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Applications of microwave energy in cement and concrete – A review

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ABSTRACT

Microwave heating is a highly efficient technique for various thermal processes. Advantages of microwave heating compared to conventional processing methods include energy-saving rapid heating rates and short processing times, deep penetration of the microwave energy (which allows heat to be generated efficiently without directly contacting the work-piece), instantaneous and precise electronic control, clean heating processes, and no generation of secondary waste. Microwave energy processes for heating, drying, and curing have been developed for numerous laboratory-scale investigations and, in some cases, have been commercialized. Microwave energy use should theoretically be advantageous in the processing of cement and concrete materials (*e.g.*, hydraulic Portland cement, aggregate, and water). These materials exhibit excellent dielectric properties and, therefore, should be able to absorb microwave energy very efficiently and instantaneously convert it into heat.

This paper provides a comprehensive review of the use of microwave energy to process cement and concrete materials, as well as a critical evaluation of currently utilized microwave heating mechanisms and high-performance microwave systems. The current status of microwave applications and future research and development trends are also discussed, including such thermal processing methods as the high-temperature sintering of cement materials, the accelerated curing of precast concrete products, as well as the drilling and cleaning of decontaminated concrete surfaces by the built-up internal pressure. The results of this review indicate that microwave heating is directly associated with dielectric loss by the cement and concrete. Microwave processing can be used to improve clinkering and to reduce the clinkering temperature by about 100 °C. Considerations when constructing mathematical models of microwave heating for cement and concrete should include the influences of heat and mass transfer during microwave curing on the temperature difference in the concrete, the degree of uniformity of the internal structure, and the ultimate performance of the product. Future studies of microwave energy in cement and concrete applications might include investigations of adaptive (time-dependent) dielectric properties, coupling chemical reactions in the presence of microwave energy, the design and construction of suitable microwave systems, and the prediction of related phenomena (*e.g.*, thermal runaway, as a highly regulated safety issue).

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1. Introduction

Cement and concrete products are well accepted as man-made construction materials. Owing to their numerous advantages (*e.g.*, easy handling of compression forces, brittle nature that enables a rigid structure to be obtained, transportability, and durability/ability to withstand severe environments), these materials are used widely in civilian buildings and universally in infrastructures. A report on global cement use published by Morgan Stanley research [1] (Table 1) found that worldwide cement consumption decreased in the 2006–2013 period due to the economic downturn. The years 2012 and 2014 showed the slowest growth for every country in the world, except China and India, since the crisis years of 2007–2009. However, cement consumption is expected to increase gradually from 2014 forwards.

The increased production of cement and concrete leads to the increased consumption of energy. Conventionally, the cement production procedure includes a clinkering process, consisting of precalcination and pyro-processing steps, as shown in Fig. 1 [2,3]. This process requires energy consumption, especially in the cyclone preheater, precalciner (cyclone preheater plus calciner), and rotary kiln steps (burning consumes 60–70% of the fuel input). The average specific thermal energy consumption in a conventional cement clinker manufacturing process is about 31.5 GJ per ton of clinker [3].

High-level energy consumption, which refers to both a high level of consumption and a long time for the burning process, is affected by the heat transfer mechanism and the thermal conductivity of the cement-making materials (*i.e.*, calcium oxide, CaO; silicon dioxide, SiO_2; alumina oxide, Al_2O_3; and ferric oxide, Fe_2O_3). When cement is made with conventional burning using fuel (*e.g.*, oil and gas), the cement components are heated by an external heat source, and heat is transferred via conduction from the outside inward. Thermal properties, such as the specific heat, latent heat, and so on, regulate the kinetics of the heating process. However, cement-making materials have intrinsically low thermal conductivities and low heat transfer rates. Thus, they must be heated for long times until the inner portion of cement melts and sinters at a high temperature, to become a cement clinker nodule (at $\sim$1450 °C). To overcome this problem, microwave heating may be applied in the burning process of cement.

Unlike conventional heating, microwave heating principally occurs when the electric field of the microwave interacts with a material. Energy from the field is transferred to the molecular bonds of the materials. This energy transfer causes the bonds to vibrate and leads to heat dissipation within the material. Microwave heating is particularly efficient for heating dielectric materials (*e.g.*, microwave heating was at least twice as effective as conventional methods for heating dielectric materials [4,5]). Therefore, microwave heating should be useful in the cement and concrete industry, as cement-making materials exhibit excellent dielectric properties and should be able to absorb microwave energy very efficiently.

Furthermore, internal (volumetric) heating by microwave energy offers many benefits for the cement and concrete industries, including [6,7]:

- Rapid heating rates and short processing times, which save energy and time.
- Deep penetration of the microwave energy (in cement and concrete materials, a microwave system operating at 2.45 GHz can typically penetrate several centimeters), which allows heat to be generated efficiently without directly contacting the cement constituents.
- Instantaneous and precise electronic control, which is convenient for designing and constructing heating systems.
- Unique and fine microstructural development, which permits better properties of produced cement.
- Clean heating processes that do not generate secondary waste.

Based on International Telecommunication Union (ITU) regulations, the electromagnetic frequency band for non-telecommunication (*e.g.* industrial, scientific, and medical) purposes ranges from 6.765 MHz to 246 GHz. Microwaves are electromagnetic waves with frequencies ranging from 300 MHz to 300 GHz (wavelengths from 0.001 to 1.0 m). Microwave systems operate at average frequencies of 896 $\pm$ 10 MHz (in the UK), 915 $\pm$ 13 MHz (in North and South America), and 2450 $\pm$ 5 MHz (worldwide, except where 2375 $\pm$ 50 MHz is used), as assigned by the International Microwave Power Institute (IMPI). When used for Industrial, Scientific, and Medical (ISM) purposes, microwave systems are most often operated in the range from 433.92 MHz to 40.00 GHz [4].

Many investigations and practices have recently reported using microwave heating for concrete applications, such as for accelerated curing [8,9], decommissioning and decontaminated surfaces [10,11], and drilling/melting [12,13]. Moreover, microwave systems have been applied as high-performance nondestructive monitoring and surveying methods for cement and concrete structures [14,15].

This paper offers a comprehensive and systematic review of the use of microwave energy in cement and concrete materials. This review systematically summarizes important results from previous experimental and numerical studies, covering such areas as the