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Development of microwave-assisted sintering of Portland cement raw meal

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ABSTRACT

Typically, using a rotary furnace as a heat generator, a temperature of approximately 1450 °C and a time of 60 min is needed to produce clinker requiring large amounts of energy. Recently, a method of sintering Portland cement by microwave furnace has been developed with the aim to reduce this high consumption of energy in the conventional cement production. In this work, cement raw meal was calcined by a microwave furnace operating at 2.45 GHz with 900 W at 1150 °C at several periods of time but was not completely successful in terms of clinker formation. Therefore, an electric furnace was used at 1300 °C and 1350 °C for 30 min to further heat the material. Chemical compositions of the formed clinker, characterized by XRD, presented C_3S, C_2S, C_3A and C_4AF as the main constituents confirming a clinker similar to those of clinker produced by rotary kiln or conventional technique. Loss on ignition and insoluble residue of the resultant clinker were analyzed by chemical analysis and the results were found to pass ASTM C-114. It was found that the raw meal sintering process using a microwave furnace followed by transfer to an electric furnace could reduce not only the temperature by at least 100 °C but also the processing time of the clinker. In addition, there is no grinding cost for clinker preparation in this process. This processing of clinker would decrease energy consumption and carbon dioxide emission to the atmosphere, a major cause of global warming.

1. Introduction

Portland cement is currently widely used to build various constructions because of its high compressive strength. Cement production is a high-energy consumption process, especially in clinker production (Bye, 1999). Most energy is consumed in the burning process for clinkerization. It was found that the burning process requires approximately 3.2–6.3 GJ of energy per ton of clinker production (Ying et al., 2010) and the energy is generally associated with CO_2 emission (Parrott, 2002). Behind power generation, the cement industry has always been among the largest CO_2 emitting industries (Fairbairn et al., 2010) with its processing emitting around 900 kg of CO_2 for every ton of cement production (Benhelal et al., 2013) and affecting the level of greenhouse gas emissions and contributing to the global warming issue. In the conventional process of cement manufacture high temperatures are maintained by rotary furnace around 1450 °C for 60 min to obtain the clinker, however the clinker process, through microwave furnace, needs lower temperature (Fang et al., 1996).

Microwave heating is a process of microwave-material interaction. The heating efficiency mainly depends on the dielectric properties of the material to be heated (Fang et al., 1996; Makul et al., 2014). Microwave heating is superior to conventional heating methods in terms of energy-saving, rapid heating rates and short processing times (Fang et al., 1996; Makul et al., 2014; Long et al., 2002). A 95% of energy saving can be achieved with the use of microwave energy over conventional heating techniques

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(Quemeneur et al., 1983). Microwave processing of ceramic materials has been reported by several researchers (Fang et al., 1996; Makul et al., 2014; Long et al., 2002; Minay et al., 2004; Leonelli et al., 2006; Monaco et al., 2015).

Calcium oxide (CaO) and magnesium oxide (MgO) are the typical clinker components, which account for 64–68% of the clinker weight. Normally, limestone used in cement production has 75–90% $CaCO_3$ in raw meal. Most CO_2 is produced in converting calcium carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$) into CaO and MgO when the temperature is above 900 °C.

At this stage, the CO_2 leaves the system and the raw meal loses over one third of its original weight. When the temperature reaches 1300–1450 °C, the reaction of clinkerization takes place, with parts of the materials becoming liquid, and finally, nodules known as clinker are formed (Tianming et al., 2015). The aim of this research was to utilize the microwave furnace operating at the frequency at 2.45 GHz at 900 W to reduce the sintering temperature by at least 100 °C and reduce times in order to decrease energy consumption and produce less CO_2 emission to the atmosphere.

2. Experimental

2.1. Materials preparation and sintering

At first, the raw meal of commercial type I Portland cement was intended to use for clinkerization by only microwave technique with a microwave furnace (CEM, MAS7000, USA, 900 W, max temp. 1200 °C). This furnace has a limitation of a maximum temperature of 1150 °C which was used for the microwave sintering. So, in addition an extra electric furnace (Nabertherm, HT18, Germany, 1200 W, max temp. 1800 °C) was utilized, for final sintering of the raw meal (at 1300 °C and 1350 °C).

The specimens were prepared by slightly compressing the raw meal powder (20 g) into alumina boats (of volume 25 ml), and then heating in a microwave furnace at 1150 °C for soaking times of 1, 3, 5, 7, 9, 11 and 20 min, respectively. Consequently, all specimens were brought to continue sintering in an electric furnace at either 1300 °C or 1350 °C for 30 min and the resultant clinkers obtained.

2.2. XRD characterization

The mineralogical compositions of the raw meal, commercial clinker and resultant clinkers were characterized. They were investigated by x-ray diffraction (XRD) (X'Pert, Philips, Netherland) in order to determine the optimum sintering conditions. The diffraction patterns of resultant clinkers were recorded by using Cu K_α radiation and generator setting was 40 kV excitation potential with a current of 35 mA. The programs typically used were scanned from 10° to 60° 2θ with step size 0.02° 2θ.

2.3. SEM analysis

The microstructures of resultant clinkers were determined by a scanning electron microscope (SEM) (XL 30, Philips) on the powders glued to Al stub with an accelerating voltage of 15 kV.

2.4. Chemical analysis

The main compounds of clinker such as SiO_2, Fe_2O_3, Al_2O_3, CaO and MgO, loss on ignition (LOI), insoluble residue (IR) of the commercial and resultant clinkers were characterized by wet chemical analysis according to ASTM C114-04 (ASTM, 2004).

2.5. Compressive strength

The compressive strength of the mortar from commercial and the experimental clinkers was determined by a universal testing machine (UTM) (Shimadzu, Japan). The mortars of both commercial clinker and experimental clinkers were prepared with a water: clinker: sand ratio of 0.485: 1: 2.75. The pastes were cast and compacted by tamping for two layers in cube molds ($2.5 \times 2.5 \times 2.5$ cm^3). Mortar cubes were demolded after being at room temperature for 24 h. Consequently, they were cured in a plastic box under water for 7 days and then tested for compressive strength according to ASTM C 109-02 (ASTM, 2002).

3. Results and discussion

3.1. XRD analysis

The XRD patterns in Fig. 1 show sharp peaks for the raw meal and commercial clinker corresponding to $CaCO_3$ (01-072-1650), SiO_2 (00-046-1045), $NaAlSiO_4$ (01-076-1733), C_3S (Ca_3SiO_5: 00-042-0551), C_2S (Ca_2SiO_4: 00-049-1672), C_4AF ($CaAl_2Fe_4O_{10}$: 00-021-0830), C_3A ($Ca_3Al_2O_6$: 00-038-1429) and CaO (00-002-1088).

XRD patterns of the resultant clinker prepared in the microwave furnace for different soaking times follower by an electric furnace at 1300 °C are shown in Fig. 2. The peaks of the main compounds of clinker such as C_3S, C_2S, C_4AF, C_3A and, especially, free lime (CaO) (37.4 and 53.8° 2θ) were found. Their effect on the mortar strength is discussed in Sections 2.5 and 3.4. With the aim to enhance the reactivity of the free lime, higher temperature treatments at 1350 °C with an electric furnace were performed. Microwave furnace sintered samples followed by electric furnace sintering at

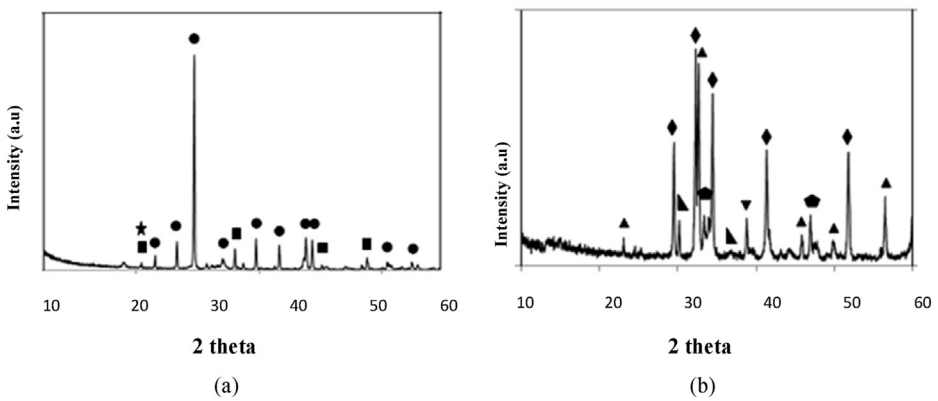

Fig. 1. XRD patterns of (a) raw meal and (b) commercial clinker. ● $Ca(CO_3)$ ■ SiO_2 ★ $NaAlSiO_4$ ◆ C_3S ▲ C_2S ◣ C_4AF ⬟ C_3A ▼ CaO.

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