Using simple soil water content sensors to measure water availability in fresh concrete

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Abstract. Preventing plastic shrinkage cracks improves the durability of concrete. This is because plastic shrinkage cracks serve as pathways by which corroding agents can penetrate concrete. Freshly cast concrete is a saturated mixture of reactive and non-reactive materials. As water moves out of the concrete mass and as water is used in the hydration process, the free water in the mixture reduces. Eventually, the mixture can be considered to be unsaturated. In this research project, the viability of using soil water content sensors to measure the change in water availability in concrete from fresh state to early-age was explored. The soil water content sensors measured dielectric permittivity. The dielectric permittivity, cumulative evaporation and setting time of mortars with varying water/cement ratios were tested. It was found that the dielectric constant was influenced by changes in fresh mortar and that the sensors have the potential to qualitatively monitor cement content, bleeding, hydration and evaporation. Further work is required in this field.

1 Introduction & background

Plastic shrinkage cracking adversely affects the durability of concrete. This is because these cracks serve as pathways by which corroding agents can penetrate concrete [1,2]. Plastic shrinkage occurs when the surface of fresh concrete becomes dry and capillary pressure is induced. Capillary pressure is caused by the menisci at the air-water interface in the mixture of water, cementitious and granular materials of concrete [3]. If there is plastic shrinkage in concrete that is restrained, tensile stress will be induced and when the tensile stress exceeds the tensile strength, cracking will occur.

Capillary pressure increases as the free water content in a concrete mixture decreases. Capillary pressure can be measured directly by pressure transducers of various configurations, but these sensors tend to be tricky to build and prepare for testing [4,5]. The presence of water in soil is of interest to soil scientists and geotechnical engineers [6]. Various techniques, based on thermogravimetry, neutron scattering, or electromagnetism, have been developed to measure the presence and amount of water in soil. Electromagnetic sensors are popular in particular due to their relatively low cost, which allows networks of sensors to be used to monitor water content [7]. These sensors are used to measure dielectric permittivity.

In this paper, commercially available soil water content sensors were used to measure the dielectric permittivity of fresh and early-age mortars. This was done over a range of water/cement ratios while keeping the original water content of each mortar mixture constant at 370 kg/m^3.

The free water content in fresh and early-age concrete (<24 hours) is dependent on water moving from the concrete body, due to bleeding and evaporation, and water being used in the hydration process. The hydration of cement consists of three phases over approximately 50 hours in terms of the rate of heat evolution [8]. In the first 24 hours, there is a spike in the rate of heat evolution when water and cement are mixed. This is followed by a dormant period of one to two hours, after which there is a gradual increase in the rate of heat evolution. The spike the in the rate of heat evolution coincides with the initial hydration at the surface of cement particles. The dormant period is due to the layer of precipitate on the surface of the cement particles that prevents further hydration. The layer is broken down, hydration can proceed and initial and final set are reached [9].

After placing, at the same time as cement hydration, the heavier mixture constituents settle, while the water moves upward to the concrete surface. This bleed water is reabsorbed or it evaporates. Bleeding starts at a constant rate, and decreases after some time. Bleeding stops when the cement has stiffened enough which according to Soutsos & Domone [9] is around final set.

Dielectric permittivity is the ability of a substance to hold an electrical charge. The dielectric permittivity of materials is often described using the dielectric constant, which is the ratio of the dielectric permittivity of the material and the dielectric permittivity of a vacuum. The dielectric constant of water and air are respectively approximately 80 and 1. Because the dielectric permittivity appears to be highly sensitive to the volumetric water content and insensitive to soil type and density, it is used to estimate the volumetric water content

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of soil [6,7,10]. Networks of electromagnetic sensors are often deployed to monitor the water content of large areas of land.

The dielectric permittivity of cement, mortars, and concrete at different ages has been studied [11–14]. Chen *et al.* [14] measured the water content of fresh concrete and Shen & Liu [12] studied the hydration in young concrete, both using electromagnetic impulse propagation with ground penetrating radar.

The dielectric behaviour of concrete is determined by the presence and amount of free and bound water, but water/binder ratio, particle size distribution, and additives can significantly influence it [15]. The populations of water in concrete are free water and chemically bound water, with gel water between the two extremes [8]. Water exists at different stages of binding with portions with high concentrations of dissolved ions which affects the permittivity [16]. Water consumption with time and water evaporation due to elevated temperatures results in permittivity decreasing [17,18]. Temperature influences permittivity due to influencing the dipole alignment, with permittivity increasing with decreasing temperatures [19]. Table 1 shows typical dielectric constant values for relevant materials [13,19].

Table 1 Dielectric constant of selected materials [19]

Material	Dielectric constant
Vacuum	1
Air	1.000536
Concrete - dry	4 - 10
Concrete wet	10 - 20
Sand - dry	3 - 6
Sand wet	10 - 30
Water	78 (25 C)
Sea water	81 - 88
Pore solution	40

2 Experimental work

In this paper, commercially available soil water content sensors were used to measure the dielectric permittivity of fresh and early-age mortars. Five mortars with varying water/cement ratios and constant original water content of 370 kg/m^3 were tested. The constituents were mixed, cast and then placed in environmental conditions of 25 ºC temperature and 50% relative humidity. The setting time and the 24-hour compressive strength were determined. The dielectric permittivity up to approximately final set and the cumulative evaporation up to 24 hours were measured continuously.

Table 2 shows the mortar mix designs. CEM I 52.5 R and fine silica sand were used. The table also shows the 24-hour compressive strength and setting times. The compressive strength was determined according to SANS 5196-1:2006 [20], but the mortar prisms were tested unsaturated. The setting time was determined according to ASTM C403 [21]. **Fig. 1** shows the particle size distribution of the cement and fine silica sand.

To determine the cumulative evaporation of water, bespoke scales were used. The scales consisted of custom-built platforms and HBM SP4M single-point load cells. The range of the load cells was 10 kg. Three samples were tested and 100 mm plastic cube moulds were used to cast the mortars in.

Table 2 Mix design, 24 hr strength and setting times of mortars

	Mix 1	Mix 2	Mix 3	Mix 4	Mix 5
w/c	0.30	0.43	0.55	0.68	0.80
Water (kg/m^3)	370	370	370	370	370
Cement (kg/m^3)	1233	871	673	548	463
Sand (kg/m^3)	629	935	1102	1207	1279
24 $hr f_c$ (MPa)	54.8	33.1	24.1	14.9	9.3
Initial set (min)	187	298	348	339	409
Final set (min)	265	419	470	463	556

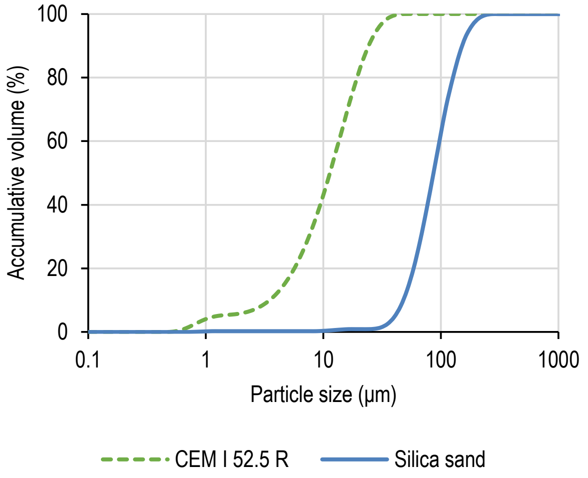

Fig. 1 Particle size distribution of cement and silica sand

The dielectric permittivity was measured using TEROS 10 sensors [22]. The sensors consist of two stainless steel needles, a sensor body and a ferrite core. The ferrite core isolates the sensor from interference in the system. A 70-MHz oscillating wave is applied to the sensor needles, which charge according to the dielectric of the material. The sensor output is a raw value in milli Volt which is based on the apparent dielectric permittivity. The output value is converted to dielectric permittivity using:

$$\varepsilon = 0.1054e^{0.002827x} \tag{1}$$

with ε as the dielectric constant and x as the sensor output.

The Teros 10 uses short excitation pulses and should not be subjected to continuous excitation. With installation, no metal should be located between sensor and the ferrite core. Sensor function can also be affected if it is installed near large metal objects. This limitation of proximity to metal makes the application of the sensor problematic in reinforced structures.

To measure the dielectric permittivity three samples per mortar mix were tested. The mortars were cast in plastic 100 mm cube moulds. The sensors were inserted vertically into the exposed surface of the mortar as illustrated in **Fig. 2**. The range of the sensor is approximately 20 mm from the needles in all directions.

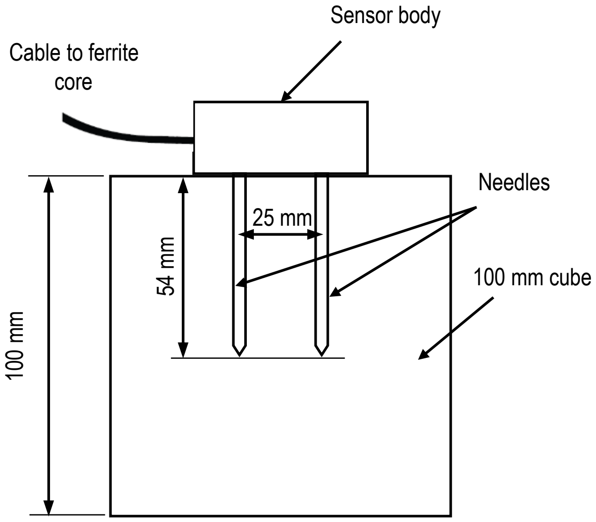

Fig. 2 Sensor elements and location in sample

3 Results

Fig. 3 shows the initial and final set for all the water/cement ratios, as well as the 24-hour compressive strength. The setting times increase steadily with an increase in water/cement ratio, which is expected. Also as expected, the compressive strength has a steep decrease with an increase in water/cement ratio. Note that all mixtures were subjected to the same environmental conditions and no admixtures were used for any of the water/cement ratios.

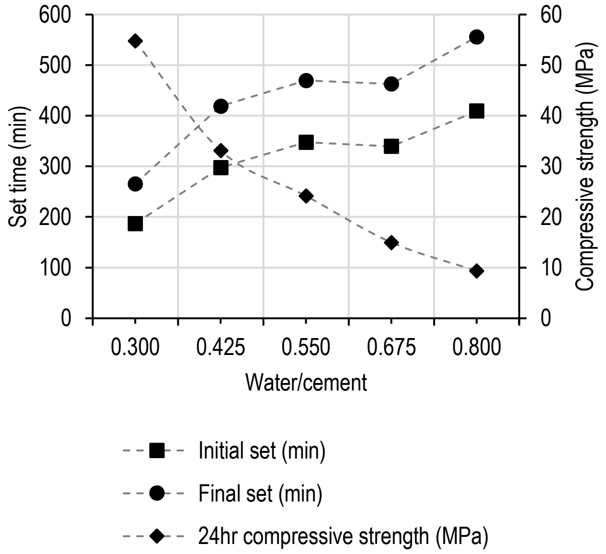

Fig. 3 Setting times and 24-hour compressive strength over range of water/cement ratios

The cumulative water loss from the concrete due to evaporation was measured continuously using bespoke scales. **Fig. 4** shows a distinct trend with the samples with lower water/cement ratios plateauing earlier, at a lower level of cumulative evaporation. The sample with the lowest water/cement ratio started to plateau at around 600 minutes (w/c=0.3) while the next two samples with water/cement ratios plateaued at 900 minutes and 1200 minutes respectively. It can be concluded that the evaporation of the samples with the two highest w/c ratios would also have plateaued if the tests were continued for a longer time.

The trend of decreasing 24-hour cumulative evaporation with decreasing water/cement ratio indicates that although the water content remained constant across the range of water/cement ratio, less water evaporated from concrete with a lower water/cement ratio, probably due to higher hydration activity. For decreasing water/cement ratios, the cement content increased while the sand content decreased and the water content remained constant. The trend of plateaus being reached earlier for low water/cement ratio is possibly due to more cement consuming more water sooner after mixing. The higher rate of evaporation for w/c=0.3 between 250 minutes and 500 minutes could be due to the increased temperature of the sample due to early hydration.

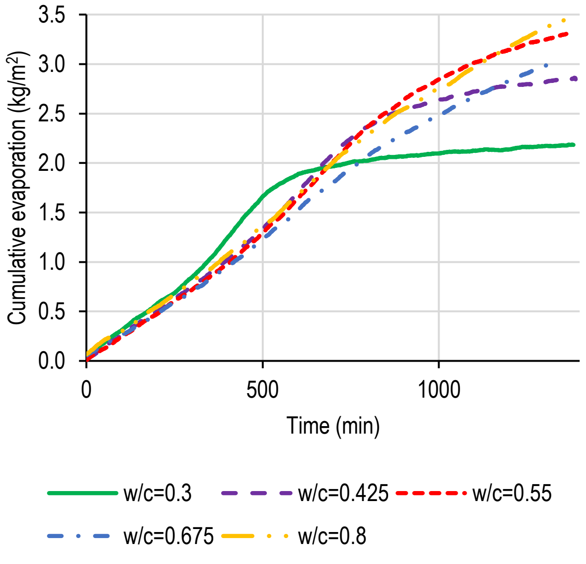

Fig. 4 Cumulative evaporation with time

Fig. 5 consists of three graphs, namely the dielectric constants over time, the cumulative evaporation over the same period for comparison, and lastly, the dielectric constants shown against the cumulative evaporation to shed more light on the relationship between the two. The initial and final set of each mixture is also indicated on each graph.

Fig. 6 shows the rate of change of the dielectric constant over time for the different water/cement ratios. It is clear the rates are similar for all the ratios tested, however, they are just phased earlier for the lower water/cement ratios. The reason for the aborted reading for w/c=0.3 at approximately 290 minutes is due to the sensors having to be removed just after final set to prevent them from having to be broken out of the hardened mortar.

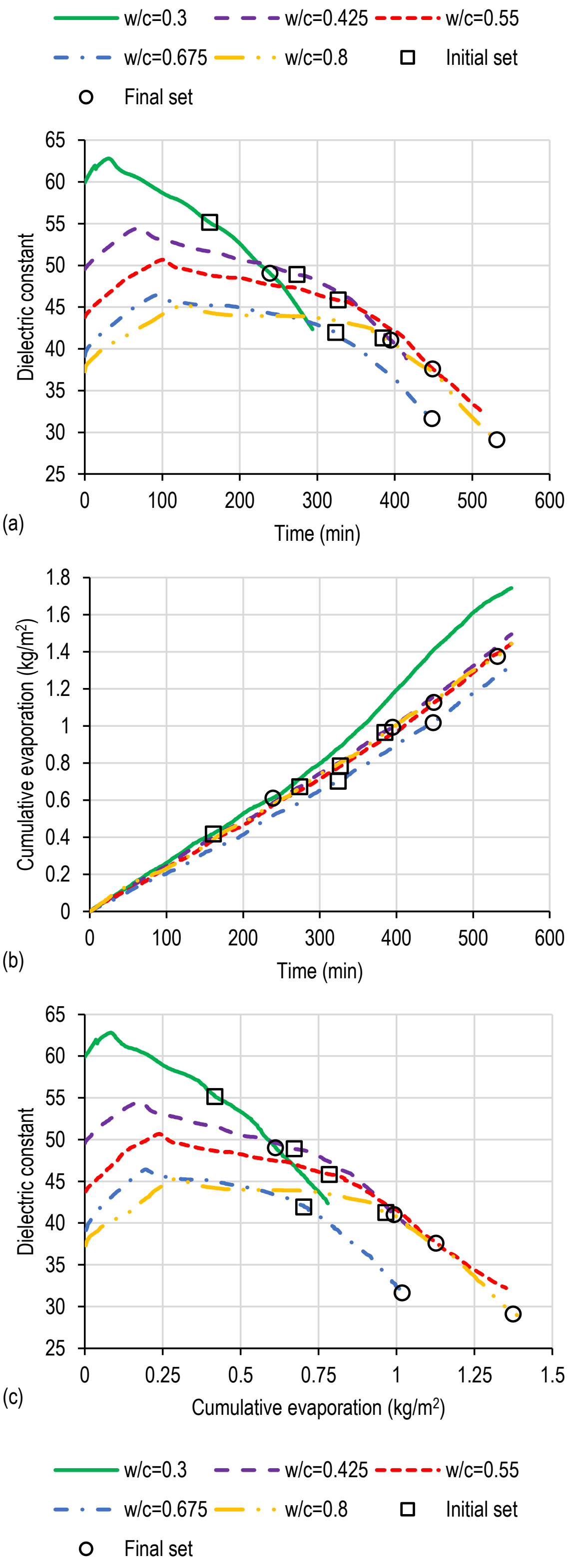

Fig. 5 (a) Dielectric constant vs time, (b) cumulative evaporation vs time and (c) dielectric constant vs cumulative evaporation

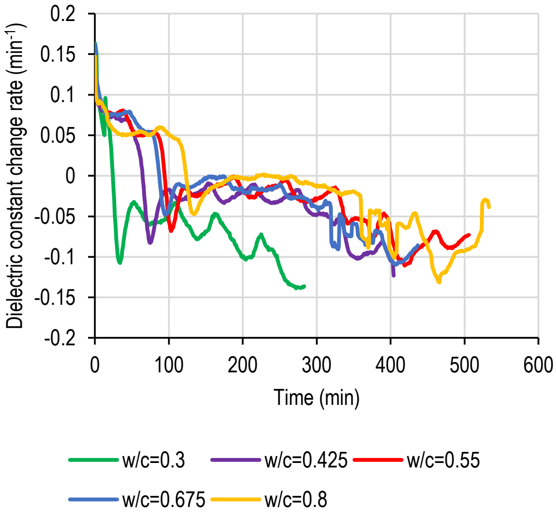

Fig. 6 Rate of change of dielectric constant with time

4 Discussion

Fig. 5 (a) shows that there are three distinct zones of dielectric response over time. These zones are illustrated schematically in **Fig. 7**. In Zone I the dielectric constant increases, in Zone II the constant decreases, and in Zone III the slope of constant decrease is steeper than in Zone II. The setting times, also plotted in **Fig. 5** (a), show that the slope change of Zone III occurs shortly after initial set. It is promising to note that all the water/cement ratios tested showed this behaviour.

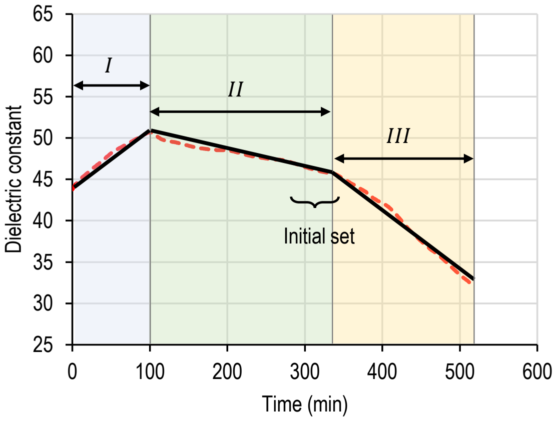

Fig. 7 Zones of dielectric constant vs time curve

From **Fig. 5** (a) it is clear that the dielectric constants at time zero are at different values for the different water/cement ratios. In **Fig. 8**, these dielectric constant values at time zero are expressed as a function of cement content because it is believed that it influences the dielectric response, rather than water/cement ratio. The peak dielectric constant values from **Fig. 5** are also included in **Fig. 8**.

Dielectric permittivity is strongly dependent on water content, but because the water content remained constant for all the mortar mixtures, **Fig. 8** shows that the dielectric constant of mortar is strongly dependent on cement content. It should be noted that the sand content was altered to alter the cement content and although the dielectric constant is relatively independent of soil type and density [10] it is suspected that the different dielectric constant are due to either the varying combination of sand and cement contents or due to only varying cement content.

Over the range of cement contents tested, 463 kg/m^3 to 1233 kg/m^3, the relationship showed a near linear relationship between the dielectric constant and the cement content. If this linear line is extrapolated to a zero cement content, the starting dielectric constant for a mix with no cement and 1670 kg/m^3 aggregate is approximately 23. Thus the dielectric constant for a mix of 82%:18% of aggregate to water by volume is 23.

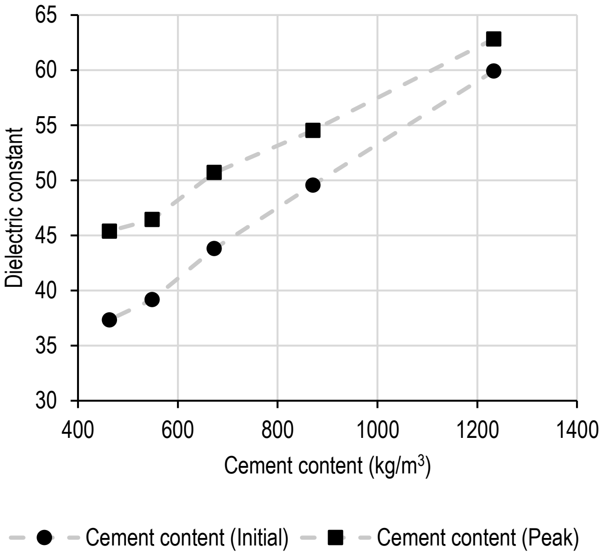

Fig. 8 Initial and peak dielectric constant values vs cement content

The peak values showed in **Fig. 8** is also significant. The values of the peak are influenced by the starting value, thus the peak values are coupled to the starting values. What is however important to note is the time until the peak for the different mixtures as a function of water/cement ratio, which is shown in **Fig. 9**. The trend is not as smooth as one would expect, but it clearly shows the time is shorter for lower water/cement ratios. As this peak indicates where the dielectric constant starts decreasing due to an accelerated loss of water or phase change of the cement, it would happen sooner in lower water/cement ratio concrete and later in higher water/cement concrete.

To accurately determine the free water in fresh concrete using the dielectric constant test, the effect of the cement content and perhaps also the phase change of the cement must be considered. This would then only work with cement that is 95% clinker before the effects of fly ash, slag, and any other supplementary materials are understood. Dielectric constants could also be used to determine the cement content of concrete and might even be able to determine the water/cement ratio if one of the two is known, or if it is combined with another type of test.

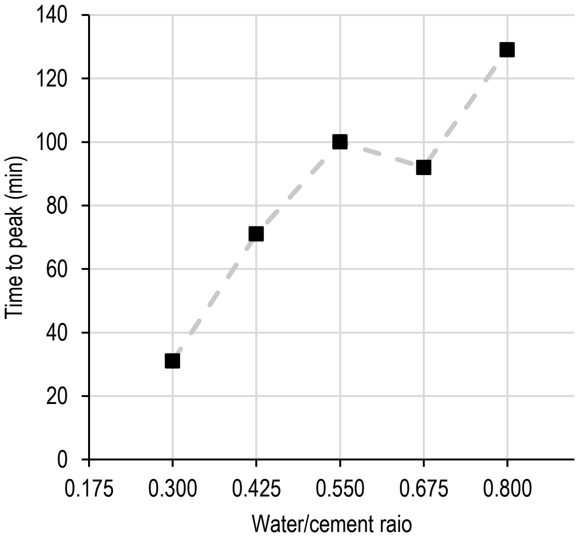

Fig. 9 Time to peak dielectric value

5 Conclusions

A study was done on the effect of time on the dielectric constant of fresh mortar of mixtures with ranging water/cement ratios and the water content remaining constant. The following conclusions can be drawn:

- Less water evaporates from mortar when a lower water/cement ratio is used (i.e. higher cement content when the water content remains constant). This is due to more cement-hydration taking place
- Dielectric constant readings can be used to follow changes in fresh mortar. It can qualitatively monitor the cement content, bleeding, hydration and evaporation in mortar samples
- The dielectric constant is strongly influenced by the cement content of a mortar, if the water content remains the same.
- Due to the simultaneous occurrence of evaporation, hydration, cement phase change from clinker to calcium silica hydrates, it is difficult for dielectric measurements to quantify the mechanisms/phenomena without input from another type of test. Further work is required in this field.

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