Cement and Concrete Research 75 (2015) 75–90

Contents lists available at ScienceDirect

Cement and Concrete Research

journal homepage: http://ees.elsevier.com/CEMCON/default.asp

Understanding the scabbling of concrete using microwave energy

A.J. Buttress [a,*], D.A. Jones [a], C. Dodds [a], G. Dimitrakis [a], C.J. Campbell [c], A. Dawson [b], S.W. Kingman [a]

[a] *Industrial Microwave Processing Research Group, Energy and Sustainability Research Division, UK*
[b] *Nottingham Transportation Engineering Centre, Infrastructure, Geomatics and Architecture Research Division, UK*
[c] *Sellafield Ltd, Seascale, Cumbria, UK*

ARTICLE INFO

Article history:
Received 10 June 2014
Accepted 22 April 2015
Available online 20 May 2015

Keywords:
Microwave processing
Concrete
Radioactive waste

ABSTRACT

Concrete blocks supplied by the UK Sellafield nuclear site were treated with microwave energy using a 15 kW system operating at 2.45 GHz. The effect of aggregate type (Whinstone, Gravel and Limestone); standoff distance; and effect of surface coating were studied to determine their influence on the systems performance in terms of mass and area removal rates and evaluate the controllability of the process. All blocks were scabbled successfully, with mass and area removal rates averaging 11.3 g s^{-1} and 3 cm s^{-1} respectively on treating large areas to a depth of 25 mm. The use of a Kevlar barrier between the block and applicator was found to significantly reduce the generation of dust as only 1.6% of the scabbled mass was in the <106 μm — that generally considered to be airborne. Importantly Brazilian disc testing of the scabbled block showed that the process did not adversely affect structural properties of the test blocks after treatment.

1. Introduction

Scabbling is the mechanical process of removing a thin layer of concrete from a structure. For freshly laid concrete, the technique allows roughening of the surface, so paints can adhere to it. It also provides grip for wheeled machinery and reduces slip hazards for people and animals. During concrete rehabilitation, it can be used to remove imperfections or surface coatings [1]. As a tool for end-of-life processing, it can be used for the benefaction of Recycled Concrete Aggregate (RCA) by separating the relatively weak mortar from aggregate stone. Another application of concrete scabbling is to separate potentially harmful surface contaminated concrete which may contain heavy metals, organic substances (including PCBs) or radionuclides when concrete material is used in structures within nuclear facilities [2–4].

It is the latter application that is the subject of this paper. Over the last 40 years, 85 commercial power reactors, 45 experimental or prototype power reactors, as well as over 250 research reactors and a number of fuel cycle facilities have been retired from operation [5]. The vast majority of the radioactivity (approx. 99%) is contained within fuel that is removed on decommissioning. The remainder is held in so-called 'activation products' like steel components that have been exposed to neutron irradiation over a long period of time and surface contamination of associated structures. Many of the concrete structures used in nuclear facilities have this residual radioactive contamination [2,6,7]. But often, the radionucleotide material is only contained in the concrete surface layer and typically comprises: strontium; caesium; cobalt; and uranium [8]. While this material is considered relatively low level waste, there is a need for an efficient system to remove the contaminated surface when decommissioning a site, so the remainder of the structure can be processed through a more conventional waste processing stream. By segregating the contaminated surface from the bulk concrete, reductions in the volume of radioactive material can be achieved leading to greater efficiencies in the downstream waste treatment process i.e. recycling; densification and disposal.

Mechanical methods for scabbling the surface layers of radionuclide contaminated concrete suffer from the problems associated with poor control over the depth of material removed [9]. The quality of the resulting surface can also be low leading to difficulty in additional remediation or processing. Excessive noise pollution and dust generation are also disadvantages [10]. Laser based techniques can also be used. Although the technique has been demonstrated at laboratory scale by a number of researchers [11–16], the development of a commercial system has not yet been achieved as it suffers from the perception that the capital costs are high and reliability is poor [17].

Microwave based treatment systems used for the end-of-life processing of cement and concrete have been shown at laboratory scale, to offer benefits over what could be considered traditional techniques [4,18–20]. Microwave systems used to decontaminate concrete may reduce both the amount of radioactive material generated during the scabbling process, as well as airborne contaminants released into the environment. The technique also generates less noise than mechanical methods, and may be developed for remote operation, leading to a safer operator environment [9,21].

The actual mechanism by which the concrete is scabbled is still open to debate. The earliest work by White et al. [2,22,23] suggested that the rapid heating of pore water results in high steam pressures within the

---

[*] Corresponding author at: The University of Nottingham, University Park, Nottingham, NG7 2RD, UK.
E-mail address: adam.buttress@nottingham.ac.uk (A.J. Buttress).

http://dx.doi.org/10.1016/j.cemconres.2015.04.009
0008-8846/© 2015 Published by Elsevier Ltd.

microstructure. This then causes explosive failure of the concrete in the heated zone. However, Bazant and Zi [24] reported an in depth mathematical treatment on the use of microwaves for this application. They concluded that the spalling action is the result of differential thermal stresses causing the surface concrete to explosively fail in compression when it is confined by cold concrete around the heated zone. While they acknowledged that pore pressure caused by the generation of steam does play a part, it was not considered to be a major contributing factor [24,25]. They also showed that as the frequency of the incident wave increases from 0.896 to 18 GHz, the power dissipation is increasingly confined in the near surface. These results are in agreement with the work of Akbarnezhad and Ong [4]. Lagos et al. [7] also showed in their modelling studies that increasing the frequency confines the heating effect to the surface layers, leaving reinforcement bars deeper within the concrete largely unaffected. This is important for the development of an industrial system, since the objective is to separate the contaminated surface concrete leaving the bulk material structurally sound if it is to be remediated, or processed as an inert waste. Removal of the top surface to a depth greater than were the contamination lies, not only creates excessive amounts of radioactive material, but may also damage the structure that is left behind.

While several patented concepts exist [22,26,27], there is relatively little experimental work has been reported. Much of the research was conducted between the late 1970s and early 1990s which still leaves opportunities for creating commercial scale systems. However, while the work reported to date has shown that microwave based scabbling is feasible, to develop a commercial scale system, fundamental understanding of how the process is controlled is required. This can then be used for the basis of design for an industrial system, which will then underpin the scale-up from laboratory studies to a pilot-scale unit.

Key objectives of the tests undertaken were to:

- determine the degree to which the removal (both depth and area) of material could be controlled by varying the microwave exposure time and the distance of the microwave applicator to the concrete surface (stand-off distance);
- determine the influence of concrete type on the performance (again as a function of depth and area removed) of the scabbling process; and
- understand how the generation of fines could be reduced during the scabbling process.

2. Experimental methodology

2.1. Materials

Four concrete types were selected for this study and each was supplied by Sellafield Ltd. These were newly cured concrete samples which had been manufactured specifically for this study. They were cast from cement and three aggregate types: limestone, whinstone, and gravel, as these aggregates had been extensively used in the concrete structures at the Sellafield Nuclear site in the UK. Blocks of using each type of aggregate were cast having dimensions 1 m × 1 m × 0.3 m. The compositions of the concrete blocks used in the study are presented in Table 1.

Table 1
Composition of concrete blocks used the scabbling trials.

Concrete Mix ID	Proportion kg/m^3		
	Limestone	Gravel	Whinstone
OPC	330	330	330
Sand	680	650	700
4–10 mm aggregate	400	380	460
10–20 mm aggregate	830	830	930
w/c ratio	0.50	0.50	0.50
Slump (mm)	40–50	50–60	40

The Whinstone was obtained from Tarmac Ltd, Northern Area and supplied from Barrasford Quarry, Northumberland. The largely quartz sand was supplied by Armstrong's as standard concrete grade material and similar to that used at Sellafield. Cement was standard Ordinary Portland Cement (OPC), supplied from Castle cement.

2.2. Material property characterisation (TGA and dielectrics)

The concrete specimens were characterised by determining their moisture content and dielectric properties. These are the key material characteristics that will govern their behaviour on application of the microwave energy [28–30]. Although conventionally TGA is used to identify chemical speciation due to loss of bound water and oxidisation with increasing temperature, here it was used to drive off the free water. This being defined as that held in the pore solution given that Almedia et al. [31], have shown that between 25 and 123.3 °C, TGA causes the dehydration pore water in concrete. 9–11 mg of each sample was heated at a rate of 2°min^{-1} up to 300 °C under nitrogen ($300\ \text{ml min}^{-1}$) using a Thermal Instruments Ltd. TGA Q500 SDT. The pore solution which is highly ionic, as a result it couples strongly to the applied microwave energy. So the greater the free water content of the concrete, the greater the heating effect and consequently the response to the scabbling treatment.

The dielectric properties were determined using the cavity perturbation technique. This technique has been used because of the relative simplicity of its design, and the ability to measure powdered samples at elevated temperature [32,33,29]. Dielectric properties are critical in all microwave systems to understand the response of the material to microwave energy and also to ensure efficient cavity/applicator design. In simple terms the dielectric properties consist of: the dielectric constant (ε'), which quantifies a materials ability to store electromagnetic energy through polarisation mechanisms, and the loss factor (ε'') which is a material's ability to convert this stored energy into heat through loss mechanisms [29].

A resonant circular copper cavity of diameter 550 mm and height 55 mm resonating in TM_{0n0} modes, was used for the measurement of dielectric properties [33,34]. A measurement of the quality factor and resonant frequency using the empty tube is taken at a frequency of 912 MHz and 2.47 GHz. The quality factor of a resonator (in this case the cylindrical cavity) is the ratio of the energy stored in the resonator to the energy dissipated in the dielectric material and the walls of the cavity per cycle. A representative powdered ($<38\ \mu\text{m}$) sample is then carefully weighed, and the height and diameter were then measured using a micrometer to determine its density. The sample holder was then reintroduced to the cavity, and the new resonant frequency and quality factor are measured. The dielectric constant and loss factor can then be calculated using perturbation equations [33]. The dielectric properties were then plotted as the value of the dielectric constant and loss factor as a function of frequency. Previous studies have shown that the determination of the dielectric constant and loss factor are accurate to 5 and 10% respectively using the cavity perturbation technique [32,35]

2.3. Electromagnetic modelling to understand the scabbling profile on microwave treatment

The evolved power density as a result of the applied electric field within the concrete block, as well as the associated heating response when subjected to microwave treatment was simulated numerically with the use of CONCERTO® 7.5 supplied by Vector Fields Ltd, UK. Fig. 1 shows the simulated model. It consists of a waveguide and a concrete block with the background material set to air. No electrical conductivity value was specified for the waveguide section and was taken as perfect electric conductor. The concrete block was taken as dielectric and a *.pmo file containing the dielectric properties (as characterised in Section 2.4.5), the enthalpy (J/cm^3) and the thermal