1% of the total binder content of the W/C ratio is 0.32 as per ACI 211.1[8]. Hooked end fibers were used in this study with the length 35 mm and diameter 0.55 mm. Mechanical properties were calculated in three Compression tests using 100 x 100 x 100mm cubes, Shear test using notched cylinders, Flexural test in notched beams.

4.1 Compression test
The compression test was conducted in Cubes of size 100 x 100 x 100mm with different fiber ratios of optimized mix design from the design of experiments.
The test was conducted in different fiber ratios with equal intervals up to 1.5%. The tests were conducted on 3rd day, 7th day, 28th day [9]. The compressive strength results increased while fiber content was 1% and decreases while fiber content reaches 1.5%.

### Table 4. Compressive Strength for Various HPC Mix.

| Mix type | Percentage of fiber | Density (kg/m³) | Compressive Strength (N/mm²) |
|----------|---------------------|-----------------|-----------------------------|
|          |                     |                 | 3rd Day | 7th Day | 28th Day |
| HPC1     | 0%                  | 2576            | 43.5    | 65.3    | 81.6     |
| HPC2     | 0.25%               | 2601            | 40.1    | 66.3    | 83.1     |
| HPC3     | 0.50%               | 2564            | 40      | 65      | 80.9     |
| HPC4     | 0.75%               | 2569            | 56.7    | 63.5    | 80.3     |
| HPC5     | 1.00%               | 2581            | 47.1    | 67.3    | 84.2     |
| HPC6     | 1.25%               | 2557            | 45.1    | 60      | 77.5     |
| HPC7     | 1.50%               | 2561            | 45.5    | 65.8    | 82.4     |
| HPC8     |                     | 2568            | 45      | 61      | 81.2     |
| HPC9     |                     | 2604            | 51.5    | 73.5    | 85.9     |

The test was conducted in different fiber ratios with equal intervals up to 1.5%. The tests were conducted on 3rd day, 7th day, 28th day [9]. The compressive strength results increased while fiber content was 1% and decreases while fiber content reaches 1.5%.

### Table 5. Compressive Strength for various HPC with Different fiber ratios.

| Mix | Percentage of fiber | Density (kg/m³) | Compressive Strength (N/mm²) |
|-----|---------------------|-----------------|-----------------------------|
|     |                     |                 | 28th Day |
| M1  | 0%                  | 2604            | 85.9     |
| M2  | 0.25%               | 2744            | 86.3     |
| M3  | 0.50%               | 2764            | 88.1     |
| M4  | 0.75%               | 2746            | 89.5     |
| M5  | 1.00%               | 2784            | 90.7     |
| M6  | 1.25%               | 2789            | 87.3     |
| M7  | 1.50%               | 2795            | 83.4     |

### 4.2 Shear test

The notched cylinders of size 250mm x100mm and notch size 10mm were cast and tested under the compressive testing machine, to find out the shear strength of the specimen. The shear test was conducted on notched cylinders using different fiber ratios and on plain concrete cement [10,11].
5. Fracture Study

To test the fracture toughness and fracture energy of a Notched specimen by conducting Three points bending test by adding different ratios of steel fibers (0.25%, 0.5%, 1.0%) and using high strength concrete of grade M80.[12] The geometry of notched specimen with 350mm x 100mm x 100mm and notch depth 35mm dimensions. The following figure dimensions are taken from the code of practice ASTM C1609. As fiber content increases, fracture energy decreases. In the same way, fracture toughness also decreases when fiber content increases. The following figures gives the idea on fracture energy specimen [15].

The following formulae give the fracture energy for the flexural beam using the three-point bending test (RILEM standards)

\[
G_f = \frac{W_o + mg \Delta}{A}
\]  

(1)

Where \(W_o\) = area under load, \(mg\) = self-weight of specimen, \(\Delta\) = max displacement, \(A\) = fracture area.
The following formulae give the fracture toughness for the flexural beam applying the three-point bending test. (RILEM standards)

$$K = \frac{Y}{\sqrt{\pi a}}$$  \hspace{1cm} (2)

Where \( Y \) = geometric factor, \( \sigma \) = stress, \( a \) = crack length

**Figure 3.** Notched specimen for three-point bending test.

| Specimen     | Peak Load (N) | Fracture Energy (N/m) | Fracture Toughness (MPa-m\(^{1/2}\)) |
|--------------|---------------|------------------------|--------------------------------------|
| PCC          | 5500          | 13.1                   | 0.76                                 |
| FRC-0.5%     | 6000          | 36.1                   | 1.27                                 |
| FRC-0.75%    | 17000         | 198.5                  | 2.37                                 |
| FRC-1.0%     | 10500         | 126.6                  | 2.9                                  |

6. XRD

The XRD results for M80 (7th day), respectively. It can be inferred that the percentage of quartz for HPC6 mix is higher than the HPC9 mix, which will be the aid for the hydration process occurring in the concrete. This excess silicon content will help in the formation of silicate hydrate products. In HPC6 mix major peak represents the element quartz corresponding (1 0 1) plane [ICSD = 01-085-0865] and the second major peak represents calcium aluminate silicate hydrate (2 2 2) plane [ICSD = 00-029-0373]. the other major role peak corresponds to ettringite at 18.061 and mullite at 22.970 etc.

In M 80 (HPC9 MIX) mix the major peak at 26.669 corresponds at 26.627 (1 0 1) plane [ICSD = 01-079-1912] and the next major peak is calcium hydroxide corresponding to peak 27.95° at (0 4 4) plane [ICSD = 01-072-0646], and the other major peaks of mullite, calcite referring to [ICSD = 00-015-0776] and [ICSD = 00-003-0596] respectively. So, the percentage of calcium silicate hydrate and calcium aluminum hydrate will be more for mix HPC9 due to excess of silica and aluminum content in the concrete mixture. Also, it can be confirmed from both the graphs that the ettringite and the calcium hydroxide content is high for mixture HPC6, which will be the major hindrance for the decrease of strength in HPC6 (7 days).
Figure 4. XRD Specimen at 7th Day of HPC6 Mix.

Figure 5. XRD Specimen at 7th Day of HPC9 Mix.

7. Conclusion

This investigative study is to determine an Optimized mix of High-performance concrete, which was achieved using Taguchi’s concept through various parameters affecting the compressive strength by infusing hooked ended steel fiber. The compressive strength of 85.90 N/mm² was attained in the optimum mix. It is observed that compressive strength is increased as the fiber content increases by up to 1%. Mix proportion having 0.75% fiber content shows best results in Shear strength by conducting the split shear test, and increasing the fiber content up to 1% increases the split tensile strength of the concrete. Under the microstructure study, the XRD test was done to determine the different chemical composition of high-performance concrete; it was found that C-S-H quartz formation is higher. Due to the increased accumulation of C-S-H directly causes the increase in strength of high-performance concrete. Whereas with 1.0 % fiber toughness was increased by 3.8 times when compared to conventional specimens.

8. References

[1] Sharma A Reddy G R Varshney L Bharathkumar , Vaze K K Ghosh A. K and Krishnamoorthy T. S 2009 Experimental investigations on mechanical and radiation shielding properties of hybrid lead–steel fiber reinforced concrete Nucl Eng Des. 239 1180-1185
[2] Meda, A Minelli F & Plizzari G. A 2012 Flexural behaviour of RC beams in fibre reinforced concrete Compos Part B-Eng.43 2930-2937
[3] Gettu R Bazant Z P & Karr M E 1990 Fracture properties and brittleness of high-strength concrete ACI MATER J. 87 608-618
[4] Arslan M. E Durmuş A & Hüsem M 2019 Cyclic behavior of GFRP strengthened infilled RC frames with low and normal strength concrete Sci Eng Compos Mater. 26 30-42
[5] Darmawan M S Bayuaji R Wibowo B Husin N A & Subekti S 2014 The Effect of Chloride Environment on Mechanical Properties Geopolymer Binder with Fly Ash Key Eng. Mater. 594 648-655
[6] Jaya N. A Abdulllah M M. A. B. RuzaidiGhazali C & Binhussain M. KamarudinHussin Romisuhani Ahmad and Januarti Jaya Ekaputri 2015 Correlation between Na2SiO3/NaOH and NaOH Molarity to Flexural Strength of Geopolymer Ceramic Appl. Mech. Mater. 754 - 755
[7] Shanmugam P & Gopalan S 2020 Effect of fibers on strength and elastic properties of bagasse ash blended HPC composites J Test Eval. 48
[8] Code of practice ACI-311326
[9] Zhang L Liu J. Liu J Zhang Q. & Han F 2018 Effect of steel fiber on flexural toughness and fracture mechanics behavior of ultrahigh-performance concrete with coarse aggregate J Mater Civil Eng. 30 04018323

7
[10] Rajkumar P K Krishnaraj L & Sundar C. S. 2018 Characteristic Studies on High-Performance Hybrid Fibre Reinforced Concrete Int J Pure Appl Math. 118 2147-2153
[11] Banthia, N. Majdzadeh F.Wu, J. & Bindiganavile V. 2014 Fiber synergy in Hybrid Fiber Reinforced Concrete (HyFRC) in flexure and direct shear Cem Concr Compos. 48 91-97
[12] Satyanarayan, L. Pukazhendhi D. M., Balasubramaniam K. Krishnamurthy C. V. & Ramachandra Murthy D. S 2009 Fatigue Crack Growth Measurements Using Ultrasonic and ACPD Techniques for Stainless Steel Pipes Narosa Publishing House
[13] Cement O. P. 2013 BIS: 12269-2013 Ordanary Portland Cement 53 grade-Specification, Bureau of Indian Standards New Delhi, India
[14] BIS I. (1970). 383 1970 Specification for Coarse and Fine Aggregates from Natural Sources for Concrete. Bureau of Indian Standards, New Delhi, India
[15] ACI Committee 226 1988 Use of Fly Ash in Concrete, ACI 226.3R-87 Makar, J. M & Chan G W (2009) Growth of cement hydration products on single-walled carbon nanotubes J Am Ceram Soc. 92 1303-1310