

The application of electrical resistance measurements to water transport in lime-masonry systems

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Abstract

The paper describes an experimental determination of impedance spectroscopy derived resistance measurements to record water transport in lime-masonry systems. It strongly supports the use of Sharp Front theory and Boltzmann's distribution law of statistical thermodynamics to corroborate the data obtained. A novel approach is presented for the application of impedance measurements to the water transport between freshly mixed mortars and clay brick substrates. Once placed, fresh mortar is dewatered by brick and during this time the volume fraction water content of the mortar is reduced. An equation is derived relating this change in water content to the bulk resistance of the mortar. Experimental measurements on hydraulic lime mortars placed in contact with brick prisms confirm the theoretical predictions. Further, the results indicate the time at which dewatering of a mortar bed of given depth is completed. The technique has then potential to be applied for in situ monitoring of dewatering as a means of giving insight into the associated changes in mechanical and chemical properties.

Key words: Impedance spectroscopy, Boltzmann's distribution law, water transport

1. Introduction

When a freshly mixed mortar in the form of render or jointing mortar is applied to an absorbent substrate such as clay brick, water is abstracted from the wet mix by the capillary suction of the substrate. This process has important implications for the subsequent strength development and engineering properties of the material [1,2]. The extent to which water is removed from the wet mix depends on both the sorptivity of the substrate and the water retaining ability (desorptivity) of the mortar [3,4]. This initial dewatering prior to setting is likely to have a significant influence on the long term durability of the mortar in terms of its mechanical strength and its resistance to environmental degradation and frost damage. The ability to monitor dewatering non-destructively is therefore of great importance in providing an insight to the long term performance of these materials.

The application of NHL mortars in the conservation, restoration, renovation and new build sectors of construction is growing rapidly. As their name implies NHLs set by reacting with water in a similar manner to cements. Compared with Portland cement NHL's have lower strength but provide for greater movement [5]. This and a number of other desirable properties make them better suited in many applications [6-8]. In the present study natural hydraulic lime (NHL) mortars in the freshly mixed state were investigated after placing on initially dry clay common facing brick.

This paper reports the use of impedance spectroscopy to monitor the dewatering of mortars prior to the early stages of the setting process. Phase angle measurements were taken over a range of frequencies and complex plane plots of imaginary versus real impedance were interpreted in terms of equivalent circuit parameters.

The application of impedance spectroscopy to cementitious materials has been developed by McCarter, among others [9-13]. Previous work in this area has concentrated on the use of impedance spectroscopy to study hydraulic or pozzolanic reactions during setting.

Recent work by Ball *et. al.* investigating physio-chemical processes in lime-based composites demonstrated that impedance spectroscopy can track a carbonation front in natural hydraulic lime mortar using an electrode array [14].

These studies have allowed a number of fundamental properties to be linked to the impedance response of a cementitious material in the set and hardened state. Such properties include pore water content, pore water ionic concentration, and porosity and tortuosity of the pore network. The following can be deduced from the literature on resistivity measurements in hardened cement mortars [13]:

- Resistivity decreases with the amount of evaporable water in the cement paste.
- Resistivity decreases with the concentration of mobile ions in the pore fluid.
- Resistivity is influenced by the connectivity (or tortuosity) of the pore network.

The impedance behaviour of hydraulic lime mortars in the freshly mixed state however has not as yet been investigated although alkali activated slag binders (from 15 minutes after mixing) and cement has not as yet been studied [11]. Results from these studies attribute changes in conductance during the first hour after mixing to an increase in ionic concentration following dissolution of soluble species from the binder into the mix water. Portland cement based binders showed changes in conductivity during the first hour followed by a dormant period lasting approximately 9 hours. A large change following this dormant period signified intense chemical activity due to hydration reactions [13]

There are few reports in the literature addressing the application of impedance measurements to monitor changes occurring in freshly mixed wet mortars following placement in contact with absorbent substrates. This may be a reflection of the experimental difficulties involved in the measurement of relatively thin layers of mortar, or that this early dewatering has been completely overlooked. It has been found [15] that between 40 and 60 % by volume of the mix water is abstracted from freshly mixed lime under the capillary pressure of dry clay brick. On site, bricks and other masonry units

will not be oven dry and so will abstract less. Nevertheless this dewatering has a significant effect on mortar strength [1] and probably on durability.

The relationship between saturation and electrical conductivity in porous media has been investigated by Hunt, for unsaturated systems, using an Archie's law approach [16]. He applied a continuum percolation theory to previously published data representing the full range of saturation. This included data obtained from sandstone, fine sandy loam, soil (consisting various ratios of sand and clay), and various types of sand. The analysis demonstrated the ability to provide good predictions and was robust in respect to secondary effects such as residual salinity and contact resistance. The correlation between electrical resistivity and soil-water content using artificial intelligence techniques has been investigated by Ozcep and co-workers [17, 18]

Water content estimation by electrical measurement of soils offers new opportunities in geotechnical and agricultural studies. Techniques including time domain reflectometry [19, 20], high-frequency capacitance sensing [21] and resistivity cone penetration testing [22] have been applied. A useful theoretical approach to the dewatering of mortars, and slurries in general, is offered by a Sharp Front model which has its origins in soil science [3]. In this model it is assumed that a wetting front of uniform water content moves into the absorbent substrate from the wet mix and that there is a sharp boundary between the wetted and the dry regions. As dewatering proceeds, a filter cake of higher volume fraction solids content than the original mortar mix forms at the interface with the substrate. This interface progresses through the slurry until all the mortar has been converted to filter cake. This model is shown diagrammatically in Figure 2(b), discussed later.

2. Theory

The Sharp Front model developed by Hall and Hoff [3] describes the relationship between the sorptivity, S , of the substrate, the desorptivity, R , of the wet mix (in this case

freshly-mixed mortar) and the transfer sorptivity, A , between the wet mix and substrate by

$$\frac{1}{A^2} = \frac{1}{R^2} + \frac{1}{S^2} \quad 1$$

This relationship has recently been experimentally validated [23]. The withdrawal of water from a wet mix by an initially dry substrate occurs by capillary action. As the wet mix is dewatered a filter cake forms at the boundary between the wet mix and substrate. As dewatering proceeds the filter cake increases in depth until all the wet mix has been converted to cake. The application of Darcy's law to the filter cake yields

$$\frac{di}{dt} = -K_c \frac{\Psi_i}{L_c} = -K_c \frac{\alpha \Psi_i}{\beta_i} \quad 2$$

where i is the cumulative volume of water desorbed per unit area of wet mix in contact with the substrate, t the elapsed time, K_c the saturated permeability of the filter cake, Ψ_i the capillary potential of the substrate, L_c the depth of the filter cake and α and β are constants defined by the volume fraction water and solids contents of the wet mix and filter cake respectively [16]. Integration of equation 2 with respect to time gives

$$i = \left(\frac{2K_c |\Psi_i| \alpha}{\beta} \right)^{\frac{1}{2}} t^{\frac{1}{2}} = R t^{\frac{1}{2}} \quad 3$$

where R is the desorptivity of the wet mix.

If the initial volume fraction of mix water is θ_0 , then the volume fraction, θ , at any time t is given by

$$\theta = \theta_0 - i A_{\text{sub}}. \quad 4$$

where A_{sub} is the area of wet mix in contact with substrate.

When a solid of charged surface is in contact with a liquid containing ions a double layer is formed at the surface. This layer is comprised of a tightly bound layer of fairly immobile ions adjacent to the solid and an oppositely charged ionic atmosphere [24]. The potential energy of ion species dissolved in the mix water may be related to the number of ions by Boltzmann's distribution law of statistical thermodynamics [25] giving

$$\frac{N_i}{N_j} = \exp\left[\frac{-(E_i - E_j)}{kT}\right] \quad 5$$

where N_i and N_j are the numbers of constituent ions in states i and j and E_i and E_j are the respective potential energies; k is Boltzmann's constant and T the absolute temperature. We suggest that when the mix water comes into contact with un-dissolved lime or sand particles a double layer is formed at the solid surface. In practice this layer will be very complex consisting of different ions, both positively and negatively charged. Tschapek reports that in the presence of water quartz sands undergo hydroxylation and charging instantaneously [26]. In the presence of water Si-O-Si bonds at the sand surface will react to form $2\text{Si-O}^-\text{H}^+$ resulting in a negatively charged surface. Chemical compounds originating from the lime will introduce ions such as Ca^{2+} , OH^- in addition to a range of metal ions. For the purpose of this analysis we assume a simple system where state i corresponds to ions within the double layer, and state j to ions in the mix water bulk. The development of a more complex analysis is beyond the scope of the current study. Nielsen applies a similar approach to soil and expresses the difference in energy between the two states by

$$E_i - E_j = ze(\varphi_i - \varphi_j) \quad 6$$

where φ_i and φ_j are the electrical potentials of states i and j , e the charge on the electron and z the summary valence of the ions [27]. Combining equations 5 and 6 gives

$$\frac{N_i}{N_j} = \exp\left[-ze(\varphi_i - \varphi_j)/kT\right]. \quad 7$$

If the volume fraction water content of the wet mix is changed by dewatering and the total surface area of solids is assumed to stay the same, then the total number of ions in the water bulk will decrease while those in the double layer will remain constant. Therefore the ratio N_i/N_j will be proportional to the volume fraction water content of the mortar, θ . The electrical potential difference, $(\varphi_i - \varphi_j)$, can be related to resistance, R_b by ohm's law therefore allowing the general expression

$$\theta = a \exp(-bR_b) \quad 8$$

to be derived where a and b are empirical constants. Constant b is a function of z , T , electrical current and sample geometry. Values of a and b are discussed in the results and discussion section. Equation 8 shows that the volume fraction water content is directly proportional to the function $\exp(-bR_b)$ and that bulk resistance should increase as the water content of the mix decreases. Substitution of equations 3 and 8 into equation 4 gives

$$a \exp(-bR_b) = \theta_0 - Rt^{\frac{1}{2}}A_{\text{sub}} \quad 9$$

which can be rearranged to give

$$\exp(-bR_b) = -\frac{A_{\text{sub}}R}{a}t^{\frac{1}{2}} + \frac{\theta_0}{a} \quad 10$$

Equation 10 can be used to produce a plot of the function $\exp(-bR_b)$ versus $t^{1/2}$. Figure 1 shows such a plot over 49 min, together with experimentally determined values of R_b also plotted against $t^{1/2}$, from which can be seen that R_b is a curve increasing with

mortar is changing from freshly placed to fully dewatered, changes in a or b may influence the gradient when $\exp(-bR_b)$ is plotted *versus* $t^{1/2}$ as in Figures 5, 6 and 7.

For the purpose of this study the point at which the extrapolated portions of the two linear sections intersect has been taken as the time at which dewatering is complete *i.e.* when all fresh mix has been converted to filter cake (in the terminology of Figure 2b). It is proposed that the time at which the change in gradient occurs indicates the end of dewatering for the 45 mm depth of mortar. In support of this Table 1 gives the values of desorptivity determined from pressure cell measurements, where these are available, for the identical NHL mortar [15]. Values of the brick sorptivity measured in this study and values of transfer sorptivity between the mortar and the brick prism were calculated using equation 1. Minor variations in sorptivity have a small effect on the transfer sorptivity. Values of time to dewater the 45 mm mortar bed can be calculated from Sharp Front theory using these values of transfer sorptivity and the approach described in [30] and are also given in Table 1 with the time to dewater obtained from the extrapolated linear regions of Figures 5, 6 and 7. The purpose of this table is not to demonstrate exact correspondence between the calculated and measured times to dewater but to present support for the proposal that the impedance method is indeed detecting the end of the dewatering process. Both calculated and measured times to dewater are of similar magnitude and the trend is the same when the hydraulicity of the lime increases, giving confidence that the measurements of bulk resistance do detect the time at which dewatering is complete.

The results presented here showing the effects of proportion of mix water, hydraulicity of lime and sorptivity of substrate on the time to dewater 45 mm bed of mortar correspond with those obtained from transfer sorptivity measurements made by experimental determination of mass and volume on 20 mm depth of mortar [30]. In summary the time to dewater, decreases with increasing hydraulicity of lime, decreases with increased proportion of mix water and decreases when increase in substrate sorptivity is large.

