PACKING ORDER THEORY FOR ULTRA-HIGH PERFORMANCE CONCRETE MIX DESIGN: A CRITICAL REVIEW

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Ultra-high-performance concrete (UHPC), also known as reactive powder concrete (RPC), is a relatively new construction material with improved mechanical properties and long-term performance. UHPC is manufactured using a specific matrix of well-graded granular particles including Portland cement, supplementary cementitious materials (SCMs), and fine aggregates. The cementitious material matrix is hydrated using a relatively low water-to-powder ratio and high range water reducing chemicals (HRWR). The hydrated mix is augmented with high grade random steel fibers. UHPC superior mechanical performance and durability is attributed to the high packing order of the granular materials within the UHPC mix resulting in lower voids, reduced permeability, and high density. Accordingly, UHPC design depends on proportioning the mix granular material to produce minimal void content (i.e., produce highest packing order). This research paper discusses UHPC mix constituents, proprietary UHPC mix designs, sizes of granular particles, and resulting packing order. Moreover, a critical review of the particles packing order approach used in UHPC mix design is presented. Possible improvement of UHPC mix design may result in economic mixes, enhanced mechanical properties, and increased durability.

Keywords: UHPC, Packing orders, Voids, Density, Cement, Fine aggregates, Fibers.

1 INTRODUCTION AND LITERATURE REVIEW

Ultra-high-performance concrete (UHPC), also known as reactive powder concrete (RPC), is a relatively new construction material with improved mechanical properties and long-term performance characteristics. UHPC is manufactured using a specific matrix of well graded granular particles including fine Portland cement, supplementary cementitious materials (SCMs) with pozzolanic effect as micro-silica, fly ash, metakaolin, or blast furnace slag, and very well graded fine sand (Akhnoukh 2008, Akhnoukh 2018a, Akhnoukh 2018b, Akhnoukh and Ekhande 2021). UHPC granular matrix is hydrated using low water-to-powder ratio and high range water reducing chemicals (HRWR). High grade random steel fibers are added to proprietary UHPC mixes to enhance the hardened concrete ductility. Current proprietary UHPC mixes include ductal developed and marketed by LaFarge-Holcim, BSI “Beton Special Industrial” developed by Eiffage, Cemtec developed by LPC. Mix designs for several types of proprietary UHPX mixes are shown in Table 1. According to the Federal Highway Administration (FHWA), UHPC is defined as “a cementitious composite material composed of an optimized gradation of granular constituents, a water-to-cement ratio less than 0.25, and a high percentage of discontinuous internal fiber
reinforcement.” UHPC minimum compressive strength is greater than 150 MPa and sustained post cracking tensile strength greater than 5 MPa (Graybeal 2014).

Table 1. Mix designs for different proprietary UHPC mixes.

<table>
<thead>
<tr>
<th>Material</th>
<th>Cor-tuf Mix Kg/m³</th>
<th>Cemtec Mix Kg/m³</th>
<th>CRC mix Kg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Portland Cement</td>
<td>790</td>
<td>1050</td>
<td>861</td>
</tr>
<tr>
<td>Sand</td>
<td>765</td>
<td>514</td>
<td>792</td>
</tr>
<tr>
<td>Silica Flour</td>
<td>216</td>
<td>-</td>
<td>215</td>
</tr>
<tr>
<td>Silica Fume</td>
<td>308</td>
<td>268</td>
<td>215</td>
</tr>
<tr>
<td>HRWR</td>
<td>14</td>
<td>44</td>
<td>9.5</td>
</tr>
<tr>
<td>Steel Fibers</td>
<td>247</td>
<td>858</td>
<td>218</td>
</tr>
<tr>
<td>Water</td>
<td>166</td>
<td>180</td>
<td>220</td>
</tr>
</tbody>
</table>

Recently, several research programs investigated the possibility of producing economic non-proprietary UHPC mixes. Non-proprietary mixes were successfully developed with comparable compressive strength by using mix constituents available at the local market and/or through the elimination of random steel fibers to minimize the cost of the final product (Akhnoukh 2020, Akhnoukh and Ekhande 2021). UHPC superior characteristics and mechanical properties are attributed to the high packing order of the mix granular constituents, low water-to-powder ratio, and steel fibers ductility. This paper focuses on the UHPC mix constituents, the impact of the granular materials packing order, and critically evaluate the effectiveness of packing order theory used in UHPC mix design.

The cementitious content of UHPC mixes includes fine Portland cement and SCMs with high pozzolanic activity. SCMs play an important role in UHPC superior properties. First, SCMs reacts with calcium hydroxide resulting from the hydration of Portland cement resulting in additional binder content and reduced efflorescence. Second, the fine size of SCMs results in increased packing order of mix constituents which reduces air voids and increase hardened concrete density. Additional research findings suggest that inclusion of SCMs results in the mitigation of alkali-silica and alkali-carbonate reactivity within hardened concrete. The mitigation of these deleterious reactions results in increased concrete durability (Akhnoukh 2013, Akhnoukh et al. 2016, Akhnoukh 2019, Akhnoukh and Ekhande 2021).

The enhancement of UHPC mix packing order is highly dependent on the fineness of granular constituents, constituents’ gradation, and the ability to effectively pre-blend all granular constituents (cement, SCMs, and fine sand) prior to adding the designated amount of water, HRWRs, and random steel fibers. Typically, proprietary UHPC mixes includes 2% to 3% of voids as compared to 6% to 9% of voids in normal strength concrete mixes.

2 UHPC MIX DESIGN THEORIES

Different UHPC mix design theories are introduced for optimized mix design of proprietary UHPC mixes. Researchers proposed mix optimization using a combination of aggregates using aggregate shapes, sizes, and bulk density to create an optimized aggregate constituent within the mix (Wille et al. 2011, and Meng et al. 2017). Other researchers proposed a different approach where a cement paste is designed including Portland cement and SCMs followed by the incorporation of aggregates and fibers to produce optimized UHPC mix design (Graybeal 2013). Finally, the particle packing order theory was introduced to the UHPC mix design. The philosophy of this technique is that the particle size distribution and their packing order will significantly impact the density of the
developed concrete mix. Thus, both the fresh and hardened properties of the UHPC are affected (Hunger and Brouwers 2006). For UHPC to have superior strength and long-term performance, the mix are generally designed according to the packing order theory to decrease the concrete porosity (El-Tawil et al. 2018). Details of the packing order theory, its advantages, and critique are provided in the following sections.

3 PACKING ORDER MIX DESIGN OF UHPC

The particle packing theory is based on decreasing the UHPC concrete porosity by filling the air voids among granular particles using smaller size constituents, as shown in Figure 1.

![Fig. 1. Schematic representation of particles packing order in conventional and UHPC mixes.](image)

Many particle packing models are available and used by different researchers. The most common model is known as The Anderson and Anderson (A&A) theory, as shown in the following equation (Eq. 1):

\[
P(D) = \frac{D^{-q}}{D_{\text{max}}^{-q}}
\]  

(1)

Where D is the particle size (in micro meters), P(D) is the volume fraction of the total solids smaller than size D, and Dmax is the maximum particle size (in micro meters) and q is the distribution modulus. Due to the fact that the A&A model does not consider the minimum particle size, a modified Anderson model was developed. The modified Anderson model is considered more appropriate as it considers both maximum and minimum sizes of mix constituents. The modified Anderson model is represented by the following equation (Eq. 2):

\[
P(D) = \frac{D^{-q} - D_{\text{min}}^{-q}}{D_{\text{max}}^{-q} - D_{\text{min}}^{-q}}
\]  

(2)

4 PACKING ORDER THEORY CRITIQUE

The modified Anderson model is currently used for UHPC mix design by optimizing the packing order of granular mix constituents. Despite the successful use of the packing order theory is UHPC mix design and development, major critique exist and represent a debate among academicians and design professionals. First, the extreme fineness of granular mix constituents, mainly cement and SCMs result in strong interparticle forces. These forces, and relevant impact, is not accounted for
in the afore-mentioned models. Also, when wet mixing starts (upon the addition of water and HRWR), the interaction between particles is changed. The change due to wet mixing is not considered (Meng et al. 2017). Other factors affecting the particle packing order including the particle shape (angular, subangular, rounded, and subrounded) is not considered. Finally, the surface condition of the granular constituent is typically ignored. These ignored parameters may result in deviations in UHPC mix design. Additional research is required to introduce empirical non-dimensional constants to account for particle fineness, impact of moisture content, and particle shape to enhance the packing order theory.

5 CONCLUSIONS

UHPC concrete mixes depend on the selection of mix constituents with superior quality to ensure improved mechanical properties and long-term performance. Several theories and design techniques are used in proportioning mix constituents. Currently, the packing order of granular mix constituents is being used in UHPC mix design. The main objective of the packing order theory is to minimize porosity by reducing air voids in concrete. Mix constituents are selected according to modified Anderson model which enable the designer to select and proportion the mix granular constituents that result in optimized density. Additional research is required to address concerns regarding the modified Anderson theory. Mainly, inclusion of interparticle forces, the impact of water and chemical effects on particles inter-relations and ensuring that particle shape and surface condition is taken into consideration. The adjustment of the packing order theory will result in a better understanding of resulting UHPC mix properties and provides researchers and industry practitioners with improved UHPC design techniques.

References


Graybeal, B. A., *Development of Non-Proprietary Ultra-High-Performance Concrete for Use in the Highway Bridge Section*, Federal Highway Administration, FHWA-HRT-12-100, 2013

