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Early-age elastic properties of cement-based materials as a function of decreasing moisture content

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ABSTRACT

The moisture content is of particular relevance in cement-based materials, as it has a strong impact on their fundamental material properties. For example, it directly affects their strength and elastic properties, which in turn are closely related to volumetric deformations and cracking susceptibility. This paper investigates the influence of the decreasing moisture content on the elastic properties at early-ages, when the material properties are still developing simultaneously to the drying process. Mortar mixtures containing either Portland cement or cement blended with slag were specifically designed to halt the hydration at predefined stages without altering the microstructure or promoting further hydration during drying (equivalent systems). The elastic modulus of the equivalent mortars as a function of the moisture content is measured through resonant ultrasound spectroscopy. At early age the elastic modulus remained constant during drying, while at later ages a steady reduction was observed as a function of the decreasing relative humidity.

1. Introduction

After placement, curing practices are considered essential for the strength development and the durability of concrete [1–3]. However, once the curing period is over (normally when a substantial amount of cement has not yet reacted), concrete structures are usually exposed to the environment, mostly resulting in water loss due to evaporation toward the environment at lower relative humidity (RH). The water loss due to drying results in significant changes of the materials properties such as the transport and mechanical ones, while at the same time inducing a volume reduction [4–6].

Generally, the mechanical properties, both in terms of strength and elastic modulus, have been shown to depend on the moisture content. An in-depth understanding of the strength and elastic modulus dependences on the internal RH of cement-based materials may be important at the designing stage of a concrete structure, when calculating both the free volumetric deformations and the stress induced by restrained deformations.

A reduction in strength and elastic properties has been observed in correspondence of an increase in the water saturation degree due, for example, to an increase in the environmental RH, thus of the internal one. This type of dependence from the RH, which we term "weakening with increasing RH", has been shown, for cement-based materials, both within a broad, e.g., from 10% to 90% [7], and a narrow, e.g., 10% to 40% [8–10], range of RH values. In those ranges, this type of weakening has been also observed via different types of elastic properties measurements and at different probing length scales, e.g., by dynamic and macroscopic measurements, based upon ultrasound waves [8–10], but also at the microscopic scale, using micro-indentation [11]. In addition to cement-based materials, such weakening has been shown to occur in many other porous materials, such as rocks [12–14].

While the effect of the moisture content on the strength has been widely investigated with experimental results clearly confirming a general weakening at higher moisture contents [5,6,9,15,16], only few studies have investigated in a systematic way the dependence of the elastic modulus on the moisture content in cement-based materials. Furthermore, these few studies report contradictory results. For example, Sereda et al. [17] measured the elastic modulus at different equilibrium RH conditions on thin cement paste samples from the load-deflection curve using a miniature testing machine, concluding that the elastic modulus remains constant in the region between 0 and 50% RH, while an increase was observed above 50% RH. Zech and Setzer [10] measured the elastic modulus of thin cement paste samples using dynamic techniques. The elastic modulus decreased with decreasing RH until about 40% RH (local minimum), then it increased up to 12% RH (local maximum), followed by a decrease while approaching 0% RH. This means that they observed a weakening with increasing RH only within the interval 12%–40%, as mentioned before. A local minimum in elastic

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modulus at about 40% was also observed for cement pastes by Wittmann [9]. Also in this case, weakening with increasing RH was limited to a range of low RH values. However, in these measurements, the elastic modulus monotonically increased with decreasing RH below 40% with no local maximum approaching 0% RH.

Duckheim [7] measured the elastic modulus of thin cement paste samples in desorption and adsorption using a three-point flexural test. With desorption, he observed a small reduction of the elastic modulus right below 100% RH followed by a continuous increase of the elastic modulus up to about 5% RH. Below 5% RH, a stronger reduction was observed. His measurements showed weakening with increasing RH within the broadest RH range among all the previously cited works.

All of these studies thus differed in terms of RH intervals within which the weakening with increasing RH was observed. However, such weakening was always observed as a common pattern. From the drying point of view, we notice that it corresponds to an increase in elastic modulus with decreasing RH, i.e., decreasing moisture content.

Other studies reported a different general pattern. Beaudoin et al. [18] measured the static elastic modulus in compression on thin paste samples as a function of the moisture content, reporting a substantial decrease during drying, especially below 20% RH. Further, they showed that the response of the elastic modulus is non-linear with respect to the moisture content and depends on the drying-wetting history.

Yurtdas et al. [5] measured the elastic modulus of mortars with uniaxial and triaxial tests, in addition to the strength. In that study, performed on relatively thick mortar samples left drying at laboratory conditions, decreases in elastic modulus with decreases in moisture content were observed as well, contrary to the trend of the strength, which increased with decreasing moisture content. Burlion et al. measured the elastic modulus of concrete samples exposed to drying at laboratory conditions (60% RH) [15], reporting a reduction of the elastic modulus during the drying process. Other authors investigated the effect of the moisture content on concrete and mortar specimens which were oven-dried (at different temperatures and for different duration) [19–22]. However, it should be noted that the use of relatively thick specimens or rapid drying (especially oven-drying) may result in a non-equilibrated internal moisture content and, more importantly, may introduce changes in the microstructure due to further hydration of residual unreacted binder, degradation of some products of hydration [23–25] or micro-cracking [26], all of them eventually altering the resulting mechanical properties. Finally, lack of control of the atmosphere in the oven (as well as in uncontrolled testing environments) may lead to carbonation, another source of microstructural changes that may affect the mechanical properties [27–29].

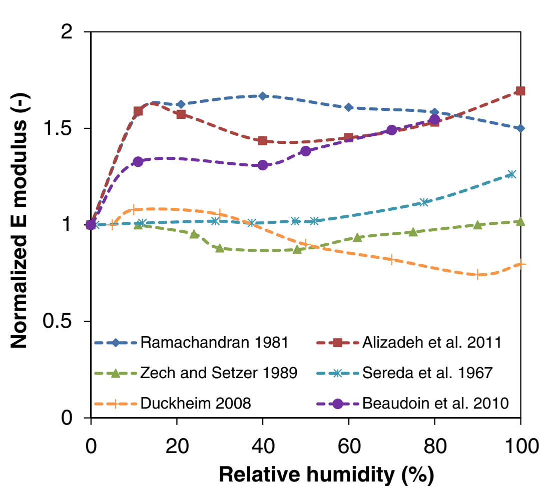

Fig. 1. Elastic modulus as a function of RH for cement paste according to [7,10,17,18,30,31]. For each dataset, the elastic modulus value is normalized by the value at 0% RH.

Fig. 1 shows the elastic modulus measurement results obtained for paste samples at different RH values by different authors using different measurement techniques, clearly showing different dependencies between the two variables. Each elastic modulus value, of each measurement, was normalized by its value at the lowest RH.

As a non-unique dependence of the elastic modulus from the moisture content has been observed, several mechanisms have been proposed to explain it. Wittman [9] ascribed the effect of the water content on the elastic modulus of hardened cement pastes to the roles of the surface energy and the disjoining pressure. Namely, the adsorption of water at RH up to 50% decreases the surface energy of the solid skeleton, while at higher RH the disjoining pressure overcomes the Van der Waals attraction and begins to separate the solid surfaces. Similarly, Zech and Setzer [10] proposed that for RH decreasing below 40% the increasing surface free energy leads to a compression of the gel particles and is responsible for the increased elastic modulus. However, below about 12% RH, hydrates lose their bound water, causing irreversible changes to the microstructure that in turn induce a decrease of the elastic modulus.

Although there is no accepted description of the physical process involved in the changes of mechanical properties during drying, two competitive effects are usually referred to affect the elastic properties. On the one hand, the capillary pressure inside the pores increases as the moisture content decreases, imposing a volumetric pressure that compresses the material and leads to an overall, macroscopic stiffening effect [5]. On the other hand, micro-cracking, due to differential drying or the presence of aggregates in the matrix acting as restraints, contributes to a degradation of the elastic properties [5,15]. The interplay between capillary pressure and micro-cracking has been proposed to be at the basis of the mechanical property's dependence on the moisture content [5]. However, other processes may contribute as well in determining how the elastic moduli vary in correspondence of a decrease in moisture content due to drying. Alizadeh et al. [31] investigated the changes in the viscoelastic properties of synthetic C-S-H samples dried at low RH (less than 11%). They observed a significant decrease in the elastic modulus with moisture loss and hypothesized that such reduction could be attributed not only to micro-cracking but also to other microscale phenomena such as collapse of the C-S-H layers when interlayer water is removed and possible cross-linking of silicates [18,31].

2. Early-age behavior investigation: equivalent systems

The change in elastic modulus due to a change in the moisture content will influence the strain and stress fields in concrete structures subjected to drying. However, at early age, the dependence of the elastic modulus on the moisture content becomes difficult to determine because of the intrinsic impossibility to decouple the elastic property's development due to the ongoing hydration from the effect of moisture changes happening simultaneously. Nevertheless, in real field applications, concrete structures are often exposed to drying at early stages of hydration [32].

In this paper, to investigate the influence of the moisture content on the elastic moduli at early age, model specimens are used to mimic the microstructure at predefined hydration stages [33,34]. The main idea behind such method lies on the replacement, at mixing time, of a specific amount of binder, which would be still unhydrated at a certain hydration age, by fine quartz filler. Such replacement leads, for the chosen curing time, to a static system (*equivalent system*) whose microstructure represents that of the corresponding specimen without the replacement (*real system*), but without changing over time and during testing due to cement hydration. In fact, once all the binder has completely reacted in the equivalent system (assumed to occur after 3 months), the equivalent system is ideally composed by only hydration products and quartz filler that substitutes the unhydrated cement present in the real system.