

Rapid starch consolidation of red clay-based ceramic slurry under simultaneous pressure-cooking and microwave irradiation

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Abstract

This study presents a simultaneous application of pressure cooking and microwave irradiation to consolidate ceramic slurry as a rapid shaping technique. The ceramic slurry, composed of red clay, feldspar, quartz and water, was solidified with the gelatinization of starch under varying heating conditions inside a domestic microwave pressure cooker. It was found out that, for a small amount of ceramic slurry, a shortest heating time of 2.52 min was achieved at microwave pressure cooking conditions of 50% power level and target temperature of 60 °C. Based on these conditions, large shaped ceramic prototypes of different shapes were successfully formed using proposed empirical equations to determine a desired heating time at any power levels. The physical characterizations revealed that the physical properties of dried and fired ceramic bodies formed under microwave pressure cooking were better than that of the conventional counterpart. Microstructural investigation into the fired samples revealed larger void spaces in conventional sample than that in microwave pressure-cooked sample.

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1. Introduction

The starch consolidation technique has been widely explored in the field of ceramic processing for forming ceramic materials through the use of starch loaded in ceramic slurry. The starch has gained popularity in ceramic processing as a pore former and forming agent owing to the lack of environmental concerns and defect-free burnout. The benefit of using starch is economically cheap for implementation in ceramic processing to produce porous ceramic compacts with diverse applications. This technique has been commonly applied to shaping ceramic powders, such as pure oxide ceramics [1–3], mullite [4], and cordierite ceramics [5]. Interestingly, important applications are gaining renewed interest for clay-based systems involving a ternary mixture of red clay, quartz and feldspar [6–8]. The clay, containing iron impurity, imparts

plasticity to the powder mix while the quartz provides filler during compaction. The inclusion of feldspar in the powder mixture reduces the firing temperature of the resulting ceramic compact. This ternary ceramic mixture offers possibility to synthesize an antibacterial ceramic filter containing natural iron and alkalis for water purification and wastewater treatment [7].

The solidification of the ceramic slurry to form a ceramic compact is imparted by the gelatinization of starch at elevated temperature. This thermal effect is a complex process, involving granule swelling and disruption of two polysaccharide molecules of starch: amylose and amylopectin [9]. The amylose is a predominantly linear molecule linked by α -1,4 bonds, and amylopectin is a highly branched polymer with branch points linked by α -1,6 bonds. The ratio of amylose and amylopectin affects the physicochemical properties of starch. In ceramic processing, the starch is commonly mixed with the aqueous ceramic suspension and poured into impermeable mold, which is subsequently heated up to a gelatinization temperature between 55 °C and 80 °C. This gelatinization

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process is usually associated with impairment and rearrangement of the intermolecular bonds in the polymeric constituents [10], while heat is applied on the ceramic slurry. During this heating process, a rapid and irreversible swelling of the starch granules takes place by water uptake that consolidates the ceramic slurry into a solid compact. The alteration of the starch granules by heat leads to increased viscosity of the slurry, which finally locks water causing the solid particles to stick together and consolidate into a rigid body [11]. Therefore, the success of the starch consolidation technique depends upon the heat transfer between the mold material and the ceramic slurry, and the method of heating employed to achieve homogeneous gelatinization of the starch component.

The starch-loaded ceramic slurry is conventionally heated in a convection oven to effect the thermal-assisted consolidation. The applied heat is transferred from the mold material to the ceramic slurry, which subsequently elevates the slurry temperature. This heating method works very well for small amount slurry, but it poses serious problems for a large amount of ceramic slurry due to a long heating time in achieving the gelatinization temperature of the starch. The long heating time results in non-uniform heating of the ceramic slurry and unavoidable sedimentation of ceramic particles. To resolve these heating problems, a microwave heating process has been explored to solidify ceramic slurries being loaded with thermally responsive consolidating agent [12]. This heating method allows uniform heating of ceramic slurry at a relatively short time due to the volumetric heating effect [13]. It means that the heating process starts from the interior of the material to its surface, leading to uniform temperature distribution. Although this method presents some advantages over conventional heating, it poses some challenges with the use of high microwave power and the heating of ceramic slurry contained in a sealed/unsealed mold. A sudden build-up of pressure is developed due to fast heating process that causes spilling and boiling of the ceramic slurry. Moreover, it is only effective for solidifying ceramic slurry at low power level (about 10%) to avoid the sudden build-up of pressure [12]. Thus, the microwave heating method also presents long heating time for the large amount of slurry, which reduces the production volume.

To avoid the boiling of ceramic slurry under the microwave field, a heating method that takes advantage of the elevation of the boiling point of water was successfully explored with the use of domestic pressure cooker [14]. This method assures the attainment of the pasting or gelatinization temperature of starch in the ceramic slurry as compared with the conventional heating process. However, the issue of long heating time was partially solved because it relied on the heat transfer of the materials and the pre-heating of the pressure cooker and the load to cause pressurized steam heating [15]. Thus, the present study demonstrates a simultaneous pressure cooking and microwave irradiation to consolidate red clay-based ceramic suspension loaded with the starch powder. This can be conveniently carried out inside a microwave pressure cooking system that speeds up the gelatinization of starch and shortens the heating time. This new system operates with the same

heating principle as the conventional pressure cooker [15,16]. The difference with this new system is that the whole assembly is made up of microwave transparent materials [17]. This means that only the loads that couple microwaves are heated while steam is produced to elevate the internal pressure in a very short time. The sudden boiling of ceramic slurry due to microwave irradiation is possibly avoided by the pressurized environment, owing to the boiling point elevation of the liquid involved [18].

This study aimed to investigate the consolidation of red clay-based ceramic suspension using the gelatinization of starch inside a domestic microwave pressure cooker. Specifically, this study has fourfold aims: (i) determine the optimum power level, microwave exposure time and temperature in terms of the gel strength of a green body, (ii) compare the physical properties of the microwave pressure-cooked consolidation to the conventional method of starch consolidation, (iii) investigate the microstructures of fired ceramic bodies formed under the microwave pressure-cooking and the conventional method of starch consolidation, and (iv) fabricate different shapes of prototypes formed under microwave pressure-cooked consolidation.

2. Materials and experimental procedures

2.1. Preparation of raw materials

The red clay used as plastic material was mined in lumped form from Lama–Lama, Tubod, Lanao del Norte, Philippines. It was dried in a conventional oven for 4 h at 110 °C to completely remove all the moisture present. The dried clay was crushed in a ball mill and passed through 100 mesh sieve with the help of a rotary shaker. The non-plastic materials such as feldspar and quartz were commercially available with average particle size (LS 100Q, Coulter Corporation) of 35.1 µm, and 27.0 µm, respectively. Correspondingly, the chemical composition of the ceramic raw materials is given in Table 1. These powdered materials were dispersed in distilled water with the aid of sodium tripolyphosphate (STPP). The non-plastic materials and dispersant were supplied by Elmar Marketing, Mindanao, Philippines. A commercially available potato starch was used as a binding agent with an average particle size of 40.92 µm. A small cylindrical mold cavities (diameter: 2.94 cm and height: 3.45 cm) for a small amount of slurry were assembled by cutting an acetate film and attaching the cut pieces with double-sided tape and masking tape.

Table 1
Chemical composition of the raw materials.

Materials	Oxide contents							
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	CaO	Na ₂ O	K ₂ O	I.o.i.
Red clay	41.6	25.2	8.2	1.1	0.5	0.5	0.5	22.4
Quartz	95.1	1.7	0.4	1.4	0.5	0.1	0.3	0.6
Feldspar	66.3	21.5	0.3	0.5	2.4	8.5	0.1	0.4

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