



Formation factor of fresh cementitious pastes

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ABSTRACT

Formation factor of fresh cementitious pastes was investigated experimentally as a function of time from initial mixing and mixture design properties such as supplementary cementitious material (SCM) replacement level, water-to-binder ratio (w/cm), and superplasticizer dosage. SCM types included fly ash, slag and silica fume. A total of 54 paste mixtures were studied. The formation factor of each fresh paste was determined at the 30th, 60th, and 90th minutes from initial mixing. It was shown that the formation factors of fresh cementitious pastes were strongly correlated with porosity, tortuosity and w/cm. Slag and fly ash considerably decreased tortuosity of the pastes, whereas silica fume did not have a significant effect. Superplasticizer addition increased tortuosity through a better distribution of the solid particles. A model representing the formation factor of the tested fresh cementitious pastes was provided. Similar models can be used to determine the initial setting time of cement-based materials and quality control of fresh mixtures in precast and ready-mix concrete plants.

1. Introduction

Each year approximately 10 billion tons of concrete is produced, making concrete the largest manufactured product globally [1]. The majority of this production is in the form of ready mix concrete [2]. In the United States alone, there are about 5500 ready mix concrete plants and about 55,000 ready mixed concrete mixer trucks that deliver concrete to the point of placement [2]. The quality control (QC) and quality assurance (QA) of this large operation have major economic, social and environmental implications. Construction projects using ready mix concrete require strict adherence to the established standards for specifying, ordering, mixing, delivering and curing, such as those defined by ASTM C94 [3], the Standard Specification for Ready-Mixed Concrete. Despite all efforts and streamlined procedures, many newly constructed structures suffer from performance and long-term durability problems due to low-quality concrete. The issue can be traced back to existing QC/QA protocols of concrete production.

Current QC protocols require the measurement of slump, unit weight and air content of fresh concrete [3]. While these measurements have value, they do not provide direct links to long-term performance and durability indicators such as water content, porosity, strength or transport properties. The absence of a QC protocol that directly assesses performance at the time of delivery is a major limitation for the construction industry. Similarly, current QA procedures have drawbacks as they mainly rely on checking compressive strength of concrete, which is

typically done weeks after concrete placement. This approach poses practical challenges in terms of the timing of the QA decisions, and it does not necessarily provide adequate information about the future performance of structures in terms of their durability because it mainly checks if the desired mechanical properties are satisfied.

There is a need for improved and practical QC/QA protocols (1) to confirm that the fresh concrete delivered to the site is the concrete that is specified, ordered, and delivered to the construction site, (2) to ensure that the delivered fresh concrete mixture will satisfy the performance specifications for long-term durability. Formation factor of fresh concrete is proposed as a parameter to address these two demands and to supplement existing QC/QA protocols. Although it has been shown in past research that formation factor of hardened concrete can be used to predict long-term durability properties of concrete [4–15]; the formation factor of fresh concrete has been investigated only in a few studies [16], and there are no systematic studies on the formation factor of fresh pastes. This paper aims to fill this gap by studying the formation factor of neat and blended cementitious materials in fresh state as a function of time from initial mixing and mixture design properties such as supplementary cementitious material (SCM) replacement level, water-to-binder ratio (w/cm), and superplasticizer dosage.

It is acknowledged that the outcome of this study might not be directly applicable to QC/QA practices as the direct measurement of electrical properties of cement paste in concrete is not trivial in the field. Therefore, the extension of this study to concrete is important to

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validate the QC/QA benefits of formation factor for fresh concrete in field applications. However, as a first step toward this goal, the research on pastes is necessary to develop fundamental understanding on the subject as there are a number of confounding factors affecting the relationships studied in this paper [17]. For example, aggregates might affect the chemical composition of pore solution, hence its electrical properties, which is difficult to isolate or control in an experimental setting. In addition, the type, grading, and volume of aggregate also affect the electrical properties of fresh concrete by changing the porosity and tortuosity of the system. Testing all possible combinations of these confounding effects is challenging, if not impossible, in a laboratory study with limited number of samples. By removing the aggregates from the study matrix, it is possible to focus on fundamental properties of the formation factor of fresh pastes. In the future, the findings of this work should be expanded further for fresh concrete, particularly for QC/QA applications. As a potential solution to this limitation, extraction of cement pastes from fresh concrete by simply sieving the concrete can be considered before conducting the electrical conductivity measurements in the field. Further studies are required to evaluate the feasibility of this solution in the field. It should also be noted that although the actual quantity of the formation factor would be different in paste and concrete with the same water-to-cementitious material ratio (w/cm) and cement content, the concepts that are presented in this paper would apply to both paste and concrete.

2. Background

Porosity in a porous material such as rocks or soils is defined as the volumetric ratio of air voids and water to the total material (i.e., solid, air and water). In a fresh cement paste, all air voids (pores) are mostly filled with water, hence, the degree of saturation can be assumed 100%. Therefore, the volume of water is equal to total void volume, and porosity in a cement paste is defined as the volumetric ratio of water content to that of water plus cementitious materials. As shown in Fig. 1, the porosity is the ratio of the space free of cementitious materials (white area) to the total volume (shaded area plus white area). As a result, increasing water content in unit volume of cement paste (i.e., higher w/cm ratio) will result in higher porosity [13,18].

Electrical resistivity of porous materials such as sandstones has been investigated by many researchers [19–26], dating back as early as 1904 [19]. Fricke et al. [20] considered sandstones saturated with water as a two-component system composed of a non-conductive solid matrix and a conductive water phase. Since the electrical resistivity of solid particles is several orders larger than that of conductive water in sandstones [27], conductivity (or resistivity) of the sandstone was assumed to be mainly governed by the conductivity (or resistivity) of the water phase. A parameter, called formation factor (F), was defined as the ratio of electrical resistivity of saturated sandstone (ρ_0) to that of water contained in its pores (ρ_w) via [19,20,26]:

$$F = \frac{\rho_0}{\rho_w} \quad (1)$$

Different empirical equations were proposed by researchers to establish a relationship between formation factor, F, and volumetric

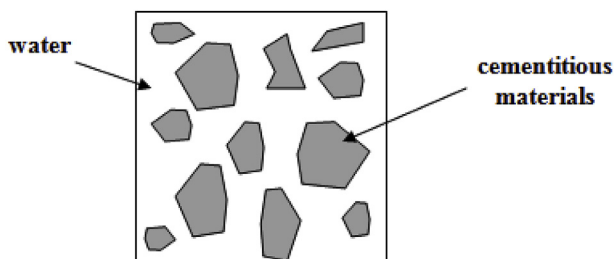


Fig. 1. Schematic representation of cement paste structure in fresh state.

fraction of conductive component (such as water in sandstones) defined mostly in terms of porosity [19,25,26,28,29], ϕ . For example, Maxwell [19] proposed the formation factor (F) as a function of porosity (ϕ) for spherical solid particles separated in a matrix by large distances compared to their radius as:

$$F = \frac{3 - \phi}{2\phi} \quad (2)$$

Similarly, Slawinski [26] derived an empirical relationship for spherical solid soil particles both in contact with each other and dispersed in the water/liquid matrix as follows:

$$F = \frac{(1.3219 - 0.3219\phi)^2}{\phi} \quad (3)$$

The first version of the Archie's law, which is still widely used today, was first proposed in 1942 [28] while he was studying electrical resistivity of sandstones (rocks) 100% saturated with water as follows:

$$F = \frac{\rho_0}{\rho_w} = \phi^{-m} \quad (4)$$

where m is a factor that depends on the type of the porous medium. Pirson [25] suggested that exponent m ranges from 1.3 to 2.2 for slightly and highly cemented rocks, respectively. Atkins and Smith [29] improved the Archie's equation (Eq. (4)) for rocks with multi-size particles (e.g., sands that are mixed with clays) by adding an empirical constant, A, to incorporate the effects of the shape and distribution of particles in the matrix via:

$$F = A\phi^{-m} \quad (5)$$

where A was defined as the geometric tortuosity of a the porous material, which affects the connectivity of the pores within the matrix.

Application of Archie's law (Eq. (5)) in cement-based materials such as concrete [9–12] and cement paste [13,14] has been studied mainly in hardened state. It has been shown in past research that electrical properties of hardened concrete, such as its electrical resistivity or formation factor, can be used to predict durability properties of concrete [4–15]. One advantage of this approach is that electrical properties of concrete can be determined rapidly and related to other more time consuming and expensive tests such as rapid chloride penetration test (RCPT) [4–8]. Recently, methodology toward performance specifications was proposed to link electrical resistivity, RCPT and chloride transport in hardened concrete using formation factor [30].

Despite the progress in hardened concrete, formation factor in fresh state has not been investigated systematically. Specifically, the applicability of the formation factor equations proposed by other researchers for hardened porous materials (e.g. Eqs. (2) and (3)) have not been tested for fresh cement paste systems. For instance, as shown in Fig. 2, the estimated F values by Slawinski's equation (Eq. (3)) cannot capture the actual F values obtained from experiments (F_{exp}) performed by the authors (R^2 of the data fit to the 45° line is less than 0.01). In addition, effects of size, shape and distribution of cementitious materials on formation factor of fresh cement paste have not been investigated. Therefore, additional studies are required to understand the variation of the formation factor in different types of fresh cement paste mixtures.

In a cement paste mixture in fresh state, paste electrical resistivity depends on the pore solution electrical resistivity and physical formation of cementitious material particles (non-conductive component) in the solution. The former is a function of the activity of the ions released into pore solution because of chemical reactions between cementitious materials and water. The latter represents the physical configuration of solid particles and their volumetric fraction (i.e., $1-\phi$) in the cement paste. Therefore, in this study the Formation factor (F) for the fresh cement paste system is defined as the ratio of the electrical resistivities of the paste (ρ_p) and the pore solution (ρ_{ps}) at 25 °C via:

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