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A novel rapid microwave-thermal process for accelerated curing of concrete: Prototype design, optimal process and experimental investigations

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HIGHLIGHTS

- Novel rapid microwave-thermal process for accelerated curing of concrete.
- MW at an operating frequency of 2.45 GHz and at powers of 400 W and 800 W.
- A mobile microwave (MW)-assisted curing unit was designed.
- Mathematical models were applied to design a horn-shaped MW cavity.
- MW energizing for 15 min/time and a paused duration of 60 min were included.

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ABSTRACT

In this work, a mobile microwave (MW)-assisted curing unit for the accelerated curing of concrete workpiece is designed based on coupled electromagnetic (MW)–thermal analysis. The design of this unit is described together with experimental investigations into the heating characteristics of concrete workpiece subjected to the MW-accelerated curing process. Mathematical models are applied to design a horn-shaped MW cavity and as a basis for constructing a stationary and a moving MW-accelerated curing unit that uses MW energy at an operating frequency of 2.45 ± 0.05 GHz and at powers of 400 W and 800 W. The experiments included the effects of MW curing on the temperature evolution, moisture content variation, and compressive strength development properties of the concrete. Also, the concrete workpiece was compared to water-cured conventional concretes and air-cured conventional concretes on the basis of these properties. Based on the concept of antenna, a rectangular horn-shaped cavity of 246.7 mm wide × 333.68 mm long is designed showing a uniform thermal distribution for concrete curing. From the experiments, it was found that the application period for curing using the mobile MW-curing unit was considerably shorter than for conventional curing methods. The appropriate preheating interval is 30 min, and MW energizing for 15 min/time and a paused duration of 60 min produces maximum compressive strength. However, the time needed for curing was considerable. When concrete was heated using MW energy for more than 90 min at over 80 °C, the effect was a continuous decrease in compressive strength. Further, at early age, the compressive strength development of the concrete workpiece subjected to MW curing was greater than that achieved by air curing or water wet-curing.

1. Introduction

Microwave (MW)-assisted heating has emerged as an innovative and popular heating-process technology for dielectric materials. A particularly efficient technique for thermal processes, MW-assisted heating can considerably reduce the time needed for heating/drying. A number of other analyses of the microwave heating process have appeared in the recent literature [1–4]. MW-assisted heating has been used successful in numerous industrial processes, including the following:

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- Food and biological materials: Regier and Schubert [5] published a book in which they give an account of a wide range of microwave processing applications used worldwide including blanching, thawing, and packaging. Afrin et al. [6] investigated thermal lagging in living biological tissue and found that the phase lag times for temperature gradient and heat flux are indistinguishable in the respective cases of blood and tissue. Irishina et al. [7] studied a level set evolution strategy in microwave imaging for early breast cancer detection. Basak [8] studied thermal MW processing and concluded that it is an efficient way to produce a high temperature in a customized plane-wave oven.
- Wood: Perre and Turner [9] presented the effects of the combined convective and microwave drying of softwood by focusing on predicting the locations of hot spots and thermal runaway within the workpiece from the viewpoint of product quality. Kaensup et al. [10] used a combined microwave fluidized bed dryer to dry pepper seeds. The results indicated that MW energy dried the pepper seeds at a faster rate than a conventional fluidized bed did.
- Accelerated-curing and repairing of concrete: Leung and Pheeraphan [11] showed that MW energy can be used to cure concrete for practical construction applications. Makul et al. [12] used MW energy at an operating frequency of 2.45 GHz and a multi-mode cavity to cure early-stage Portland cement paste. Their research showed that based on steady heat transfer conduction the temperature increased consistently in accord with the mathematical model.

Up to the present time, the focus of research and development pertaining to the technology used to repair concrete has focused on reducing the time taken to complete repairs. However, the time needed to cure concrete is still lengthy and the process relies on conventional curing technology for repairs such as applying a curing compound, water ponding [13], and using a wetting sag to cover the concrete surface so that the concrete retains moisture content. This long period leads to problems; for example, when roads are repaired, traffic jams inevitably ensue as fewer lanes are available. Therefore, any method such as the use of streams or hot air with the potential to reduce the time needed in the initial concrete-curing phase is of great interest. However, these methods have the drawback of producing intermittent thermal distribution in concrete, leading to a reduction in compressive strength and causing the internal structure to break down [14]. Therefore, MW-heating technology applied to concrete curing in the initial phase is advantageous because heat can be produced in a way that is more efficient than with other methods.

It is well known that thermal-curing methods have an adverse effect on the properties of concrete—both at early age and in the long term. Therefore, a crucial question arises: Can the MW-heating method be applied in the concrete industry? Theoretically, it is possible. This is because materials used to make concrete, such as hydraulic Portland cement, aggregates, water, and admixtures are dielectric; i.e., they can absorb MW energy effectively. For example, Xuequan [15] proposed a new kind of MW-curing technique for concrete. Based on removing free water from the internal concrete's structure before any plastic shrinkage and loss of porosity has taken place, the strength and durability of the concrete significantly developed. In addition to Hutchison's [16] research in this area, and Sohn and Johnson [17] used MW energy to accelerate the curing process without incurring any significant loss of compressive strength in the cement mortar.

As a principal material in the production of concrete, water should be considered carefully in regard to the curing process. In particular, compared with the other components of concrete, water has a relative dielectric constant (ε_r') and loss tangent (tan δ) with higher values. As a result, when the electric field $\vec{E}$, which is a main part of the electromagnetic field, interacts with the concrete's constituents, MW electromagnetic energy is quite dramatically transferred and then converted into heat via an interaction with water molecules. This mechanism causes the bonds of polar molecules to vibrate such that energy is dissipated as heat and transferred within the concrete workpiece to be processed, thus giving rise to accelerated hydration reactions. Consequently, free water molecules in the capillary pores of the concrete are quickly removed from the internal concrete structure before setting, which means that plastic shrinkage from drying is taking place. The result is the collapse of the capillary pores collapse and microstructure simultaneously becomes more dense.

However, MW-assisted heating is still limited in terms of the types of concrete materials to which it can be applied. In this regard, Jeppson and Calif [18] reported that MW-assisted heating could only be used for conventional concrete. Until the present time, the non-uniformity of temperature distribution has been a main problem in attempts to use continuous MW heat in concrete applications [19]. The disadvantage of the dielectric materials is that its thermal distribution is inconsistent, which leads to problems associated with hot spots and cold zones [20]. Therefore, MW distribution with multi-mode cavity has been developed using MW technology applications whereby concrete is heated such that its moisture content evaporates while heat is transferred to its top surface.

The present research focuses on the design and construction of a portable prototype for concrete-accelerated curing that relies on applying MW energy. Experiments are performed, and the results are reported. The studied parameters are temperature evolution, moisture content, curing time, and compressive strength. Further, a comparison of MW curing and conventional (air or water) curing is also presented.

2. Design of a horn-shaped cavity using a mathematical model

It is generally accepted that uneven field distribution generates cold and hot spots and that the latter can contribute significantly to the phenomenon of runaway. For dielectric products (such as concrete), cold spots are unwelcome as they induce the internal structure to break or crack, thereby undermining the concrete's performance and rendering the concrete less durable. It is for this reason that a uniform electromagnetic heating is normally required. Researchers have devised multiple ways to improve the electric field as well as to improve heating distribution by varying the degree of achievement by changing either the source, the MW feeding system, the shape of the cavity, or the environment surrounding the load. Some ideas have been developed in regard to empty cavities; however, these do not work in applied situations [21]. For analysis, electromagnetic waves in the cavity were simulated to design the MW–vacuum system. The distributions of electric field strength and mode generation were studied in the simulation. The COMSOL MULTIPHYSICS® program version 3.4 [22] was used to construct domain meshes and the Finite Element Method (FEM) was employed to solve the problems. Generated resonant modes inside the multimode cavity, where the reflections from the cavity walls constructively reinforce each other to produce a standing wave, were calculated by determining the number of half-wavelengths in each of the principal directions. The quality factor (Q-factor) and the maximum electric field strength (E_{max}) were calculated by using the equations found in [19]. The time-average complex power flow through a defined closed surface was calculated from Poynting's theorem [23] when a MW source is connected to the cavity.