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The wetting water in cement-based materials: Modeling and experimental validation

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HIGHLIGHTS

- A model that considers the wetting of particles is proposed.
- The model quantifies the minimum volume of water necessary to wet cement particles.
- The model considers the compactness of the granular system and the particle size.
- The water needed to wet the particles in cement pastes is experimentally assessed.
- A good correlation between the model and the experimental results is found.

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ABSTRACT

The physical role of water in cement-based materials is observed through the wetting of the grains, the need to fill the voids between particles and to separate these particles from one another, providing fluidity. The objective of this article is to develop a model for quantifying the minimum volume of water necessary to wet the particles in cement-based materials. This model takes into account the compactness of the granular system and the particle size. An experimental program was performed to assess the minimum water required. The results obtained agree with the predictions provided by the model.

1. Introduction

Water is a basic component of Portland cement based materials, being responsible for the chemical reactions that enable setting and hardening. Although this is of general knowledge, the chemical role is not the only one played by water in such materials. Even before hydration advances, water has also a physical role that affects both the fresh and hardened state properties [1]. Water absorption by aggregates is the first physical phenomenon that takes place in a mix and it is higher, the higher is the porosity or the consumption of the aggregate grains [2,3]. Parallel to absorption, water also contributes to wet the particles of both aggregates and fine materials. There is a minimum amount of water required solely to wet the surface of the particles. This surface wetting amount marks a limit above which any increment in content will contribute to separate the particles and to the fluidity of the mix.

The minimum wetting water amount in a cement-based material is related to the packing density and the solid surface area of the particles. For the same surface area, the higher the packing density, the smaller will be the volume of water trapped into the voids between particles [4–6]. This means that if the amount of water is kept constant, an increase in the fluidity may be observed as the packing density increases since an excess of water will be left to separate the grains [7,8]. This is based on the same principle stated by Powers in the 1960s, concerning the packing density of aggregates and the fluidity promoted by the cement paste [9].

However, as the solid surface area increases water has to spread out over a larger area, leading to a thinner water film around the particles. In other words, more water will be required to wet all

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the particles. Therefore, the increase of the packing density through the addition of finer particles to the mixes can either increase or decrease the workability. The situation observed in practice will depend on the amount of fine particles added, how these particles affect the packing as well as the solid surface area and, most importantly, the equivalent thickness of the water film formed [10–12].

In this context, it is also important to observe that fine particles added to mixes will tend to deposit in the spaces between the large particles, thus releasing the water that was previously occupying that space. Therefore, it might be interesting to quantify not the total amount of water necessary to fill the voids in a packed system, but the amount of water necessary to wet the particles in the same system. By doing this, the mixes could be designed in a way that the amount of fine particles added would be just enough to fill the spaces occupied by air (not filled with the wetting water). This would optimise the release of trapped water to act in the fluidity of the mix. The use of superplasticizers might help in these situations, since this chemical admixture acts breaking the agglomerates of fine materials; thus, improving the filling effect of mineral admixtures [13]. This consideration might also improve the hardened state properties since particles will be closer to each other. Cement hydrates will fill the space between particles faster, creating stronger links among hydrates and, in consequence, a stronger material [14].

The in-depth analysis of the roles of the water has special relevance in the design of ultra-high performance cementitious composites. In these materials, the high strength is obtained through a strong reduction of the water-to-cement ratio combined with the use of pozzolanic mineral admixtures and superplasticizers. Although the filler effect contributes to improve strength, pozzolanic reaction is limited as a result of the low water-to-cement ratio [15,16]. Therefore, even small changes on the water-to-cement ratio may lead to significant variations in the strength achieved. Self-compacting concretes are also very dependent on the use of different types of fine materials and, as a consequence, on the packing density of the grains in the mix [17,18]. Consequently, it is necessary to know in advance the water demand depending on the characteristics of the materials used.

The aim of the present work is to develop and to validate a simplified model to quantify the amount of water necessary to wet the grains in a cement-based material. This model takes into account the compactness of the granular system and the particle size. The wetting water is presented in terms of an equivalent water film thickness and the surface area of the grains is considered in the calculation. An experimental program was performed to estimate the minimum wetting water. The results obtained agree with the predictions from the model, showing that it may be used to estimate the wetting water depending on the packing and the surface area. This study helps to further understand the roles of water in cementitious systems. It may also be useful in a more rational design of mixes to predict variations in the amount of water due to changes in the composition.

2. Simplified analytical estimation of the wetting water

2.1. Work philosophy and hypothesis

In order to facilitate the analysis of the tri-dimensional system of particles, as well as the calculation, some hypotheses were adopted. The hypotheses considered are presented below.

- The grains composing the system are spheres of the same size. This consideration facilitates the analytical development and it is, alone, a problem known as the Kepler conjecture. The latter was first formulated in the 17th century and solved numerically only in the early 21st century [19].
- The particles are in contact with each other, forming a regular packed system.
- The distribution of particles in the system is periodic. Therefore, the particles arrange themselves in three-dimensional geometric unities, called base unit, which are repeated throughout the structure of the granular assembly.
- Water added to the granular system accumulates initially at the points of contact between particles and expands towards the centre of the pores as the volume of water increases, as shown in Fig. 1. This is a reasonable assumption considering the surface tension at the water-grain interface [20].
- In accordance with a previous study by the authors [21], the contact angle (θ) in the water-cement grain interface is equal to zero. Higher contact angles for cement and silica particles are only achieved by using some chemical admixtures capable of modifying the particle affinity with water [22].

According with the hypotheses adopted, a meniscus is formed where water comes in contact with the surface of the grains. With the increase of the amount of water, adjacent menisci increase in size until they meet at the intermediate position of the inter particle void (see Fig. 1). Once this happens, all of the grains in the system may be considered wet. From this point on, any additional amount of water would only contribute for the separation of the particles.

Observe that the water layer covering the grains has a variable thickness. The equivalent water film thickness (T_{Eq}) is defined as the average thickness the water layer would present if its volume was evenly distributed over the total surface of the grains. This thickness is related with the volume of wetting water (V_{Wet}) and the surface area of the grains (SA), as shown in Eq. (1).

$$V_{Wet} = T_{Eq} \cdot SA \qquad (1)$$

In order to determine the volume of wetting water it is necessary to define a tri-dimensional geometric unity that repeats periodically throughout the granular assembly. This so-called base unit is formed by the union of the centres of eight adjacent grains arranged in two layers, as shown in Fig. 2a and b. Inside the base unit, three phases are present: the solid phase represented by

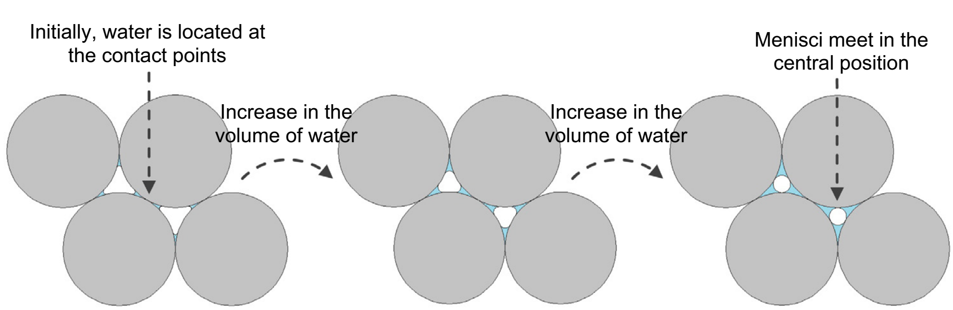

Fig. 1. Progressive addition of water in a packed granular system.