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Dielectric Properties and Numerical Modelling of Microwave Heating of Portland Cement/Fly Ash Blends

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ABSTRACT

Due to its volumetric heating mechanism, microwave is increasingly being recognized as a potential alternative low-energy heating technique for curing cementitious products. However, its heating capacity, among other factors, heavily relies on the dielectric properties of the raw materials, which, in turn, can be affected by moisture content, temperature and the degree of hydration. Unfortunately, current understanding on these issues is still very limited. Consequently, it is difficult to predict the heating profile of the cementitious products heated in microwave, even though a good knowledge of this is essential to optimize the microwave operation condition in order to ensure the quality of cementitious products.

In this paper, the dielectric properties of Portland cement/fly ash blends were investigated during a 24-hour hydration period under 25°C, 40°C and 60°C at a frequency of 2.45GHz. The Portland cement was replaced by fly ash at the levels of 0% and 55% by weight at water-to-binder ratios of 0.25 and 0.35, respectively. Setting times were also measured in order to interpret the changes of the dielectric properties at different stages of hydration. Based on the obtained dielectric properties data, heating models were developed using two different software packages, namely, ANSYS and COMSOL, which were then validated by the heating profiles obtained in a tailored microwave system using FBG sensor and thermal imaging techniques. It showed that both simulated results overestimated the real temperature within the sample. However, COMSOL can give a better prediction of the overall temperature profile, whilst ANSYS is more reliable in predicting single temperature. Further investigation is still needed in order to identify which modelling technique is the best option for predicting both the temperature profile and the temperature within cementitious materials cured under microwave.

1. INTRODUCTION

The manufacture of Portland cement (PC) is an energy intensive process with large amount of CO_2 emitted into the atmosphere. For every tonne of PC produced, 0.83 tonne of CO_2 is emitted. Fly ash (FA), a by-product from thermal power plant can be used as a partial replacement to PC, which can result in lower levels of CO_2 emission. For each tonne of FA, the embodied CO_2 is only 10kg (Hammond and Jones, 2008). However, low early strength is associated with high FA levels in concrete. Conventional thermal oven is, therefore, usually used to gain sufficient early strength, which, unfortunately, is energy intensive.

Microwave heating is an alternative heating solution to conventional thermal oven heating for curing concrete products due to its volumetric heating mechanism, thus, higher early strength can be obtained at low energy consumption (Wu et al., 1987, Bai et al.). Under the alternating electromagnetic field of microwave, the dipolar molecules vibrate and, thus, generate frictions between the molecules, which can convert microwave energy into heat energy instantly and volumetrically.

Although all the components in concrete, such as water, cement and aggregate, are dielectric materials, their capacity in absorbing microwave energy differs. This leads to the difference in temperature change in cementitious materials and consequently, the difference in strength development due to different temperature profile formed. *Dielectric properties* (ε*) govern the interaction between microwave and dielectric materials, which is expressed as: ε*=ε'-jε''. The *dielectric constant*, ε' is a measure of how much energy from an external electric field is stored in a material. The *loss factor*, ε'', represents the ability of a material to convert the electromagnetic energy to heat energy. (Metaxas and Meredith, 1983). Therefore, the measurement of dielectric properties is crucial for predicting the heating potential of cementitious materials under microwave.

On the other hand, the non-uniform temperature profile associated with microwave heating, i.e. the presence of hot and cold spots, and the shortage of dielectric data of various cementitious materials become the main obstacles facing the wider industrial application of microwave curing technique in construction industry (Knoerzer et al., 2006). Modelling the temperature profile formed under microwave curing provides a powerful tool for concrete industry and microwave manufacturers to simulate the heating process of different cementitious products under microwave (Boldor and Sabliov, 2011) which can then be used to optimize the microwave process parameters and microwave oven design in order to minimize the heating non-uniformity whereby to achieve optimal mechanical properties of cementitious materials with no compromise to the durability.

In this paper, the effect of water to cement ratio, curing temperature and FA replacement levels on the dielectric properties were studied respectively and two comprehensive models were developed to predict temperature profile and single temperature of microwave cured PC and PC/FA blends.

2. EXPERIMENTAL

2.1 Materials

The cement used was CEM I 42.5 supplied by Quinn Cement. Fly ash used in this study was supplied by Drax Power Station, North Yorkshire.

The dielectric properties of cement paste sample were investigated during the first 24-hour hydration period at a frequency of 2.45 GHz.

The PC was replaced by FA at the levels of 0% and 55% by weight respectively. The water-to-cement (w/c) ratios used in this study were 0.25 and 0.35.

Setting time study (both initial and final setting times) was carried out with an automatic Vicat in order to interpret the changes observed in the dielectric properties at different stages of hydration.

2.2 Tests and sample preparation

The mixing of paste and the setting time test were carried out according to BS EN 196-3.

Agilent E5071C network analyser along with an Agilent 85070E dielectric probe was applied to measure the dielectric properties.

A water bath was used to maintain the curing temperature at 40^{o}C and 60^{o}C.

A FLIR E60bx thermal camera was used to capture the thermal image of the cross section of the microwave cured sample. Fibre Bragg grating (FBG) temperature sensor was embedded in the sample in order to monitor the temperature at the centre-point of the specimen.

3. RESULTS AND DISCUSSION

3.1 Dielectric properties and setting time

Table 1 shows the dielectric properties of the raw materials (i.e. water, PC and FA) used in this study under 2.45 GHz. As expected, water is a dielectric material with much higher dielectric constant and loss factor than both PC and FA, which is expected to dominate the dielectric properties of different pastes to be investigated below.

Table 1 Dielectric properties of raw materials

	ε_r'	ε_r''
Water (25^{o}C)	77.13	9.15
PC	3.41	0.01
FA	4.18	0.06

Figure 1 shows the evolution of the dielectric properties (ε*) of PC pastes at water-to-cement ratio of 0.25 and 0.35 over time after mixing. It can be seen that both the dielectric constant (ε') and the loss factor (ε'') of PC pastes increased with the increase of w/c ratio. For the PC paste with w/c ratio of 0.25, both of the ε'' and ε' decreased remarkably after final setting. This indicates that the transformation of the free water into bound water would reduce cementitious materials' capacity in absorbing microwave energy since it is the free water which has a much higher dielectric properties (Jumrat et al., 2011).

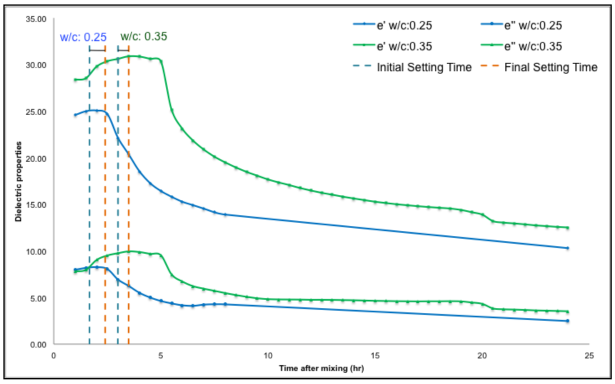


Fig. 1 Effect of w/c ratio on the dielectric properties of PC paste

Figure 2 shows the effect of curing temperature (25^{o}C, 40^{o}C and 60^{o}C) on the ε* of PC pastes. It can be seen that, compared to 25 ^{o}C, both ε' and ε'' decreased at 40^{o}C and 60^{o}C, which could be attributed to the accelerated hydration and, hence, shorter setting time at 40^{o}C and 60^{o}C. In general, the ε* at 60°C is higher than that at 40°C – it is not clear at this stage the reason behind this phenomenon. Further study is still needed.

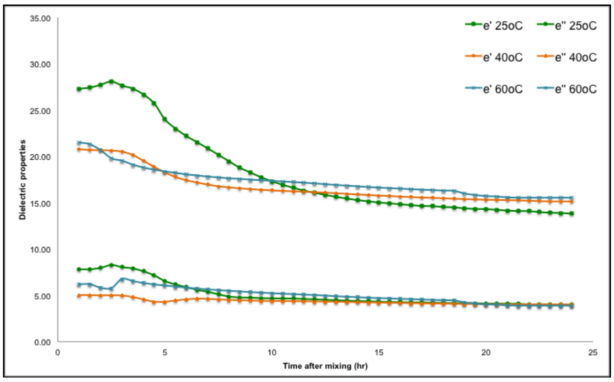


Fig. 2 Effect of curing temperature (25°C, 40°C, 60°C) on the dielectric properties of PC paste

Figure 3 shows the evolution of ε* of PC paste and 55/45 FA/PC blend over time after mixing. Overall, the ε' and the ε'' in both samples decreased over time. At the initial stage, the ε* of both samples was high, which can be attributed to the high ionic concentrations in the fresh pastes due to the dissolution of ions from the cement particles as well as the ease of mobility of the charges due to the availability of free water. This period is known as the dormant period and where the chemical composition of the aqueous changes is very little so that the properties are upheld until the final setting time (Makul et al., 2010). It can be further observed that there is a decrease of ε* over time. The coincidence of the drop of both ε' and ε'' at almost the same time is a testament of chemical activity in the system, notably an irrotational binding of charges and a decrease in the ionic concentration (Schwarz et al., 2007).

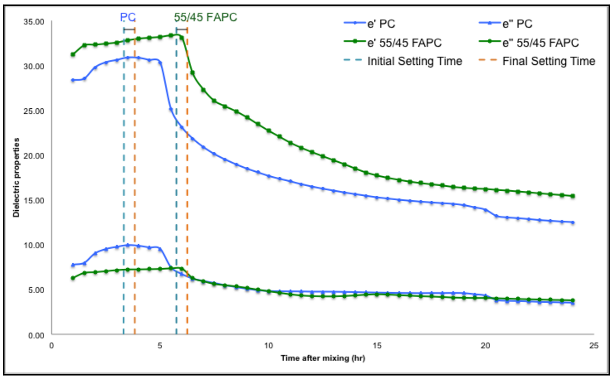
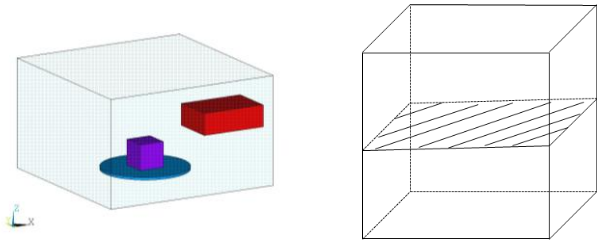


Fig. 3 Effect of replacement of FA on the dielectric properties of FA/PC blend paste (w/c: 0.35)

3.3 Modelling and validation

Computer modeling gives the opportunity to simulate any curing conditions and processing parameters under microwave, which can be used to optimize the curing process and the design of microwave systems. Based on the data obtained from the dielectric properties study, heating models were developed using two different software packages, namely, ANSYS and COMSOL, which were then validated by the heating profiles obtained in a tailored microwave system through FBG sensor and thermal imaging techniques.

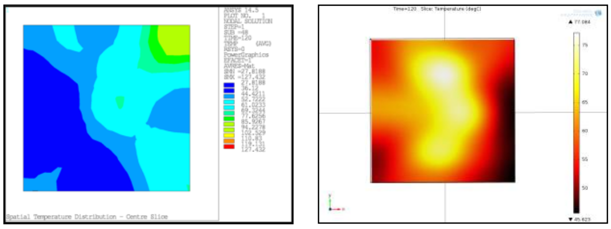
Figure 4 shows the three dimensional geometry of the microwave oven and a cubic sample (the shadowed cross-section indicates the location of simulated and validated area). A PC paste sample with a w/c ratio of 0.35 was selected to compare the reliability of the two numerical models. It was supposed that the PC paste sample was cured in the microwave oven after initial setting.



a) 3D model geometry of microwave oven   b) Cubic sample layout (50mm×50mm×50mm)

Fig. 4 Schematic diagram of microwave oven and PC sample

Figure 5 shows the cross-sectional temperature distribution of the simulation results. It can be seen that COMSOL shows a roughly radiant temperature distribution and the highest temperature is located in the core around 77°C, whilst ANSYS shows an irregular temperature distribution and the hottest spot is found in the corner around 90°C.

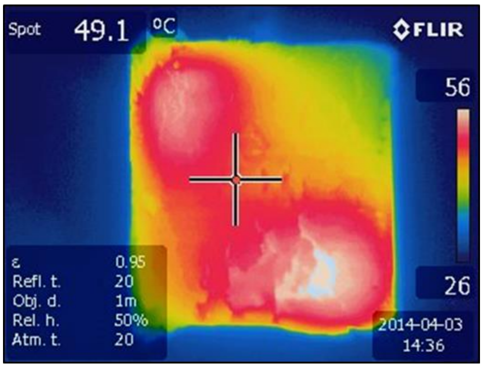


a) ANSYS   b) COMSOL

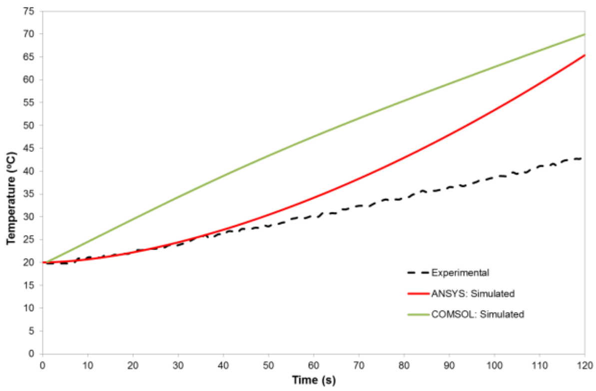
Fig. 5 Simulation results

In order to validate the above simulation results, thermal camera and FBG sensor were applied to obtain the temperature distribution and the temperature at the center point of the specimen (see Fig. 6). From the thermal image captured (Fig. 6a) by thermal camera, it can be seen that the temperature is not uniformly distributed on the cross section of the PC sample. However, the overall temperature distribution showed a radiant pattern, indicating COMSOL is more reliable in predicting the overall distribution of the internal temperature. Fig. 6b presents the comparison between FBG data from the center-point of the sample and the simulation results. It can be observed that both simulated results overestimated the real temperature in the sample. Nonetheless, ANSYS showed a very good correlation with the real temperature measured by FBG sensor up to

40 seconds after heating. After the first 40 seconds, ANSYS also showed better correlation with the real data than COMSOL. Therefore, it can be concluded that, although ANSYS is less reliable in predicting the overall heat pattern, it is more reliable in predicting the temperature within the specimen. However, it should be noted that in the current study, both models were developed without considering the thermo-physical and chemical changes during the microwave curing. Further study is still needed in order to identify which modelling technique is more suitable for predicting both the heating pattern and the temperature within cementitious materials cured under microwave.



a) Thermal imaging of cross section of the sample



b) Comparison between FBG data and simulation results

Fig. 6 Validation of simulation results by experiment data

4. CONCLUSIONS

With the increase of water-to-cement ratio, both the dielectric constant and loss factor increased, which could facilitate the conversion of the microwave energy into heat energy. However, increasing curing temperature would not benefit the absorption of microwave energy by cementitious materials.

Both simulated results overestimated the real temperature in the sample. However, COMSOL can give a better prediction of the overall temperature pattern, whilst ANSYS is more reliable in predicting temperature. Further investigation still needs to be carried out in order to identify which modelling technique is the best option for predicting both the temperature profile and the temperature within cementitous materials cured under microwave.

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