Construction and Building Materials 182 (2018) 80–93

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

A new mixture design methodology based on the Packing Density Theory for high performance concrete in bridge engineering

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HIGHLIGHTS

- The 4-parameter CPM model was used for HPC mix design for the first time.
- A systematic method for HPC mix design with specific requirements has been developed.
- Mixtures designed by the proposed method have good performance.
- The proposed method is more efficient than the extensive series of trial batch tests.

ARTICLE INFO

Article history:
Received 13 May 2018
Received in revised form 7 June 2018
Accepted 8 June 2018

Keywords:
Concrete mix design method
Particle packing theory
Durability
High performance concrete
Compressible packing model

ABSTRACT

In this study, a new mixture design methodology based on the 4-parameters compressible packing model (CPM) of Packing Density Theory was proposed to satisfy the specific performance criteria of high performance concrete for prestressed concrete bridge construction. Iterative algorithms were developed to determine the parameter of critical cavity size ratio x_0 which reflect the crushed aggregate particles shape property and optimize the proportions of aggregates with different size range. After the optimization of aggregates, all the components in concrete were calculated. Thirty-one concrete mixtures with coarse aggregate from 5 different sources have been formulated according to this method to validate it both in fresh and hardened state. The workability, mechanical, and durability properties are verified during the slump, compressive strength, shrinkage, chloride-penetration resistance, and freeze-thaw resistance tests to characterize the obtained high-performance concrete. It is clear from the study that the proposed method is a successful theory for optimizing composition of high performance concrete.

1. Introduction

Concrete is one of the most widely used materials in bridge construction for its economic advantages, ease with manufacturing at the site, good durability. It is generally a combination of aggregate (fine and coarse aggregate), cement, water and admixtures (mineral and chemical admixture). Concrete mixture design is the process of selecting appropriate and economical combination of concrete ingredients using local materials to achieve desired properties. Good-quality concrete needs to be well mix designed for balance among the various desired properties, environment-friendly requirement and lower cost.

Attempts have been recorded in the past decades to improve the concrete mixture design methods, the followings are the dominant strategies: (i) Fully experimental methods which involve an extensive series of trial-error-adjust batch tests. Some parameter analysis results obtained by empirical relations, charts, graphs, and tables or Taguchi Method are used for reducing the number of trial mixtures [1,2]. (ii) Analytical methods, which replaced the time-consuming experimental work with a calculation process based on detailed knowledge of the relationship between components under certain basic assumptions and empiric formulas [3,4]. (iii) Numerical-experimental combination methods, which combine experiments data with mathematical programming, sometimes artificial intelligence algorithms can be employed to data analysis [5–7]. (iv) Statistical methods which introduce standard statistical methods to analyze the data of experimental results and propose empirical models for concrete mixture optimization [8–10].

Nevertheless, there continue to be some obstacles in the technological advancement in mix design of concrete. It is difficult to develop a universal method because properties of materials from different sources vary widely in their physical characteristics, so

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https://doi.org/10.1016/j.conbuildmat.2018.06.062
0950-0618/

that a conclusion drawn from the experiment in a single material source is not applicable to other situations. The trial mixing process is necessary in the various mix methods to verify the effect of the variation of concrete constituents on the various performance attributes.

In recent years, a new trend is becoming active in increasing the solid components packing density of concrete (named Packing Density Theory) that resulting in the decreasing of the voids content. In fact the aggregate typically represents 60%–75% of the volumetric proportion per unit volume concrete, the concrete mixture proportion algorithms from aggregate to paste have many advantageous [11] as reported by the literature, including:

- Paste volume required to fill the voids between the aggregate is reduced in the case of aggregate with maximum packing density. That can lower heat of hydration [12], reduce the drying shrinkage and creep [13], reduce the cement content which help to decrease environmental pollution and save non-renewable resources [14].
- Better packing density aggregates improves the mechanical properties of concrete such as strength, elastic modulus [15].
- Better packing density aggregates can reduce permeability in concrete which can improve the corrosion resistance of concrete, and improves the durability of the structure [16].

Generally, the Packing Density Theory can be divided into two main branches: The Continual Packing Theory and Discrete Packing Theory. This type of approach considers that the continuous gradation of aggregate an essential factor to obtain a higher packing density. The optimization process of aggregates is transformed into a problem of adjusting the material composition for fitting its cumulative granulometric curve to a calculated ideal parabola curve [14,17]. As there is no idealized continuous gradings in the real world, the Discrete Packing Theory was proposed as an improvement. In this theory, the solid particle system is divided into several discrete particle size classes where at least one class is dominant and other classes are packed to the skeleton. Many works have been reported for predicting model of maximum packing density under different particle size-class aggregate combinations [18–21]. Most of the modern models consider the structure and interaction effects in describing the mechanism of particles with different size packing process [22,23].

However, the particles are seen as mono-sized spherical particles in most existing particle packing models, although many efforts have been made for expanding the models with non-spherical particles [24–26]. In 2017, G Roquier [27] has developed the 4-parameter Compressible Packing Model (CPM) by incorporating the parameters of loosening effect parameter a, wall effect parameter b, compaction index K and critical cavity size ratio x_0, which was confirmed to be more accurate than the old models and have potential in the field of concrete technology.

The main objective of this study is to establish a method for optimizing high performance concrete mix design based on Packing Density Theory for the special requirements of bridge constructions. For this purpose, first, the mix proportioning algorithm was proposed with the 4-parameter Compressible Packing Model (CPM). Restrictions and recommended parameter ranges were also presented. Then, mix designs were calculated by the proposed method by optimization programming with materials from different aggregate plants. Finally, experiments were carried out to investigate the effects of some major parameters. The workability, mechanical properties, and durability of concrete designed by the proposed method are demonstrated by the experimental results.

2. Research scope and objectives

The definition of high performance concrete (HPC) is not clear since it has been proposed. Although widely used, there is no single best criteria fit for describing this material [28]. Many derivatives of HPC designed with different requirements under different application scenario, such as Self-Compacting Concrete (SCC), High Strength Concrete (HSC), Pervious Concrete, Super Workable Concrete, etc. [29–31]. In the present study, the scope of the concepts of high performance of concrete is defined:

- Better early strength. Early strength is an important criterion for long-span cantilever construction bridge to meet the post-tensioned prestressed construction progress requirements, which usually need to reach more than 90% of designed 28-day strength in 4 or 5 days after casting in China. And the strength growth in later must be stable.
- Better workability and flowability. Good rheological properties enable the concrete pumping to a great height, which is important in the high pier or tower construction. That can also reduce labor intensity and improve the quality control of concrete.
- Better sustainability. Due to the irreplaceability of large-scale infrastructures, the durability properties of concrete such as low permeability, high corrosion resistance, less shrinkage and creep, freezing and thawing resistance etc. should be taken to account for.

Mix design of HPC is a critical issue for the special features including low water-binder ratio, multi cement replacement materials, and the high dose of superplasticizers, which can change the properties of fresh and hardened concrete [32]. Therefore, a simple and accessible mix design method for HPC with the modern concrete science is needed, which have a relatively consistent performance despite some variations exist in the properties of concrete constituents. In this article, the proposed method aims to improve concrete mix design methodology to be more scientific and efficient, which can save time and labor cost during the "trial-error-adjusted-trial again" cycle, and available for the industry practice.

3. The 4-parameters Compressible packing model (CPM) of packing density Theory

The 4-parameters Compressible packing model (CPM) is a mathematical model purposed by Roquier [27] and has the ability of describing the packing process and predict the packing density of mixed binary particles. The four parameters in this model are loosening effect coefficient a, wall effect coefficient b, compaction index K and critical cavity size ratio x_0.

Size ratio x is defined as the particle ratio of fine particle class to the coarse particle class. The loosening effect occurs at the condition of coarse particles are dominant, when the fine particle disrupt the packing of coarse particles by squeezing themselves between them. The wall effect occurs at the fine particles are dominant, when the boundaries of the coarse particle interrupts the fine particle class packing. Both the two effects have a negative effect in obtaining the maximum packing density, which is illustrated in Fig. 1. The packing process also affects the packing density. The densification effect of particles by mechanical perturbation has been considered by the compaction index K under the different situation, presented in the Table 1.

The critical cavity size ratio x_0 is the discriminant index of loosening effect occurs. When the size ratio $x < x_0$, a fine particle can be inserted into the cavity of coarse particles without disturbing them, when $x > x_0$, the loosening effect occurs. The parameter x_0 is the crucial factor in the development of the Roquier's CPM model