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Modelling of packing density for particle composites design

Ondřej Koutný*, Jiří Kratochvíl, Jiří Švec, Jan Bednárek

Materials Research Center, Brno University of Technology, Brno, Czech Republic

Abstract

Effective packing of solid particles is one of the main topics in the field of ceramics, powder metallurgy and concrete technology. In these material sectors it is necessary to maximise or optimise the packing density of particles. Therefore, it is necessary to obtain the ability not even to measure the packing density effectively but especially to predict it and affect it with sufficient accuracy. Despite of large experiences in field of metallurgy and ceramics technology, it is still relatively difficult to predict packing density in the concrete technology. Prediction is based on de Larrard linear packing theory expanded by third parameter including wedging effect of particles to the form of 3-parameter packing model. In this paper the model is calibrated for fillers using in Particle composites technology with respect to their granulometry, mainly aimed on UHPC technology. Calibration is based on correlation with experimentally determined values of packing density of model particles mixtures. Successful optimization of particular system composition in concrete technology then could lead not even to decrease of final price but it has also a beneficial influence mainly on mechanical properties and durability of final product.

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Keywords: Packing density; particle packing model; particle interaction; mix design

1. Introduction

Particle composites such a Ultra-High Performance Concretes (UHPCs) is a group of unique inorganic composites which are characterized by very high compressive strength over 150 MPa, high durability estimated at 200 years and nearly no permeability for corrosive agents. Besides other factors, these properties are achieved by precise selection of raw materials with respect to their particle shape, particle size and granulometry to reach highly

* Corresponding author. Tel.: +420-777-502-604.
E-mail address: xckoutnyo@fch.vut.cz

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compact structure with minimum free volume, with maximum packing density, respectively [1]. In spite of large experiences of particle packing in the field of ceramics, powder metallurgy or pharmacy, in modern concrete technology it is still relatively difficult to predict and effectively influence the particle packing density. Particle packing has a fundamental influence on final properties of solid particular materials, such as rheology of prepared suspensions, porosity, permeability or strength. Therefore it is necessary to understand particle packing mechanisms. If we assume a particular system consisting of same size sphere particles, it is easy to calculate that the packing density of such a system is 74.05% (hexagonal close package). Unfortunately, in fact, it is not possible to reach such a high value with mentioned system where maximum packing density is not higher than 64% [2]. For increasing the packing density it is necessary to add such a particle which fill the gap between coarser particles. Fundamentally, the particle packing theory can be divided into two main branches.

First of them is continual packing theory, firstly introduced by Fuller and Thompson and modified by Dinger and Funk to modern form known as Modified Anders-Andreassen model. Continual theory considers that particles are packed continuously according to decreasing particle size [3]. From mathematical formulation of mentioned models is evident that the highest grade of packing is reached when the cumulative granulometric curve of particular system is close to be parabolic. Unfortunately, real systems are not able to pack in such a way in real time due to irregularities in packing. Also real systems has not continuous grading, because they are consist of particles with discrete size. It is only possible to get close to this ideal grading which is mainly limited by number of raw materials stored in real production facility.

Limitations of continual packing theory can be partially solved by using of discrete packing theory. In this theory the particular system is divided to the discrete particle size classes where at least one class is dominant and it is packed preferably. The others particle size classes are then packed to this skeleton. First discrete packing model was introduced by Furnas and Westman on binary systems where particle size ratio was near to zero. In this model there were defied two effect which increase packing density; namely filling effect of fine particles in gaps between coarse particle class and occupying effect of coarse particles which replace the porous space of fine particle size [1,4].

When the particle size ratio is not in limit case (0 or 1), irregularities which decrease packing density take place. These irregularities, also called packing restrictions were firstly introduced by Stovall in the form of two structural effects which disrupt the regular packing and therefore decrease the packing density; namely loosening effect of the fine particle class which disrupt the packing of dominant coarse particle class by squeezing themselves between them; and wall effect of the coarse particle class by disrupting of dominant fine particle class packing by forming wall-like structures on boundaries between particle classes. Participation rate of each effect depends on diameter ratio of interacted particle class and it is presented as interaction function of diameter ratio of two particle classes where one is dominant class. Several authors (de Larrard, Yu) derived their own interaction function and incorporated them to the form of so called Linear Packing Density Model [3,4].

Dependence of packing density on volume percentage of fine particle class is actually not linear, as many authors suggest (de Larrard, Kwan) [4,5]. Especially in the optimum composition point where linear packing theory overestimate the packing density i. e. there should be another effect which decrease the packing density especially around the optimum. This effect was called wedging effect and it was firstly introduced by Kwan. Wedging effect occurs in both cases, when the dominant particle class interact with fine particle class and also with coarse particle class. In the case where the dominant particle class interact with finer particles where the fine particles can be wedged between the coarser particles instead of to fill the space between them. It results in displacement of coarse particles and therefore decrease of packing density. Contribution of wedging effect is higher when the size of small particles is close to size of the gaps between coarse particles because there is the highest probability that particle can be wedged. Therefore, wedging effect acts at most in the optimum percentage of fine particle class. Wedging effect also occurs when the dominant class interacts with coarser particle class. These coarser particles are dispergated each other between the fine particles of dominant class but the dispergation is not homogenous. In the case when the gap between coarser particles is too small for fine particle from dominant class the incomplete layer of this particles is formed around the coarser particles which caused decrease of packing density. In other words when the fine particles from dominant class closer in size to gaps between coarser particles, the probability of incomplete layer increases. Therefore, contribution of wedging effect also increases around the optimum combination [5].