Mixture design methods for high performance concrete:a review

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Abstract. Mixture design is a very important step in production and application of concrete. Many mixture design methods have been proposed for high performance concrete (HPC). This paper presents a critical review on HPC mixture design methods in publications. The procedures, advantages and disadvantages of each method were discussed. According to actual situations to obtain high quality HPC with satisfactory properties conveniently, the proportioning design methods of high performance concrete tend to computerization and standardization.

Introduction

Over the years, concrete has been used as a construction material widely, whether in moderate aggressive environments, or in strongly aggressive environments. It is attributed to the fact that it possesses excellent water resistance, can be moulded into any shapes, and for being cheaper and more easily available in the field[1, 2]. To illustrate such statement, it is estimated that more than 25 billion tonnes of Portland cement concrete is produced annually making it the world's most widely used manufactured material[3].

Besides the aspects mentioned above, the rapid surge of high-rise building challenge the technology of concrete construction, and also the form of high-rise building structure becomes larger and more complicated. Good workability is required to ensure the construction of concrete molding smoothly, higher mechanical properties should be guaranteed, in order to meet the load requirements of the building, and improved long-term resistance and durability satisfied the demand of longer building service life[4, 5]. Concrete emerged which possesses high strength, high performance, and high durability, named high performance concrete (HPC) by the developed countries based on durability of concrete structures at the beginning of 1990s[6].

With the emergence and development of this new advanced concrete, the problem of mixture design methods for the concrete becoming more and more complicated. Firstly, HPC is rich in content, which characterized by a superior level of properties: workability, strength durability and volume stability. Secondly, new components appeared, like organic admixtures, supplementary cementitious materials (as fly ash, filler, etc.) and fibers. Determined by high demanding of performance and characteristics in preparation, factors have little effect on ordinary concretes may affect HPC significantly, and laws applied in ordinary concretes may not work in HPC[7-9].

Restricting us to the aspects most commonly considered in mix designing, dry to ultra-fluid mixtures are available nowadays. Likewise, compressive strength from 1MPa to 200 MPa (for ultra-high strength mortars) ones have been used, e.g. in accordance with Domone and Soutsos[10], the optimization of the material proportions is harder for high strength concrete than for conventional concrete. Besides, many existing proportioning methods for concrete are based on data and knowledge of existing materials in a specific region or country, and generally are restricted to Portland cement, aggregates and water. To summarized, the problem of mixture design for HPC involves more variables and more dimensions in a larger space than before.

Overviews of HPC mixture design methods

There are many mixture design methods for HPC. Mehta and Aitcin[11] developed an approach on the basis of practical experiences. In 1990, the Laboratory Central des Ponts et Chausses (LCPC)[12] presented a new method capable of proportioning HPC mixtures with specified compressive strength and workability. Domone[13] introduced a process of HPC designing method derived from the maximum density theory. Chen J[14] proposed the overall calculation method which is generally applicable for all kinds of concrete. Lim C, e.g.[15] used genetic algorithm prepared economical HPCs. Moreover, there are some modified mixture design methods based on those existed methods[16-20]. The following sections discuss these methods in details.

Mehta/Aitcin method. There are some main points in Mehta/Aitcin method [11], a typical method based on practice experience of HPCs' applications. For HPC, it seems that 35% cement paste by volume represents an optimum solution in balancing the conflicting requirements of strength, workability, and dimensional stability. Water consumption and sand percentage in concrete can be determined according to strength requirement. The slump and maximum size aggregate (MSA) are not necessary for consideration since slump can be controlled by the superplasticizer dosage. Mineral admixtures are necessary to obtain technical benefits. The optimum proportion between fine aggregate and coarse aggregate is 65% by volume. Because of important parameters in the concrete mixture, such as ratio of water/cement, sand percentage, are determined primarily by assuming, so the initial mixture prepared without considering requirements of performance. A large amount of work should be taken if we want to get an optimal mixture.

Wang C[17] combined the Bolomey empirical formula with Mehta/Aitcin method, brought in a coefficient γ, related to the water-binder ratio, and a coefficient A, used for adjusting the activity of mineral admixtures. The strength of HPC mixes can be determined by modifying the Bolomey equation as

$$f_{cu,k} = \gamma \cdot \alpha_a \cdot f_{ce}\left(\frac{B}{W} - \alpha_b\right) \tag{1}$$

$$\gamma = -0.4952 + 5.514\frac{W}{B} \tag{2}$$

where the $f_{cu,k}$ is the required strength in MPa, α_a and α_b is the empirical coefficient as same as in the Bolomey empirical formula, f_{ce} is the compressive strength of cementitious materials in MPa.

Study found that water consumption related to water-cement ratio while keeping the cementitious material composition, while keeping the cementitious materials composition, water content and slump constant. Water consumption can be calculate by the formula

$$W_0 = k_1 + k_2\frac{W}{B} \tag{3}$$

Where the k_1 and k_2 are the constants determined by the cementitious material composition and the dosage of superplasticizer.

Comparing with the Mehta/Aitcin method, the modified method proposed formulas calculating water consumption and water-cement ratio, quantified the main parameters of HPC mix proportion. However, a lot of improvements still are needed for the empirical formulas, due to the empirical coefficients as γ are calculated by a certain amount of experimental data, therefore be updated based on test data constantly, and the formula only applied effectively for HPCs which water-cement ratio between 0.22 and 0.32. And in this range outside there are some limitations, still need more test data improvements.

LCPC method. LCPC method [12], mainly used to design concrete which strength between 60MPa~100MPa, give us a convenient way to design the high performance concrete mix proportion with two semi-empirical mix-design tools. The strength of the concrete is predicted by Feret's formula from a limited number of mix-design parameters. The workability is assumed to be closely related to the viscosity of the mix, which can be computed using the Farris model, a rheological model dealing with viscosity of a polydispersed suspension. The theoretical model and the empirical formula presented allows determination of the composition of concrete mixture having a given strength and workability with a minimal number of trial concrete batches.

Based upon these considerations, LCPC decided to develop concrete mixture-proportioning software[21-22]. One of products, proposed in 1992, was created for tutorial purposes. A sort of 'electronic laboratory' was given to the user, in order to allow him to cast concrete on his desk. Emphasis was put on the ease of utilization. After having filled up a small number of boxes dealing with the constituents, one could simulate the production of laboratory trial batches. The advantage was to immediately obtain the test results, with the drawback of limited precision of the simulations. But the aim was to provide the user with an understanding of the system behavior, so that he could efficiently react in a real situation. This product has been widely distributed in France (about 300 copies), and remains a suitable tool, especially for training students or professionals.

Compactness method. The compactness method，basing on the most density theory, can be described as follows[13]: (1) water-cement ratio should be determined according to the relationship between water-cement ratio and strength. (2) determining the dosage of superplasticizer. (3) in order to find out the sand percentage corresponding the minimum porosity, the porosities of aggregates are measured under different sand percentage. (4) testing the comprehensive effect of voids content and surface area. (5) determining the optimal sand percentage. This method is scientific because of taking full account of the density of concrete, which the performance, strength, volume stability closely related to can be well guaranteed.

Overall calculation method. The overall calculation method, proposed by Chen J[14], based on the volume model for concrete, not suitable for ordinary concrete, but applicable for designing proportioning of HPC, such as high flowing concrete, is a kind of extensively adaptable mixture design method. Through the volume model water consumption formula and sand percentage formula is deduced. The overall calculation method follows the same approach as Mehta's research results[11]. Keeping the ratio of cement paste and aggregate by volume 35:65 represents an optimum solution in balancing the conflicting requirements of strength, workability, and dimensional stability.

Overall calculation method was used by Jiang D[23] to design the self-compaction concrete. It was found that concrete mixture designed by the overall calculation method, consumption of components can be accurately calculated, workability, strength and durability of concrete can be guaranteed. With the generation of overall calculation method, HPC proportion designing developed from semi-quantitative to quantitative, from empirical to scientific.

Genetic algorithm. In recent years, with the continuous development of computer technology, genetic algorithm, a branch of artificial intelligence, closely related to the computer science has been widely used. Lim C H[15] proposed a mix design method for high-performance concrete using genetic algorithm, which is a stochastic search technique based on the mechanism of natural selection and natural genetics. First, large amount of sets mixtures should be used for this experiment program. Based on the results of mixing test, using SPSS, the fitness functions developed from the mixtures. After that, the fitness functions were applied in genetic algorithm, using MATLAB, and the results from genetic algorithm were compared to the sets of test mixtures for the verification and validity of the algorithm.

The genetic algorithm is used for high strength concrete mixture proportion design by Wang J[18]. Results indicated that the genetic algorithm decrease the cost of concrete 18.8%, ensuring the workability and mechanical properties meet the design requirements. As a branch of artificial intelligence, genetic algorithm is simple, universal, and high efficiency, will be applied to HPC design with optimized ratio will have broad prospects.

Overviews of HPC mixture design methods

The selection of mix proportions is the process of choosing suitable ingredients of concrete and determining their relative quantities with the object of producing as economically as possible concrete of certain minimum properties, notably strength, durability, and a required consistency[8,24]. Because the ingredients used are essentially variable and many of the material properties cannot be assessed truly quantitatively, selecting proportions for concrete can also be defined as the process of finding the optimum combination of these ingredients on the basis of some empirical data as stated in relevant standards, experience, and some rules of thumb.

Durability. HPC is proposed based on the durability of concrete structure, therefore, meeting the durability requirements, including impermeability, resistance to chemical attack, carbonation resistance, dimensional stability, is the first principle of HPC mix designing. Since most origin of the deterioration of concrete is due to the intrusion of harmful medium through the water, so the permeability resistance of concrete affects the durability of concrete directly.

Mechanical property. Mechanical performance is the most basic performance characteristics of concretes, which is the main structure in construction engineering material. With the rapid development of construction industry, a lot of tall buildings, large span bridge springing up, and higher strength requirements are put forward to HPC. It is generally believed that as long as the water-cement ratio is less than 0.40, HPC can be made by a variety of intensity levels concrete. The main factors affecting the strength of HPC are the water-cement ratio and the amount of mineral admixtures.

Workability. The workability of HPC is the key to ensure the quality of concrete pouring, the stand or fall of HPC workability directly determine whether the concrete can meet the required mechanical properties and durability or not. HPC has high liquidity, palpability, volume stability, and should have no segregation or bleeding at the same time. The factors affecting the HPC is the amount of cementing material, aggregate gradation, admixtures and dosage.

Economic efficiency. Mix Concrete Design is the decisive factor, but also determines the quality of the building project, but the economy is the direct target of the concrete pursuit of business. In order to meet the requirements of HPC performance, with design often involves more than the type of material, therefore, HPC Mix design economy more worthy cause for concern. Cause concrete failure are many, in addition to their own material, mixing ratio and other factors, there is the impact of external factors on the concrete, so, during the design process, to a comprehensive, systematic, scientifically considered, using reasonable measures to achieve the comprehensive economic indicators is effective.

Main proportioning parameters of HPC

Water-cement ratio. Low water-cement ratio is one of the characteristics of the preparation of high performance concrete. To achieve the low permeability of concrete and ensure its durability, no matter how much the design strength, water-cement ratio of HPC is generally not greater than 0.40, in order to ensure dense concrete. Practice has proved that, when the water-cement ratio dropped to 0.40, with the lower water-cement ratio, concrete strength was able to continue to improve. The reason is that, although incomplete hydration of cement, but lower water-cement ratio can reduce concrete porosity and pore size is reduced, but not the hydration of cement particles as a strong fine aggregate play its role. In the lower water-cement ratio (≤0.40) range, small changes in the water-cement ratio of concrete strength can make a large difference occurs, so it is a key point that controlling the water-cement ratio strictly to ensure the quality of concrete.

Cement paste -aggregate ratio. Mehta and Aitcin believe that ideal HPC mix can be prepared when using a appropriate aggregate, fixed cement paste-aggregate ratio as 35:65 by volume is a good way to balance contradictions belong the strength, workability and dimensional stability (modulus of elasticity, shrinkage and creep) of HPC. Generally speaking, the cementitious material consumption of HPC should be limited between 300 kg/m^3~500kg/m^3, and decreased with the decrease of concrete strength grade. To reduce the hydration heat and shrinkage, improve the ability of resistance to chemical attack, increase compactness, reduce cost, the Portland consumption in HPC should be minimized, replacing by the mineral admixtures.

Sand percentage. Sand ratio mainly affect the workability of concrete. The consumption of coarse aggregate in HPC should be a little bit more the traditional concrete. The optimal sand ratio of HPC ranges at different water-cement ratio. In general, with the increase of sand ratio of concrete, strength increases at first, and then decreases, while the elastic modulus is declining. Sand ratio of HPC can be selected according to total amount of cementitious material, the aggregate particle distribution , pumping requirements and so on.

Superplasticizer. In order to guarantee high strength and high durability, HPC should be prepared at low water-cement ratio and low water consumption, superplasticizer is the only way to achieve greater liquidity. Superplasticizer dosage should be determined according to concrete slump. In general, larger the dosage, higher the slump, but after more than a certain dosage, the effect is no longer significant, uneconomical.Main proportioning parameters of HPC.

Conclusion and prospects

Standardization. The problems of calculation of mineral admixtures content and HPC mix design still unsolved in the existing standards of concrete. HPC mix proportion was designed, before the concrete mix proportion adjustment, basing on experience, rather than on a unified theory like the Bolomey empirical formula for ordinary concrete， which is a simple and effective way to the mix proportion. Water-cement ratio is the determining factor of high performance concrete. HPC should be formulated considering the quality requirements and cementitious materials, water-cement ratio and the performance of superplasticizer selected, determining the cementitious materials consumption before water consumption, which is different from determining the water consumption first in the traditional concrete.

Computerization. HPC proportion designing includes not only concrete mix design, namely the proportions of the materials in the concrete, also includes computerized, a different developing direction rather than designing. components in the HPC makes the influential factors on the quality more complex, so computerized method was introduced, in order to improve the accuracy and economy of mixture designing. As Sandor Popovics, a famous American Concrete expert said: The future modern concrete technology must be that concrete computerized, mixed with chemical admixtures and mineral admixtures widely used.

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