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A NEW MIX DESIGN METHOD FOR HIGH PERFORMANCE CONCRETE UNDER TROPICAL CONDITIONS

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ABSTRACT

High performance concrete (HPC) has become more popular in recent years. However, mix proportioning of HPC is a more critical process than normal strength concrete (NSC). Mix design methods of NSC are not directly applicable for designing HPC mixes.

Tropical countries usually show substantial variations in temperature and humidity. These variations have profound effect on properties of HPC as mix proportions are usually decided at laboratory conditions. Therefore, mix design of HPC in tropical climate requires special attention to incorporate the variation in its properties.

This paper presents a new method for proportioning HPC mixes considering effects of varying humidity and temperatures by exposing them to different artificially created environments. Proposed method is experimentally found to be valid and provides mix proportions giving desired workability and strengths.

Keywords: High performance concrete; mix design; temperature; relative humidity; tropical conditions.

1. INTRODUCTION

Concrete technology has been changing rapidly and constantly since its discovery. More and more concrete is used nowadays for infrastructure projects. High cost of such projects coupled with non replacement possibilities put higher emphasis on durability. Normal concrete, though versatile is not very suitable against severe aggressive conditions, chemical conditions and thermal stresses. High strength concretes were introduced few years back to take care of strength requirement for such higher durable structures. However, structures exposed to aggressive environments have revealed that high strength of concrete alone

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cannot guarantee long term performance. This fact has led to the development of high performance concrete (HPC) [1]. In the present scenario HPC is emerging as a construction material which will serve the basic dual purpose of strength and durability. However, the basic method of mix design of HPC has not yet been established as it includes other admixtures to serve the requirements of fresh and hardened concrete. These admixtures include silica fume, fly ash and plasticizer or super plasticizer (SP) [2].

The mix design of NSC is based primarily on the water-cement (w/c) ratio law first proposed by Abrams in 1918 [3]. In recent years, concrete mixture proportioning problem, which involves more variables than before has become more and more complicated [4]. However, for high strength concretes (HSC), all the components of the concrete mixture are pushed to their limits. In case of HPC there are many other factors to consider and hence selection of ingredients and their appropriate proportions is difficult. Also it is uneconomical and time consuming to use the traditional empirical approach of making alternative trial mixes of all possible combinations to arrive at the optimum mix. Thus, the procedures of existing mix design methods that are commonly adopted for designing NSC mixes cannot be directly applied for designing HPC mixes [5]. Mix design of HPC is different from that of usual concrete because of the following reasons [6]:

- Water-binder ratio is very low.
- Concrete quite often contains cement replacement materials that drastically change the properties of fresh and hardened concrete.
- Slump or compaction factor can be adjusted using high range water reducing admixture (HRWRA) without altering water content.

The mix design of HPC cannot be based on general tables and graphs. The mix has to be developed for the specific application and for the given set of ingredients. There are many popular methods of mix design of HPC such as method proposed by Aitcin [7], ACI [8], Mehta and Aitcin [9] among other methods. These methods have been in use successfully by the engineers over the years. However, these methods do not take into account the effects of humidity and temperatures. Several methods have been proposed over the years for proportioning of mineral admixture based HPC mixes. However, as on date there are no clear cut mix design procedures available for designing HPC mixes with an exception of some tentative procedures developed using fly ash and silica fume [10].

Tropical countries usually have different environments with varying humidity and temperatures [11]. The weather and environmental conditions at the time of casting of the concrete may require variation in proportions. Since water-binder (w/b) ratio significantly affects the properties of concrete in both fresh and hardened state, the variation in the temperature and humidity of the surroundings could significantly affect the properties if w/b ratio as per the mix-design is used. The water-cement (w/c) ratio and minimum cement content may also have to be varied for durability considerations. However, the various required performance attributes of HPC, including workability, strength, dimensional stability and durability, often impose contradictory requirements on the mix parameters to be adopted, thereby rendering the concrete mix design a very difficult task.

In the present paper a new method for proportioning HPC mixes of different grades (M50 to M90) considering climatic conditions of tropical countries is discussed. The developed mix design method is based on extensive experimental investigation and it follows the concept of Bureau of Indian Standards (BIS) Code, method of mix design (IS 10262) [12, 13]. The proposed method takes into account the effects of different variables namely, w/b ratio, relative humidity and temperature conditions and desirable contents of different material ingredients that affects mixture proportions.

2. PROPOSED MIX DESIGN FOR HPC

2.1 Methodology Adopted

A number of standard mix proportioning methods are available for conventional NSC. However, the well established mix design procedures for designing NSC mixes include method developed by BIS, American Concrete Institute (ACI), US Bureau of Reclamation (USBR) and Department of Environment (DOE), a British Standard method. All these existing mix design methods of NSC are not directly applicable for designing HPC mixes due to several reasons, primarily due to the presence of mineral admixtures. These methods have some common threads in arriving at proportions but their method of calculation is different. All these existing methods of mix design suffer from one or more limitations. The BIS and ACI method do not take into account the addition of supplementary cementitious materials such as fly ash, micro silica, ground granulated blast furnace slag (ggbfs), metakaolin etc. However, the DOE method, a British method of concrete mix design, utilizes British test data and can be used for concrete containing fly ash or ggbfs [14]. None of these methods provide the traditional curves expressing the relationship between w/c ratio and the strength by testing concretes made with chemical admixtures [10]. On the contrary HPC usually contains both pozzolanic and chemical admixtures. It has been an established fact that HPC mixes can be prepared without the use of mineral admixtures but cannot be without the chemical admixtures [15].

The mix design of NSC is based primarily on the w/c ratio. However, for high strength concretes, all the components of the concrete mixture are pushed to their limits. In case of HPC there are many other factors to consider and hence selection of ingredients and their appropriate proportions is difficult. Also it is uneconomical and time consuming to use the traditional empirical approach of making alternative trial mixes of all possible combinations to arrive at the optimum mix. Thus, the procedures of existing mix design methods that are commonly adopted for designing NSC mixes cannot be directly applied for designing HPC mixes [16].

Though, the use of mineral and chemical admixtures is permitted in the revised mix procedures of mix design methods (like IS10262-2009), these methods do not allow the use of two or more number of mineral admixtures. Also, these methods do not take into account the effects on the properties of concrete mixes due to the prevailing humidity and temperature conditions. A literature survey indicates that HPC mixes have been developed using existing mix design methods of NSC or by combining principles of one or more methods. Several researchers have proposed the methods for designing HPC mixes considering different mineral and chemical admixtures. However, none of them have proposed a method for proportioning HPC mixes by incorporating the effects of relative humidity and temperature for various grades of HPC.

2.2 Proposed Mix Design Method of HPC

The proposed mix design method for HPC mixes is based on the principles of existing IS

Code method of mix design (IS 10262-1982 and IS 10262-2009). The method proposed considers the use of micro silica as mineral admixture along with suitable superplasticizer and effects of varying humidity and temperature conditions. The method provides the established curves indicating different relationships such as w/b ratio, 28 day compressive strength, binder content etc. incorporating the effects of varying humidity and temperature combinations. Referring to these curves and relationships it is possible to arrive at the mix proportions that will provide the HPC mixes with desired workability, strength and durability properties. The curves developed indicating various relationships include the following:

Curves giving relationship between 28 days compressive strength and w/b ratio for different humidity and temperature conditions.

Curve giving relationship between binder content and w/b ratio.

Curve giving variation of Micro Silica content with 28 days Comp. St. of HPC.

Curve giving variation of SP for different Cement contents.

Curve giving ratio of volume of coarse to total aggregate and 28 days compressive strength.

3. EXPERIMENTAL PROGRAM

3.1 Materials

The various ingredients used in the study were based on extensive preliminary experimental work. Ordinary Portland cement of 53 grade conforming to IS: 12269-1987 [17] has been used throughout the experimentation. The locally available natural sand passing through 4.75mm IS sieve having fineness modulus of 3.20, specific gravity of 2.80 and conforming to grading Zone I of IS:383-1970 [18] was used. The sand was washed with clean water and dried in the sunlight before its use.

The cubical shaped coarse aggregates of two different fractions having specific gravity and fineness modulus of 2.90 and 7.125 respectively were used. Fraction I was obtained by passing through 20mm IS Sieve and retained on 12.5mm IS sieve and was taken at 60% of the total coarse aggregates content. Fraction II was obtained by passing through 12.5mm IS sieve and retained on 10mm IS sieve and was taken at 40% of the total coarse aggregates content. Micro silica (Grade 920-D) having specific gravity of 2.2 obtained from was used as a mineral admixture for developing HPC mixes. Polycarboxylic ether (PCE) type SP having specific gravity of 1.10 was used in the development of all the five grades of HPC mixes (M50 to M90).

3.2 Mix Proportions

The mix proportions for making different grades of HPC mixes were initially obtained by following the guidelines of IS Code method without considering any addition or replacement of mineral admixture (i.e. micro silica). However, mix proportions so obtained were required to be modified by varying contents of different ingredients and also by altering the ratio of fine aggregate to coarse aggregate in order to get desired workability and strength properties. After several trials, the desired quantities of cement, w/b ratio; micro silica and SP doses were finalized based on their desired workability (slump/flow) and 28 days compressive strength properties. The w/b ratio was calculated by dividing the weight of mixing water by combined weight of cement and micro silica.

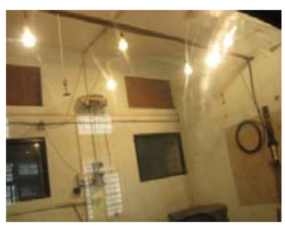
3.3 Preliminary Trials on HPC Mixes

Several preliminary trials were carried out to study workability and compressive strength properties of different grades of HPC mixes. During the extensive trial experimentation work carried out to study the properties of M50 grade HPC mixes under ambient humidity and temperatures, it was observed that the relative humidity and temperature conditions affects w/b ratio of mix leading to changes in various properties of the mix. Therefore, a detailed study of properties of different grades of HPC mixes (M50 to M90) was undertaken by exposing them to different humidity and temperature combinations in a room (Humidity Chamber) controlled for specific humidity and temperatures [Figure1(a)].

3.4 Humidity and Temperature controlling Room (Humidity Chamber)

In order to develop HPC mixes incorporating effects of varying humidity and temperatures an air tight room equipped with all the necessary machines for making HPC mixtures was erected in the laboratory [(Figure 1(a) and (b)] which can control the specified humidity and temperature condition. The machines / equipments such as Pan Type mixer, Flow Table, Table Vibrator, room heater, flood lights and lamps (1000W), ceiling fan, foggers; and humidity and temperature recording indicator (hygro-thermometer) duly provided with all safety measures were installed to prepare HPC mixes and to artificially create the environmental exposure conditions of specific humidity and temperature combinations [Figure 1 (c) to (g)].

(a) Exterior View of Humidity Chamber



(b) Interiors of Humidity Chamber

(f) Vibrator, Flow Table and Pan Mixer

(c) Room Heater

(d) Hygro-Thermometer

(e) Fogger

(g) Halogen Lamp (1000W)

Figure 1. (a-g) Details of Humidity Chamber

Based on results of trial measurements for variations in humidity and temperatures in the humidity chamber it became necessary to define the humidity and temperature values in a specific range. Humidity was defined by considering a permissible variation of ± 5%, whereas the temperature was defined by considering a permissible variation of ±0.5^{O}C. Thus, a humidity of 30% means the humidity variation, which has a range of 25%-30%-35% and a temperature of 30^{O}C means the temperature variation, which has a range of 29.5^{O}C-30^{O}C- 30.5^{O}C.

3.5 Preparation of HPC Cube Specimens

All the ingredients required for making HPC cube specimens were taken in appropriate quantities by weigh batching using digital weighing machine having an accuracy of 0.005kg. The measured quantity of coarse was added in the mixer followed by the required quantities of fine aggregates. The desired quantities of cement and micro silica were then added. All the ingredients were mixed thoroughly in dry state and then water was added for mixing. About 75% of the total quantity of water was added initially to the dry mix so as to get a homogeneous concrete mixture. A specified quantity of SP, measured by weight of cement and remaining quantity of water were taken, stirred well and then added to the already prepared wet mix in Pan Type mixer. Once again the concrete is mixed in wet condition so as to obtain a homogenous mixture. The mixing of ingredients was carried out for specified duration (approx. 3 minutes) in each operation.

Reference mixes for each grade of HPC were prepared under prevailing (ambient) humidity and temperature conditions in humidity chamber using predetermined w/b ratio and suitable SP content (by weight of cement) in order to get desired workability. HPC mixes were then prepared for each grade (M50, M60, M70, M80 and M90) in the humidity and temperature controlling room. All the HPC mixes of specified grade were prepared using the same mix proportion (as used in making reference mixes), w/b ratio and superplasticizer dose under different combined humidity and temperature conditions.

All grades of HPC mixes were exposed to a humidity range of 30% to 90%; and a temperature range of 30^{o}C to 45^{o}C. Humidity was varied by an increment of 10% whereas the temperature was varied with an increment of 5^{o}C. Thus, each grade of HPC (M50, M60, M70, M80 and 90) was exposed to a specific temperature of 30^{o}C, 35^{o}C and 40^{o}C for a set (range) of humidity conditions such as, 30%, 40%, 50%, 60%, 70%, 80% and 90%. Thus, for each grade of HPC and considering three specified temperatures (30^{o}C, 35^{o}C and 40^{o}C) and seven humidity values (i.e. 30% to 90% through an interval of 10%), in all 21sets of 3cubes (total 63 cube specimens) for each grade of HPC were prepared to study workability and strength properties of the HPC mixes subjected to varying humidity and temperature conditions in the room controlled for specified humidity and temperature. Therefore, for all the five grades of HPCs, a total number of (63x5) 195cube specimens were cast under specified humidity and temperature conditions. The reference mixes of each grade of HPC were also prepared additionally to perform compression strength test and four durability tests namely, sulfate attack, chloride attack, acid attack and chloride penetration tests. Thus, for performing compression test and durability tests of reference mixes of five grades of HPCs (M50 to M90) a total number of additional (3cubes x 5tests x5 grades)75 cube specimens were cast in the humidity and temperature controlling room.

The HPC mixes thus exposed to different combinations of humidity and temperatures were studied for their workability and compressive strength. The reference mixes of each grade of HPC were also studied for the workability, compressive strength and durability properties. The workability properties of all the mixes were studied by conducting slump and flow tests as per the standard procedure given in IS 1199-1959 [19]. Standard cube specimens of 150mm x 150mm x 150mm size were cast using the procedure described in IS:516-1959 [20] and were immediately covered with plastic sheet and kept in the humidity chamber for 24 hours and then released in water tank for 28 days curing. All the mixes were prepared in this chamber right from stage of mixing to the stage of compaction.

4. TEST RESULTS AND DISCUSSION

4.1 Workability

From the results of workability tests namely, slump and flow, it is observed that slump and flow values of all the grades of HPC mixes significantly increase with increase in humidity at a constant temperature.

4.2 Compressive Strength

From the results of compressive strength test it is observed that the compressive strength of HPC mixes is significantly affected by the variation in temperature and humidity. The results indicate that the compressive strengths of HPC mixes decreases for increased relative humidity levels under a specific constant temperature. This implies that the combined effect of humidity and temperatures on HPC mixes is necessary to be taken into account while proportioning HPC mixes at site, particularly in the context of tropical countries.

5. PROPOSED MIX DESIGN METHOD FOR HPC

The proposed mix design method for HPC mixes is based on the principles of existing IS Code method of mix design (IS 10262-1982 [12] and IS 10262-2009) [13]. In the development of this proposed method, the basic mix proportions were obtained for making HPC mixes using w/c ratio’s worked out by extrapolating the established relationships between free water cement ratio and concrete strength for different cement strengths given in IS Code (IS:10262-1982) [12]. The quantities of fine aggregate and coarse aggregate were determined using the equation given in IS Code method (IS: 10262-1982) [12].

The basic mix proportions thus obtained by following the guidelines of existing IS Code method were used in making trial HPC mixes by incorporating desirable contents of micro silica and SP in view of achieving the desired workability and strength properties. Further, based on experimental observations and results of compressive strengths of various grades of HPC mixes, the curves given in IS Code method are modified so as to arrive at w/b ratios best suited to different grades of HPC mixes (Figure2 to 4). From the experimental observations, the basic mix proportions adopted for making trial HPC mixes were modified by altering coarse aggregate to fine aggregate ratio and incorporating appropriate micro silica and SP contents so as to get desired workability and compressive strengths for different combinations of humidity and temperature.

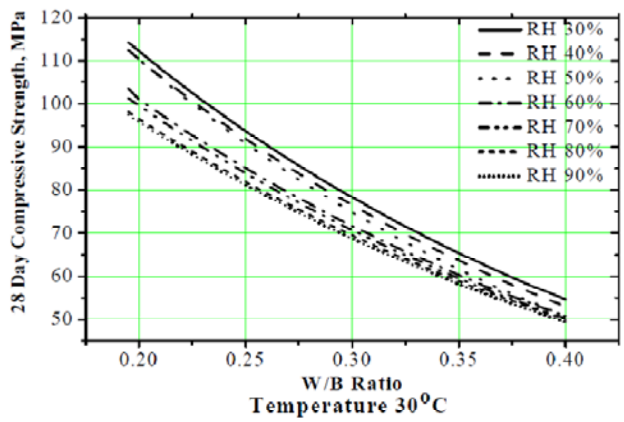


Figure 2. Relation between Comp. St. of HPC and W-B Ratio for different RH at $30^{O}C$

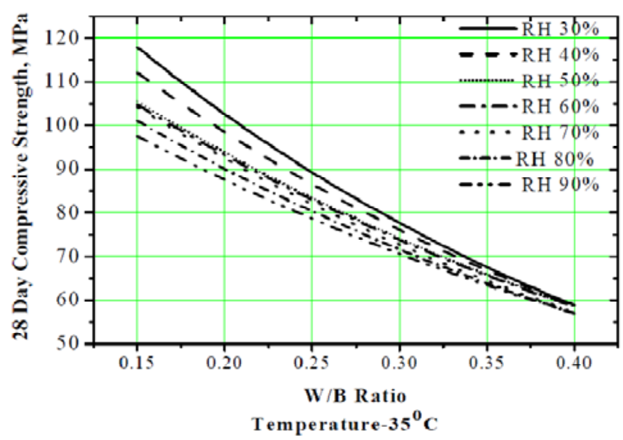


Figure 3. Relation between Comp. St. of HPC and W-B Ratio for different RH at $35^{O}C$

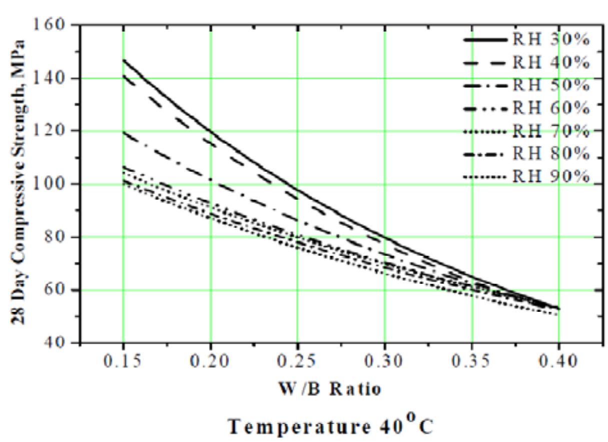


Figure 4. Relation between Comp. St. of HPC and W-B Ratio for different RH at $40^{O}C$

The proposed mix design method for HPC thus provides the final mix proportions taking into account the parameters or variables necessary to be incorporated in achieving the desired workability and strength properties for different grades of HPC mixes. The various variables or parameters considered in the proposed mix design method for HPC mixes are as given below:

Grade of the HPC mix under consideration
Desired workability for the mix
Prevailing Relative Humidity in the atmosphere
Prevailing Temperature in the atmosphere
Total binder content
Total cement content
Desired micro silica content
Desired water-binder ratio
Desired coarse aggregate to fine aggregate ratio
Desired SP dose (by weight of cement)

5.1 Stepwise Procedure of Proposed Mix Design Method for HPC

The mix design procedure consists of a series of steps, which when completed provide a mixture meeting strength and workability requirements based on the properties of selected and proportioned ingredients. Following are the necessary steps.

Step I: Test data for Materials

The test data of ingredients of HPC mixes namely specific gravity, fineness modulus; water absorption, moisture content etc. should be obtained.

Step II: Target Mean Compressive Strength of HPC

The target mean compressive strength at 28 days curing period for HPC mix is determined using the relationship given below:

$$f'ck = fck + 1.65\ x\ S \qquad (1.0)$$

where,

$f'ck$ = target mean compressive strength,

fck = characteristic strength of concrete (grade of concrete) and

S = standard deviation (as per IS 456-2000) [21]

As the strict quality control is necessary in making HPC mixes, the standard deviation (SD) is not likely to exceed 5 MPa [22]. Hence, a standard deviation value of 5MPa is assumed for arriving at target mean strength.

Step III: Determination of Water-Binder Ratio

The determination of w/b ratio is done by referring to the plotted relationships between the 28 day compressive strength of concrete and w/b ratios for different humidity and temperature conditions as given in the Fig. 2 to 4. These curves are developed through experimental work and extrapolation of the existing curves (IS Code).

Selection of Water-Binder Ratio

The maximum w/b ratio for different exposure conditions from view point of durability is to be adopted as per IS 456-2000. The values of w/b ratio obtained from the developed relationships taking into account the ambient RH and Temperature is compared with the values specified in IS 456-2000 for different exposure conditions and the value whichever is smaller is selected for designing the HPC mixes.

Step IV: Determination of Binder Content

From the w/b ratio obtained for the target mean compressive strength and for the specified humidity and temperature condition, the required binder content is determined based on the proposed relationship between binder content (cement + micro silica) and w/b ratio (Figure5). From the selected w/b ratio and the obtained binder content the total water content is calculated using the following relationship:

$$\frac{water}{binder} = water\ to\ binder\ ratio \tag{1.1}$$

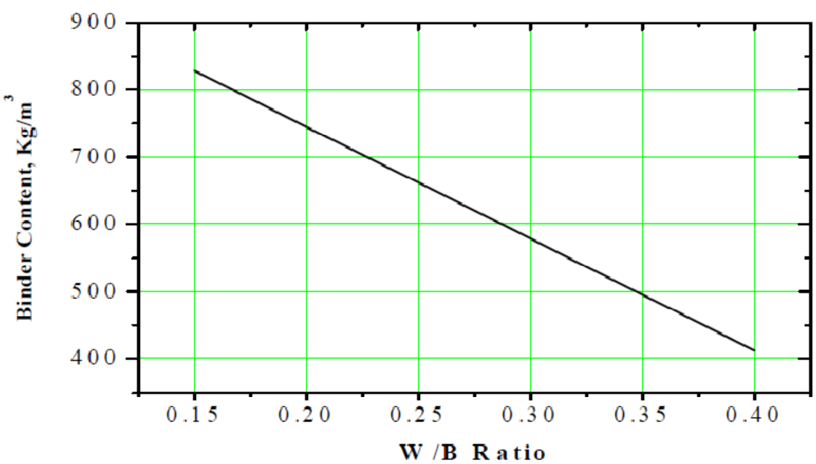


Figure 5. Variation of Binder Content with W-B Ratio for HPC mixes

Step V: Determination of Desirable Contents of Mineral Admixture (Micro Silica) and Cement Content

The desirable contents of micro silica required for making different grades of HPC mixes can be obtained from the established relationship of micro silica content and compressive strength of HPC (Figure6). Thus, knowing micro silica content, required quantity of cement can be worked out by subtracting micro silica content from the total binder content.

$$Cement\ Content = \ Total\ Binder\ Content - \ Micro\ silica\ content \tag{1.2}$$

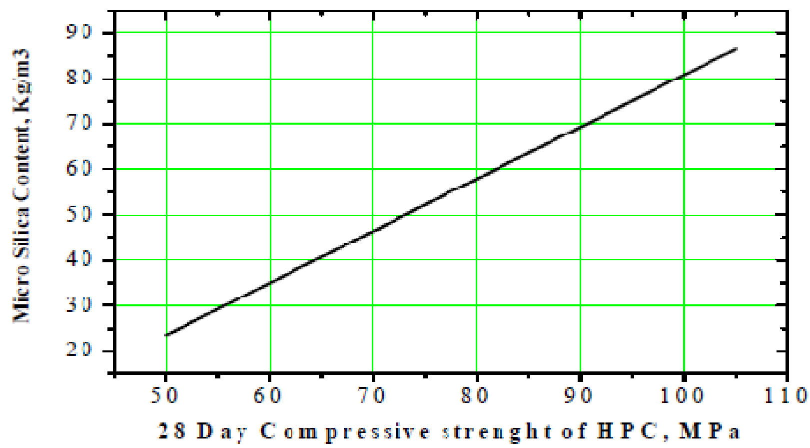


Figure 6. Variation of Micro Silica Content with 28 Day Comp St of HPC Mixes

Step VI: Determination of Desirable Contents of SP

The type and desired dosage of SP needs to be decided by trials to produce and maintain reasonable workability and enhance the strength of concrete when micro silica is used as a mineral admixture. Though, in market different brands of SPs are available, research and experience have indicated that admixtures based on polycarboxylic ethers (PCE) are the best suited as they have a water reducing capacity of 18%-40% in reference to the control concrete. In the present research work, HPC mixes have been developed using PCE based SPs. The dosage of SP was determined by weight of cement used for HPC mix. In the proposed mix design method the approximate SP dosages for different grades of HPC mixes corresponding to different w/b ratios can be obtained using the plotted relationship between SP content and cement content required for the specified grade of HPC mix (Figure7).

Step VII: Determination of Coarse and Fine Aggregate Contents

Taking into account the adopted volume of coarse aggregate in the total aggregate volume during the experimentation, a relationship between ratios of volume of coarse aggregate to the volume of total aggregate per unit volume of concrete (Figure8) is established for corresponding 28 days compressive strengths obtained.

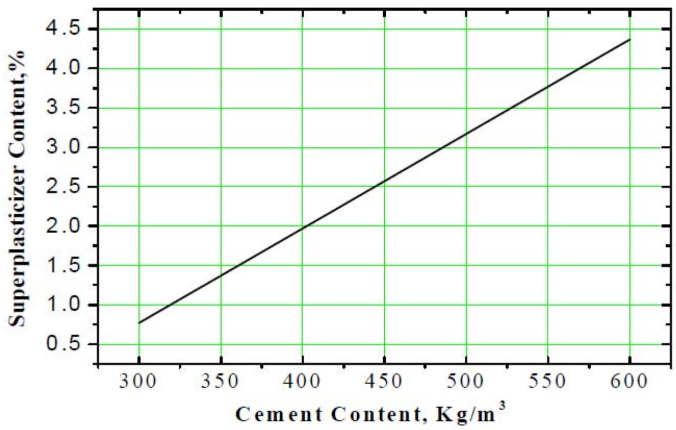


Figure 7. Variation of Superplasticizer Content with Cement Content

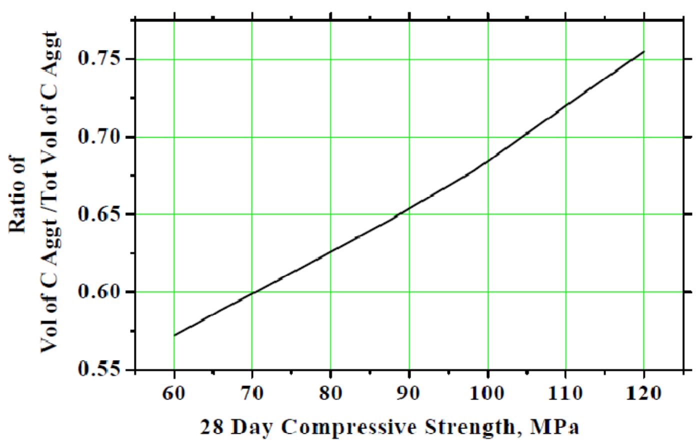


Figure 8. Comp St. Vs Ratio of Vol of CA to Tot Vol of CA

From the established relationship the ratio of volume of coarse aggregate to the volume of total aggregate is determined for the specified 28 days compressive strength of the concrete. Thus, the following variables required for mix design process are determined:

Water-Binder Ratio

Binder content = (Cement + Micro silica) content, Kg/m^3

Water Content = (water-binder ratio x total binder content), kg/m^3

SP (by weight of cement)

Total Aggregate Content

= Volume of Concrete – (water + binder + SP) content

CA / FA Ratio

Volume of Fine and Coarse aggregate

6. EXPERIMENTAL VALIDATION OF PROPOSED MIX PROPORTIONING METHOD FOR HPC

The mix proportions for different grades of HPC mixes are obtained by using the established relationships (curves) developed through experimental studies. The proposed method of mix proportioning of HPC mixes provides the mix proportions for different levels of humidity and temperature combinations for the grades of M50 to M90 HPC mixes. To verify the validity of the proposed mix design method, a trial HPC mix of M50 grade was prepared using the mix proportion obtained by the proposed method. The mix was designed for a slump range of 75-100mm considering a humidity of 80% with a temperature of 30^{o}C. The mix proportion, expressed as parts of water : binder content (cement + micro silica): fine aggregate: coarse aggregate, adopted for making the HPC mix was 0.36:1(0.93:0.07):1.81:2.29. A SP content of 0.56% by weight of cement was used as obtained from the mix design.

The trial mix produced using the above proportion showed a very good quality with a slump of 90mm and a flow value of 23.67% and a compressive strength of 54.07MPa at 28 days curing. The slump and flow tests conducted on the trial mix are shown in Figure9 and Figure10 respectively. Since the trial HPC mix prepared was found to give satisfactory workability with good flow property and also in a single trial for the mix proportion obtained by the proposed method, it can be stated that the proposed method of mix design is valid for proportioning HPC mixes for specified humidity and temperature conditions.

Figure 9. Slump Test of Trial HPC

Figure 10. Flow Test of Trial HPC Mix

7. CONCLUSIONS

Based on the observations and the test results of experimental work following conclusions are drawn:

1. Most of the existing mix design methods of HPC are not applicable for tropical climatic conditions due to wide variations in relative humidity and temperatures prevailing in different regions of tropical countries.

2. Various parameters or variables involved in the mix design process have not been quantified in the existing methods and are usually left to the judgment of designer.

3. The mix design method developed for HPC mixes in the present study involves the parameters like w/b ratio, ambient relative humidity and temperature, desirable contents of various ingredients, coarse to fine aggregate ratio suitable for tropical climatic conditions.

4. The mix design procedure is found to give the desirable design parameters in a minimum number of trials.

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REFERENCES

1. Shridhar R. Use of chemical admixtures in HPC for durable structures, *The Indian Concrete Journal*, **76**(2002) 579-80.
2. Krishnan B, Singh A, Singhal D. Mix design of high performance concrete and effects of different types of cement on high performance concrete, *Proceedings of National Conference on High Rise Buildings:Materials and Practices*, New Delhi, 2006, pp.11-18.
3. Shah S, Ahmad S. *High Performance Concrete: Properties and Applications*, New York, Mc-Graw-Hill Inc, Publication, 1994.
4. Bhanja S, Sengupta B. Review of classical water-cement ratio for present day high performance concretes and need for further research, *ICI Journal*, **6**(2005) 27- 9.
5. Gopalkrishnan S, Rajmane NP, Neelamegam M, Peter JA, Dattatreya JK. Effect of partial replacement of cement with fly ash on the strength and durability of HPC, *The Indian Concrete Journal*, **75**(2001) 335-41.
6. Laskar AI, Talukdar S. A new mix design method for high performance concrete, *Asian Journal of Civil Engineering (Building and Housing)*, **9**(2008) 15-23.
7. Aitcin P. *High Performance Concrete*, E & FN Spon, London, 1998.
8. ACI 363 R-92, State-of-the-art report on high strength concrete, ACI manual of concrete practice, part-I, *American Concrete Institute*, 1993.
9. Mehta PK, Aitcin PC. Principles underlying productions of high performance concrete, *Cement, Concrete and Aggregate*, **2**(1990) 70-8.
10. Ramarao GN, Seshagiri Rao MN. High performance concrete mix proportioning with rice husk ash as mineral admixture, *New Building Materials & Construction World*, **10**(2005) 100-8.
11. Patnaikuni I, Roy SK. High strength–high performance concrete for tropical climates, *Proceedings of International Conference on Maintenance and Durability of Concrete Structures*, JNT University, Hyderabad, India, 1997, pp.148-50.
12. Bureau of Indian Standard. Code of Practice for Recommended Guidelines of Concrete Mix Design (IS: 10262-1982), 1998.
13. Bureau of Indian Standard. Concrete Mix Proportioning - Guidelines (IS: 10262-2009), 2009.
14. Shetty MS. *Concrete Technology*. S. Chand and Company Ltd, Ramnagar, New Delhi, 2008, pp. 66-500.
15. Shridhar R. Use of chemical admixtures in HPC for durable structures, *The Indian Concrete Journal*, **76**(2002), 579-80.
16. Gopalkrishnan S, Rajmane NP, Neelamegam M, Peter JA, Dattatreya JK. Effect of

partial replacement of cement with fly ash on the strength and durability of HPC, *The Indian Concrete Journal*, **75**(2001) 335-41.
17. Bureau of Indian Standard. Specification for 53 grade Ordinary Portland Cement (IS: 12269 -1987), 1999.
18. Bureau of Indian Standard. Specification for Coarse and Fine Aggregates from Natural Sources for Concrete (IS: 383-1970), 1993.
19. Bureau of Indian Standard. Code of Practice for Methods of Sampling and Analysis of Concrete (IS: 1199–1959), 1991.
20. Bureau of Indian Standards. Code of Practice for Methods of Tests for Strength of Concrete (IS: 516–1959), 1999.
21. Bureau of Indian Standard. Code of Practice for Plain and Reinforced Concrete (IS: 456-2000), 2000.
22. Mullick AK. High performance concrete for bridges and highway pavements, *Advances in Bridge Engineering*, (2006) 51-63.

APPENDIX

Illustrative Example for Mix Design of M50 Grade Hpc Mix

An illustrative example for mix proportioning of M50 grade HPC mix using the Proposed Mix Design Method is presented below.

STIPULATIONS FOR MIX PROPORTIONING

Characteristic comp. strength: 50 N/mm^2

Maximum size of aggregate: 20mm (angular)

Degree of workability – (slump): 50-100

Degree of quality control : Good

Type of Exposure : Severe

Temperature : 30^{o}C

Relative humidity : 50%

TEST DATA OF MATERIALS

Cement : OPC – 53 Grades

Specific gravity of cement : 3.15

Specific gravity of coarse aggt : 2.90

Specific gravity of fine aggt : 2.80

Water absorption%

Coarse aggregate : 2.03

Fine aggregate : 1.48

Free (surface) moisture%

Coarse aggregate : 1.98

Fine aggregate : 1.33 (Confirming to grading zone I of table 4 of IS: 383-1970)

Target Strength for Mix Proportioning

$$f'ck = fck + 1.65 \times S$$

Where,

$f'ck$=target average compressive strength at 28 days

fck= characteristic compressive strength at 28 days.

S = Standard deviation (Table 8 of IS456-2000)
= 5 N/mm^2.

Therefore target strength

$f'ck$ = 50 + 1.65 x 5 = 58.25 N/mm^2

Selection of Water-Binder Ratio

Referring to the plotted relationship between 28 days compressive strength of concrete and w/b ratio (Figure 8) for a target mean compressive strength of 58.25MPa and for specified humidity level of 50% and 30^{o}C temperature a w/b ratio $\left(\frac{W}{B}\right)$ of 0.371 is obtained.

Determination of binder content, micro silica and cement

From the proposed relationship between binder content and w/b ratio (Figure 11) for a compressive strength of 58.25 MPa, binder content (cement + micro silica) of 460.28 Kg/m^3 is obtained. Also, referring to the established relationship between micro silica and 28 days compressive strength of HPC mixes (Figure 12) a micro silica content of 32.94 kg/m^3 (7.71%) is obtained. Thus, knowing the total binder content and the amount of micro silica in it, the quantity of cement required can be calculated by subtracting the micro silica content from the total binder content. Thus, the quantity of cement is calculated as given below:

$$Cement\ content = binder\ content - micro\ silica\ content$$
$$Cement\ content = 460.28 - 32.94 = 427.34\ kg/m3$$

Determination of desirable contents of sp

The desirable content of SP required for the desired workability is determined by weight of cement. The SP dosage is obtained from the established relationship between SP dosage and the cement content required to attain the specified compressive strength under given humidity and temperature conditions (Figure 13). Thus, from the calculated quantity of cement a SP dose of 0.54% is determined. The quantity of SP per m^3 of concrete is obtained as given below:

$$\text{SP content} = [\text{Cement Content x SP dosage (\%)}]\ /100\ = 2.3\ \text{kg/m3}$$

Determination of water content

From the obtained w/b ratio and binder content the required water content is calculated as given below:

$$\frac{water}{binder} = water\ to\ binder\ ratio$$
$$water = binder\ x\ water\ to\ binder\ ratio$$
$$water = 460.28\ x\ 0.371$$
$$water = 460.28\ x\ 0.371 = 170.76\ kg/m3$$

Proportion of volume of coarse aggregate and fine aggregate content

The estimation of volume of coarse aggregate in the volume of total aggregates is determined using the established relationship between 28 days compressive strength and ratio of volume of coarse aggregate to the volume of total aggregate per unit volume of concrete (Figure 14). Thus, for M50 grade HPC the ratio of volume of coarse aggregate to the volume of total aggregate per unit volume of concrete as obtained from the established relation is 0.55m^3. Hence the volume of fine aggregate is obtained as given below:

Volume of fine aggregate = (1- 0.55) = 0.45m^3

Mix calculation

Mix Calculations per unit volume of concrete shall be as follows:

$$a)\ Volume\ of\ Concrete\ \ = 1m3$$

$$b)\ Volume\ of\ cement\ \ = \frac{Mass\ of\ cement}{Specific\ Gravity\ of\ cement}\ x\ \frac{1}{1000}$$

$$= \left(\frac{427.34}{3.15}\right) \text{x} \frac{1}{1000} = 0.14\text{m3}$$

$$c) Volume\ of\ micro\ silica = \frac{Mass\ of\ Micro\ Silica}{Specific\ Gravity\ of\ Micro\ Silica}\ x\ \frac{1}{1000}$$

$$= \frac{32.94}{2.2} \text{x} \frac{1}{1000} = 0.01\ \text{m3}$$

$$d)\ Volume\ of\ water\ \ = \frac{Mass\ of\ water}{Specific\ Gravity\ of\ water}\ x\ \frac{1}{1000}$$

$$= \left(\frac{170.76}{1}\right) x \left(\frac{1}{1000}\right) = \ 0.17m3$$

$$e)\ Volume\ of\ SP\ = \frac{Mass\ of\ Superplasticizer}{Specific\ Gravity\ of\ Superplasticizer}\ x\ \frac{1}{1000}$$

$$= \left(\frac{2.30}{1.10}\right) x \frac{1}{1000} = 0.002m3$$

$$f)\ Volume\ of\ all\ in\ aggt\ \ = [a - (b + c + d)]$$

$$= [1 - (0.14 + 0.01 + 0.17 + 0.002)] = 0.68m3$$

$$g)\ Volume\ of\ fine\ aggt\ \ = 0.45m3$$

$$h)\ Volume\ of\ coarse\ aggt = 0.55m3$$

$$i)\ Mass\ of\ coarse\ aggt\ \ = 0.68\ x\ vol.of\ coarse\ aggt\ xSp.Gr.x1000$$

$$= 0.68\ x\ \ 0.55\ \text{x}\ 2.9 = 1084.60\ \text{kg/m3}$$

$$j)\ Mass\ of\ fine\ aggt\ \ = 0.68\ x\ vol.of fine\ agfingt\ xSp.Gr.x1000$$

$$= 0.68\ x\ \text{vol. of fine aggt x Sp. Gr. x1000}$$

$$= 0.68\text{x}\ 0.45\ \text{x}\ 2.8\ \text{x}1000 = 856.80\ \text{kg/m3}$$

Final Quantities of Ingredients and Mix Proportion

Cement = 427.34 kg/m^3

Micro Silica = 32.94kg/m^3

Water = 170.76 kg/m^3

Fine Aggregate = 856.80 kg/m^3

Coarse Aggregate =1084.60 kg/m^3

SP = 2.56 kg/m^3

Mix Proportion obtained is: 0.37:1 (0.93: 07):1.86:2.36

The mix proportions so obtained are adjusted for field conditions as per usual procedure before preparing trial mix.