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The optimization of aggregate blends for sustainable low cement concrete

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HIGHLIGHTS

- The aggregate blends have considerable effect on concrete performance.
- The correlation of compressive strength and aggregate packing was established.
- Aggregate packing parameter must be considered to optimize concrete mixtures.
- The power curves and coarseness chart can be used for aggregate optimization.

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ABSTRACT

The volume of aggregates in concrete is approximately 60–75%, and so the concrete performance is strongly affected by the aggregate's properties, proportioning and packing. Optimized aggregate blends can provide concrete with improved performance and can be used to design concrete at lower cementitious material content. Due to complexities in aggregate packing, and irregularities in shape and texture, there is no universal approach to account for the contribution of aggregate's particle size distributions and packing degree affecting the performance of concrete in fresh and hardened states.

This paper attempts to develop the best aggregate blends and investigates the effect of aggregate packing on concrete performance through multiple criteria based on simulation and experiments. It was demonstrated that the aggregate packing can be used as a tool to optimize concrete mixtures and improve compressive strength. The correlation between the grading, packing of aggregates and concrete performance is developed. The grading techniques based on power curves and coarseness chart provide valuable information on expected performance and, therefore, can be effectively used to optimize the concrete mixtures.

1. Introduction

Aggregates form 60–75% of the volume of concrete mixtures. The properties and behavior of portland cement concrete depends on the properties of their main constituent – the aggregates [1–9]. Therefore, the optimization of aggregates is an attractive option to improve the engineering properties, lower the cementitious materials content, reduce the materials costs, and minimize environmental impacts associated with concrete production. Early reports on concrete technology have already emphasized the important effects of aggregates packing and grading related to performance [5,9–11]. Effect of aggregate proportions on properties of concrete, such as strength and modulus of elasticity was investigated and widely discussed in the literature [2–4,7,8,11–18]. The advent of ready mixed concrete and the use of large capacity pumps for transporting concrete demanded the use of improved aggregate blends for mixtures with high workability and imposed new limitations on maximum size of aggregates (D_{max}). Furthermore, the optimization of aggregate blends by packing or particle size distribution (PSD) techniques can bring significant savings due to the reduction of the volume of binder [11].

Indeed, the importance of aggregate characteristics is widely discussed in the literature. Abrams stated that "...the problem is to put together the aggregates available in order to have the best concrete mixture we can for a given cost or at a minimum cost" [1,2]. In 1961, Gilkey [1,3] proposed the modification of Abrams'

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w/c to strength relationship by considering the ratio of cement to aggregate, grading, shape, strength of aggregate particles, and D_{max} [1,3]. Other researchers also discussed the relevance and importance of these factors [4–9].

The theory of aggregate particle packing has been discussed for more than a century [16–31] and includes discrete particle packing theories, continuous theories, and discrete element models (DEM). Discrete models consider the interaction effects between the particles to calculate the maximum packing density for binary, ternary or multi-component mixtures [22–25]. Continuous models are believed to reach the maximum density mixtures [9,20,28]. It is postulated that the optimal PSD corresponds to the "best" or the densest packing of the constituent particles; however, modeling of the large particulate assemblies had demonstrated that the densest arrangements of particles corresponding to Random Apollonian Packings (RAP), are not practically achievable in concrete [31]. The static or dynamic DEMs generate virtual packing structures from a given PSD using random distribution of spherical particles [29–31]. The experimental packing depends on a loose or compacted condition of packing, packing energy, packing methods which have to be specified prior to correlating the experiments and the models. A better understanding of the packing mechanisms for aggregates of various combinations and sizes as required in concrete applications needs further attention and is the primary objective of this study. The PSD is a commonly known criterion towards the optimization of aggregate blends affecting the fresh and hardened properties of concrete. The effect of PSD on workability, density and compressive strength of concrete mixtures is reported in the literature [24,32–34]. Packing criteria for optimizing concrete mixtures are occasionally used for various applications including high-strength concrete, self-consolidating concrete, low cement concrete for pavement applications, and heavyweight concrete [6,12,13,19,35]. The purpose of this paper is to investigate the effect of combined criteria such as grading, the location on coarseness chart, and corresponding experimental packing (loose vs. compacted state), on properties of low cement concrete mixtures.

The use of packing degree as a specific tool to optimize binary and ternary aggregate blends for the lowest void content (or the maximal packing degree) was accomplished by some researchers [6]. The problem of the best-possible aggregate packing and its beneficial effects on concrete has been the subject of experimental and theoretical investigations [4–11,36–39]. Other researchers have proposed a comprehensive theory and scientific insight providing a better understanding of the role of aggregates on compressive strength [13,24,32,41–43]. To address the aggregate mixture proportions, ACI Education Bulletin E1-07 recently recommended using an intermediate aggregates (IA) fraction to compensate for the missing grain sizes [10], and ACI 211 Technote drafted a document for the use of multiple criteria for aggregates optimization. In spite of several reports discussing the importance of theoretical models representing the packing of natural or artificial aggregate assemblies [11,38–40], the empirical approach remains very important tool to verify the models by testing different aggregate combinations and correlating the packing degree to the strength characteristics of particular composites [32,35,39].

The identification of the best aggregate blends for concrete and the relationship between the packing and performance, therefore, remains an ambitious task for further research. To address the objective of this paper, the best aggregate blend in concrete is selected using multiple criteria, and the effect of maximal aggregate packing is investigated by simulation and experiments. These criteria include grading techniques with power curves (PC), coarseness factor chart [16], and the experimental and simulated packing. The experimental PSD and corresponding packing values are compared with associated packing simulations based on the best fit to corresponding PC. The effect of aggregate packing on concrete strength is further examined.

2. Materials and procedures

2.1. Material properties

The type and properties of coarse (CA), fine (FA) and intermediate (IA) aggregates in saturated surface dry (SSD) condition as used in this research are summarized in Table 1. The particle size distribution of aggregates was determined by the sieve analysis according to ASTM C33 (Fig. 1). ASTM Type I portland cement was used; the chemical composition and physical properties of cement (as provided by manufacturer) are presented in Table 2, along with the requirements of ASTM Standard Specification for Portland Cement (C150).

2.2. Experimental testing methods for packing density

The VB apparatus was initially developed for zero slump concrete and is currently used to measure the consistency and density of roller-compacted concrete. In this research, the VB vibro-compacting apparatus is adopted (from the ASTM C1170, method A) to test the packing of aggregate combinations. Different aggregate blends (with a total weight of 5.0 kg) were selected and tested for density and packing degree in loose and compacted conditions. Aggregates were thoroughly mixed before the entire sample was placed into the cylindrical mold of the VB consistometer to form a conical pile. The conical pile was carefully flattened to a uniform thickness by spreading the aggregates with a scoop. An aluminum disk attached to the base was placed into the cylinder on the top of the aggregate sample. The distance between the bottom of the mold and the bottom of the disk for loose and compacted aggregates was then determined using four different points. For compacted samples, the trials with different combinations of aggregates were performed to determine the time required for compaction. A time period of 45 s was used as an appropriate time for compaction. At least five tests were performed for each aggregate combination, and bulk packing density (BPD) was determined using the following equation:

$$\gamma = \left(\frac{W}{\Pi D^2}\right)(H - \Delta h)(1000) \quad (1)$$

where: γ: Bulk packing density of combined aggregates in loose or compacted conditions, kg/m^3. W: Mass of combined aggregates, kg. H: Height the container, mm. D: Diameter of the cylindrical container, mm. Δh: Height reduction of the compacted materials in cylindrical container, mm.

Loose and compacted densities of aggregates and aggregate's blends were determined by the following equation:

$$\varphi = \gamma.\sum_{i=1}^{n}\frac{A_i}{P_i} \quad (2)$$

where: γ: Packing density of aggregates blend, kg/m^3. P_i: Grain density of aggregates fraction, kg/m^3. A_i: Percentage of aggregates fraction, %. n: Number of aggregate fractions.

2.3. Proposed packing simulation model

The sequential particle packing simulation algorithm developed by Sobolev and Amirjanov [17,30,31] used for this research assumes that the particles are spherical (or circular in a 2D educational model) [40]. Spherical particles with radii in the range of $r_{min} < r \le r_{max}$ are sequentially placed into the cube with the centers glued to the node of a very fine lattice grid [31]. The radius r_{max} is defined depending on the container size and is fixed at the beginning of simulation, but r_{min} is decreased gradually by a controllable procedure, thus allowing larger spheres to be placed prior to the placement of smaller ones [31]. To realize the packing routine, a set of parameters including the reduction rate for the minimal size of the particle (K_{red}), the initial separation between the particles (K_{del}), the step of separation (S), and the number of packing trials are defined as inputs. Before locating the sphere with radius r_i, the various conditions are examined: (a) the center of a new sphere cannot be located inside of any already packed spheres; (b) new sphere cannot cross any already packed sphere; and (c) the minimum distance to the surface of any already packed sphere should be greater than r_{min} [31]. The cube can be pre-packed with initial objects including intersecting spheres enabling the combinations of different packing rules to assemble the "real world" particulate composite.

In this study, the simulation of aggregate packing established by Sobolev et al. [31] was used for the optimization of concrete mixtures. The performance of the proposed algorithm is illustrated by a 2D packing achieved with a limited number of objects (500 disks) and a relatively low reduction coefficient (K_{red} = 1.001) as represented in Fig. 2(a). Higher initial separation coefficient value (K_{del}) results in larger initial separation between the particles [31]. The separation was introduced to provide the spacing between the larger objects, but allow for smaller separation between the midsize and small particles as achieved by the use of separation with a