Effect of heating rate on gas emissions and properties of fired clay bricks and fired clay bricks incorporated with cigarette butts

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ABSTRACT

In general, the firing process of clay bricks generates a range of gas emissions into the atmosphere. At high concentrations, these volatile emissions can be a serious source of environmental pollutions. The main purpose of this study was to evaluate the effect of different heating rates on gas emissions and properties during the firing of clay bricks and clay bricks incorporated with cigarette butts (CBs). In this investigation, four different heating rates were used: 0.7 °C min⁻¹, 2 °C min⁻¹, 5 °C min⁻¹ and 10 °C min⁻¹. The samples were fired in solid form from room temperature to 1050 °C. During the firing cycles, carbon monoxide, carbon dioxide, nitrogen oxides, hydrogen cyanide and chlorine emissions were measured at different heating rates. All bricks were also tested for their physical and mechanical properties including dry density, compressive strength, tensile strength, water absorption and initial rate of absorption. Results show that gas emissions were reduced significantly with higher heating rates (10 °C min⁻¹) followed by 5 °C min⁻¹ and 2 °C min⁻¹ for both types of brick samples. Higher heating rates also decrease the compressive strength and tensile strength value but demonstrate an insignificant effect on the water absorption properties respectively. In conclusion, a higher heating rate is preferable in terms of decreasing gas emissions and it is also able to produce adequate physical and mechanical properties especially for the CB brick.

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1. Introduction

Brick is one of the most accommodating masonry units due to its properties. The firing process of clay bricks generates a range of gas emissions into the atmosphere. These gases include water vapour (H₂O), oxygen (O₂), carbon monoxide (CO), carbon dioxide (CO₂), sulphur dioxide (SO₂), ammonia (NH₃), chlorine (Cl₂) and fluorine (F). At high concentrations, these volatile emissions can be serious sources of environmental pollutions (Morgan, 1993). Therefore, innovation in the firing process is essential to prevent the environmental impact of the brick manufacturing process.

Many studies have been carried out to investigate the evolved gas from fired clay bricks. Attempts have been made to investigate the volumes of gases released at different temperatures and their correlations with the clay properties; see for example the studies by Parsons et al. (1997), Santos et al. (2003) and Toledo et al. (2004). In particular, Dunham et al. (2001) and Rasmussen et al. (2012) investigated shorter firing times in the manufacturing of clay bricks while Dondi et al. (1999) compared the influences of fast firing and traditional firing on physical and mechanical properties of clay bricks. Gonzalez et al. (2002), Cusido et al. (2003), Gonzalez et al. (2006), Gonzalez et al. (2011) and Shen et al. (2013) emphasised the reduction of gas emissions, specifically of fluorine, chlorine and sulphur, by controlling the firing temperature and mineral contents of the clay during the manufacturing process. Nevertheless, previous research provided very limited discussion on the effect of different heating rates, particularly on the gas emissions and on physical–mechanical properties of manufactured fired clay bricks. In this study, two types of brick samples were used: the clay bricks and clay bricks incorporated with cigarette butts (CBs). Recycling cigarette butts as an inert component into clay bricks can be a practical solution to one of the important pollution problems in the world (Abdul Kadir and Mohajerani, 2010, 2011; Abdul Kadir et al., 2010). The main purpose of this study is to evaluate the effect of different heating rates on gas emissions during firing as well as the properties of clay bricks and bricks incorporated with CB. In this investigation, the gas emissions are presented as Estimated Total Emission (ETE). The ETE is the estimated total gas emission from the fired brick samples during the heating period.

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2. Materials and methods

In this study, in order to investigate the evolved gas released under conditions analogous to the actual clay brick firing process, clay brick and CB brick samples are prepared in extruded forms. The chemical composition of the raw clay samples was determined using an X-ray fluorescence analyser (XRF) and the major crystalline phases of silt and clay fraction of the brick soil were examined using a Bruker X-ray diffractometer (XRD).

The preparation of the manufactured fired clay brick and CB brick samples was explained in detail in previous studies (Abdul Kadir and Mohajerani, 2010, 2011; Abdul Kadir et al., 2010). In this investigation, clay brick and fired clay brick samples with 5% of CB content were prepared. The brick samples were manufactured in three different sizes: cube (100 mm × 100 mm × 100 mm), brick (225 mm × 110 mm × 75 mm) and beam (300 mm × 100 mm × 50 mm), in compliance with the minimum requirements for testing under the relevant Australian/New Zealand Standards (AS/NZS 4456.1, 2003). The mixes were made using a Hobart mechanical mixer with a 10 l capacity for 5 min. In order to achieve uniform distribution of CBs, they were initially mixed with dry soil in the mixer and then water was gradually added to the mix. Potable water was used for the optimum moisture content in order to make high dry density brick samples. Before compaction, the test mould was sprayed with oil to prevent any effect of the mould inner wall on the sample. The samples were compacted manually by pressing and kneading the mixes in the respective moulds using predetermined masses corresponding to the maximum dry density. The brick samples were dried in an oven at 105 °C for 24 h prior to heating experiments.

Four different heating rates were used: 0.7 °C min⁻¹, 2 °C min⁻¹, 5 °C min⁻¹ and 10 °C min⁻¹. The samples were fired in solid forms from room temperature to 1050 °C. The procedure developed is shown in the flow diagram (Fig. 1). The gas detector (Industrial Scientific iBrid Multi-Gas sensors) used in this study was equipped with five gas sensors for carbon monoxide (CO), carbon dioxide (CO₂), chlorine (Cl₂), nitrogen oxide (NO) and hydrogen cyanide (HCN). These gases are the expected main gases emitted from fired clay bricks. The iBrid Multi-Gas sensors are temperature-compensated using an on board temperature sensor that enables accurate readings across the full temperature range of the instrument. Furthermore, an internal gas-permeable filter is provided to limit the amount of dust and contaminants that may enter the internal sensor chamber and affect the sensor readings. The instrument also alerts the user audibly and visually if over-range values are detected. Over-range values are those values outside the normal operating ranges of the sensors. Moreover, the iBrid instrument utilises optical media interfaces for infrared data transmission (IRDA) at a speed of 115,200 bytes/s and can save up to three months of data collected at 1 minute intervals for five sensors simultaneously. The detection limit range for CO is from 0 ppm to 1500 ppm, CO₂ is from 0% to 5% by volume, Cl₂ is from 0 ppm to 50 ppm, NO is from 0 ppm to 1000 ppm and HCN is from 0 ppm to 30 ppm. The principal means used to determine CO, Cl₂, NO and HCN is by using an electrochemical sensor while for CO₂ an infrared sensor is used.

2.1. Estimated Total Emission (ETE)

In this investigation, the effects of different heating rates on Estimated Total Emission (ETE) were determined. The ETE from the fired brick samples during the heating period was approximated by calculating the total area under the curve from the ‘Gas emissions per unit mass of brick’ (ppm kg⁻¹) versus the ‘Heating time (hour)’. These values could be obtained by employing the trapezoidal method, in ppm·hr·kg⁻¹. The ETE values obtained are indicative of the total gas emissions under the conditions applicable to this study. Example calculations to determine ETE are shown in Eq. (1) based on data provided in Table 1. The mass of the fired CB brick used is 2.72 kg.

\[
ETE = \frac{1}{2.72kg} \left( \frac{0 + 12ppm}{2} \cdot 4.75hr + \frac{12 + 28ppm}{2} \cdot 1.20hr \right)
+ \frac{12 + 1500ppm}{2} \cdot 1.18hr + \frac{1500 + 429ppm}{2} \cdot 2.39hr
+ \frac{429 + 122ppm}{2} \cdot 2.38hr + \frac{122 + 20ppm}{2} \cdot 2.38hr
+ \frac{20 + 12ppm}{2} \cdot 2.39hr + \frac{12 + 8ppm}{2} \cdot 2.36hr
+ \frac{8 + 8ppm}{2} \cdot 2.39hr + \frac{7 + 7ppm}{2} \cdot 2.38hr
+ \frac{7 + 7ppm}{2} \cdot 1.2hr \right) = 1583.80ppm·hr/kg.
\]

A gas measurement set-up was developed at this stage to measure ETE, as shown in Fig. 2. Emissions from the brick samples were measured.

Fig. 1. Flow diagram for measuring Estimated Total Emission (ETE).
directly from the furnace (Furnace 30400, Barnstead Thermolyne Muffle) using a connector from the gas detector. The connector transfers gas flow from the furnace to the gas detector once the gas detector pump is switched on. A quartz tube with resistance to high temperature was inserted into the furnace through the ventilation opening. The quartz tube was connected to the copper tube held by the magnetic tube holder. A 20 mm perforated copper tube was equipped to release the trapped water vapour to prevent the gas detector from clogging and also to prolong the distance to ensure that the desired temperature would be achieved before the gases were extracted by the gas detector pump with an absorption rate of 2.41 cm³ s⁻¹. The gas detector sensors are very sensitive and only resistant to temperatures from −20 °C up to 50 °C. The gas emissions were detected by the sensors and recorded in ppm unit at specific times by the gas detectors. Gas measurements were recorded at 5 minute intervals at the following specific temperatures: 200 °C, 250 °C, 300 °C, 400 °C, 500 °C, 600 °C, 700 °C, 800 °C, 900 °C, 1000 °C and 1050 °C. Measurements were not conducted at low temperatures (0 °C to 200 °C) to allow all the water vapour inside the brick samples to be released, which corresponded to the expulsion of adsorbed water and hydroxyl groups from the clay mineral. The emissions from the empty furnace with different heating rates were measured and subtracted from the gas measurements as control procedure. This procedure was followed by the clay brick and CB bricks and each sample was duplicated. The values reported in this paper are the average values from the experimental work.

### 2.2. Physical and mechanical properties

Physical and mechanical laboratory tests (dry density, compressive strength, tensile strength, water absorption and initial rate of absorption) in accordance with the relevant standards (AS/NZS 4456.0, 2003) were also carried out to determine the performance of clay bricks and CB bricks fired at different heating rates (0.7 °C min⁻¹, 2 °C min⁻¹, 5 °C min⁻¹ and 10 °C min⁻¹).

#### 2.2.1. Dry density

The dry density of the clay brick and CB bricks was measured in accordance with AS/NZS 4456.8 (2003). As stipulated by the standards, samples were manufactured with dimensions of 225 mm × 110 mm × 75 mm. The mean values were recorded to the nearest 0.5 mm. The samples were dried at 110 °C ± 8 °C at intervals not less than 4 h to constant weight (weight change not greater than 0.1%). The consecutive weight was taken as the weight of the sample after the sample cooled to room temperature from oven temperature.

#### 2.2.2. Compressive strength

The preparations of the clay brick and CB brick for compressive strength testing were carried out in accordance with AS/NZ 4456.4 (2003). Cubes for each mixture were manufactured for this test. The dimension of the cube was 100 mm × 100 mm × 100 mm which complied with the minimal allowable dimension for the compressive strength test according to AS/NZS 4456.1 (2003). The compressive strength test was carried out using a MTS Universal Testing Machine (IIICLB.14. Alfred J. Amsler & Co) with a capacity of 1000 kN. The testing machine was computer-controlled by the MTS Test-Star controller and software with the testing specifications and configuration data acquisition system.

#### 2.2.3. Tensile strength

The tensile strength test measures the extreme fibre tensile stress at the face of a masonry unit in bending. The preparation of the clay brick and the CB bricks for the test was adopted from AS/NZS 4456.15 (2003) and a Tinius & Olsen Testing Machine (101025) was used.

#### 2.2.4. Water absorption

Preparation of the clay brick and the CB brick samples for water absorption testing was conducted in accordance with AS/NZS 4456.14 (2003). The brick samples (225 mm × 110 mm × 75 mm) were prepared and dried at 110 °C ± 8 °C in the drying oven and weighed at intervals of not less than 4 h to constant weight (change in the mass not greater than 0.1%). The weights were measured after the sample was cooled to room temperature. The 24-hour cold water immersion test and the 5-hour boiling test procedures were followed in compliance with the aforementioned standards.

#### 2.2.5. Initial rate of absorption

Initial rate of absorption (IRA) was analysed in accordance with AS/NZS 4456.17 (2003) for both the clay and the CB bricks. The IRA is important for laying and durability of the brick. Three samples each with a size of 225 mm × 110 mm × 75 mm were dried to constant mass in a ventilated drying oven at 110 °C ± 8 °C and weighed after cooling to room temperature. The weights were determined to an accuracy of 0.001 g. A water bath tank was prepared that contained two bars made from corrosion-resistant materials. Two bars (each not more than 6 mm wide) were placed in the tank to support the bed face of the test samples, which were placed in parallel to each other and 3 mm beneath...
the water surface. The water level in the tank was maintained at 3 ± 1 mm above the bars. The sample was placed on the bars for a period of 60 ± 1 s, measured from the time the specimens were in contact with the water. Upon removal from the water tank, the sample was wiped dry immediately and then reweighed within a minute.

3. Results

This section reports the results of the following: (1) composition of clay samples (2) different heating rates on the ETE of five gases (CO, CO2, Cl2, HCN and NO) measured and (3) the physical and mechanical properties of the clay brick samples and the CB brick samples. All results reported are means of the three values and the graphs obtained are valid only within the testing conditions of this study.

3.1. The composition of clay soil

The XRF results obtained for the test samples are presented in Table 2. The test results show that silica (SiO2) was the most abundant in the samples followed by alumina (Al2O3). Appreciable amounts of hematite (Fe2O3 = 5.032) and potash (K2O = 3.446) were also present with traces (less than 1%) of total TiO2, MgO, MnO, CaO, Na2O and P2O5 for each of the oxides. The presence of Fe2O3, K2O, MgO, CaO and Na2O in the clay minerals was also advantageous to the preparation of the glassy material in the brick fraction for this soil would indicate that the clay minerals was also advantageous to the preparation of the soil. During the test, carbon dioxide (CO2) was possibly released from 2004). A loss on ignition (LOI) test was also performed on the clay body, besides lowering the melting point of the clay (Liew et al., 2005). For each of the oxides the concentration of water vapour which was maintained within the pore system. Upon removal from the water tank, the sample was wiped dry immediately and then reweighed within a minute.

<table>
<thead>
<tr>
<th>Compound Formula</th>
<th>Composition (wt %)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO2</td>
<td>58.730</td>
</tr>
<tr>
<td>Al2O3</td>
<td>18.750</td>
</tr>
<tr>
<td>Fe2O3</td>
<td>5.032</td>
</tr>
<tr>
<td>K2O</td>
<td>3.446</td>
</tr>
<tr>
<td>MgO</td>
<td>1.639</td>
</tr>
<tr>
<td>TiO2</td>
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</tr>
<tr>
<td>Na2O</td>
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</tr>
<tr>
<td>CaO</td>
<td>0.189</td>
</tr>
<tr>
<td>Loss on ignition</td>
<td>9.60</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Heating rates (°C min⁻¹)</th>
<th>Heating time (h)</th>
<th>Firing time (h)</th>
<th>Mixture identification (%)</th>
<th>Estimated Total Emission (ETE) (ppm hr kg⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>CO₂</td>
<td>Cl₂</td>
<td>HCN</td>
<td>NO</td>
</tr>
<tr>
<td>0.7</td>
<td>25</td>
<td>3</td>
<td>CB (0.0)</td>
<td>270.03</td>
</tr>
<tr>
<td>2</td>
<td>8.8</td>
<td>3</td>
<td>CB (0.0)</td>
<td>120.84</td>
</tr>
<tr>
<td>5</td>
<td>3.5</td>
<td>3</td>
<td>CB (0.0)</td>
<td>143.25</td>
</tr>
<tr>
<td>10</td>
<td>1.8</td>
<td>3</td>
<td>CB (0.0)</td>
<td>79.29</td>
</tr>
</tbody>
</table>

3.2. Estimated Total Emission (ETE) of clay brick samples

For each heating rate (0.7 °C min⁻¹, 2 °C min⁻¹, 5 °C min⁻¹ and 10 °C min⁻¹), the ETEs of each gas emitted (CO, CO2, Cl2, HCN and NO) from the clay bricks were calculated using the trapezoidal method. The results are presented in Table 3. The results show that the ETE values for the clay brick samples decreased significantly as the heating rates increased from 0.7 °C min⁻¹ to 10 °C min⁻¹ for CO and NO. For CO2 and HCN gases, lower ETE values were demonstrated at 0.7 °C min⁻¹ and 10 °C min⁻¹ respectively. Although the Cl2 ETE values seemed to fluctuate at different heating rates, the lowest ETE value is still recorded at 10 °C min⁻¹.

The ETE values that followed the decreasing trend were compared and it was observed that the ETE for CO decreased from 270.03 ppm·hr·kg⁻¹ to 79.29 ppm·hr·kg⁻¹ (71% less). As for NO, the ETE decreased from 72.09 ppm·hr·kg⁻¹ to 21.51 ppm·hr·kg⁻¹ (70% less) when the heating rate was increased from 0.7 °C min⁻¹ to 10 °C min⁻¹ (Table 3). In the case of CO2 and HCN, eventhough a decreasing trend was observed starting from 2 °C min⁻¹ to 10 °C min⁻¹, the lowest ETE was obtained at 2 °C min⁻¹ and 10 °C min⁻¹ with 89.30 ppm·hr·kg⁻¹, 90.25 ppm·hr·kg⁻¹, 3.33 ppm·hr·kg⁻¹ and 4.83 ppm·hr·kg⁻¹ respectively. The same reduction trend was observed in Cl2 but the lowest gas concentration was 0.46 ppm·hr·kg⁻¹ at 10 °C min⁻¹.

The results for clay bricks show that the lower ETE values obtained at fast heating rates (5 °C min⁻¹ and 10 °C min⁻¹) could be due to the high concentration of water vapour which was maintained within the pore system and thus inhibited the organic content oxidation. Moreover, according to Santos et al. (2003) and Toledo et al. (2004), CO2 emissions are due to the oxidation of organic content, while CO evolution is due to incomplete oxidation of organic content. This condition explains the significantly decreasing values of these gases at fast heating rates.

In contrast, at slow heating rates particularly at 2 °C min⁻¹ accessibility to oxygen was expected to improve due to the low level of water vapour within the pore system. Under this condition, oxidation of organic content was able to occur completely because of the free water vapour pore system, thus producing higher gas emissions. In bricks, the pore system is important because it affects the gas emissions that occur during dehydration, oxidation, dehydroxylation, decomposition and the formation of new phases and vitrification that generally improve the product’s mechanical strength, durability and other properties. A slow heating rate is preferable to prevent the texture from being disrupted by the evolution of water vapour (Murad and Wagner, 1998; Parsons et al., 1997; Santos et al., 2003; Toledo et al., 2004). However, it leads to higher gas emissions.
3.3. Estimated Total Emission (ETE) of CB brick samples

The ETEs of CO, CO$_2$, Cl$_2$, HCN and NO determined from CB bricks are presented in Table 4. Similar reduction patterns at different heating rates were observed for most of the gases determined from CB brick samples during the experiment. Most of the gases obtained the lowest ETE at 10 °C min$^{-1}$ except for HCN at 0.7 °C min$^{-1}$.

The ETE of CO decreased from 1583.80 ppm·hr kg$^{-1}$ to 303.66 ppm·hr kg$^{-1}$ (a reduction of 81%) at 0.7 °C min$^{-1}$ compared with 10 °C min$^{-1}$. Meanwhile, Cl$_2$ dropped from 5.15 ppm·hr kg$^{-1}$ to 0.38 ppm·hr kg$^{-1}$ at 0.7 °C min$^{-1}$ compared with 10 °C min$^{-1}$. As for CO$_2$, NO and HCN, lower ETE concentrations were obtained at 0.7 °C min$^{-1}$. Then, the values dropped steadily at 2 °C min$^{-1}$ compared with the values at 10 °C min$^{-1}$. The ETE values reduced by 46% (from 3261.90 ppm·hr kg$^{-1}$ to 1751.90 ppm·hr kg$^{-1}$), 76% (from 157.79 ppm·hr kg$^{-1}$ to 38.31 ppm·hr kg$^{-1}$) and 66% (from 34.03 ppm·hr kg$^{-1}$ to 11.52 ppm·hr kg$^{-1}$) correspondingly.

For CB brick samples, the ETE values were significantly higher for CB brick samples compared with clay brick samples when fired at the same heating rates, especially for CO and CO$_2$ at 0.7 °C min$^{-1}$ and 2 °C min$^{-1}$ respectively. However, the emissions for CB bricks dropped significantly at higher heating rates.

This condition is due to the additional organic content provided by the incorporation of CBs. The existence of CBs at slow heating rates also helps to improve the condition of the pore system in the brick. This reduces the water vapour level, thus increasing accessibility to oxygen. In this case, the oxidation of the organic content was almost completed, thus reducing in higher gas emissions. On the other hand, the gas concentrations released were significantly lower at higher heating rates (5 °C min$^{-1}$ and 10 °C min$^{-1}$). As shown in Table 4, although some of the peak values of the gas emissions were quite high (due to the shorter time period of using high heating rates) the gas emissions were significantly lower over time.

3.4. Physical and mechanical properties of clay brick samples

The effects of different heating rates on the physical and mechanical properties are presented in Table 5. Firing clay bricks at high heating rates (5 °C min$^{-1}$ and 10 °C min$^{-1}$) reduced the measured values gradually but not significantly for compressive strength and water absorption. The compressive strength values reduced from 25.65 MPa at 0.7 °C min$^{-1}$ to 17.90 MPa at 2 °C min$^{-1}$, but as the heating rate increased to 5 °C min$^{-1}$ the strength slightly decreased to 16.34 MPa. The results indicate no significant changes between the applied heating rates. Furthermore, the results show that higher heating rates have insignificant effects on water absorption properties. The values increased from 5% at 0.7 °C min$^{-1}$ to 7% at 2 °C min$^{-1}$ and remained at 5 °C min$^{-1}$ then reduced to 5% at 10 °C min$^{-1}$. For tensile strength, the values increased from 2.79 MPa to 6.04 MPa as the heating rate increased from 0.7 °C min$^{-1}$ to 2 °C min$^{-1}$. However, this condition might be due to the different mixing times conducted on the brick samples for tensile strength.

On the other hand, higher heating rates appear to increase the initial rate of absorption values. Lower results were obtained at 0.7 °C min$^{-1}$ with 0.24 kg m$^{-2}$ min$^{-1}$ but then increased to 1.00 kg m$^{-2}$ min$^{-1}$ at 2 °C min$^{-1}$, followed by 3.57 kg m$^{-2}$ min$^{-1}$ and 3.11 kg m$^{-2}$ min$^{-1}$ at 5 °C min$^{-1}$ and 10 °C min$^{-1}$ respectively. The same situation was observed for the dry density as the measured values gradually increased with higher heating rates. Dry density increased from 2118 kg m$^{-3}$ to 2213 kg m$^{-3}$ at 0.7 °C min$^{-1}$ and 10 °C min$^{-1}$ accordingly. High heating rates reduced the porosity and increased the density of the clay brick samples.

The obtained results indicate that careful selection of heating rates for the firing process can still produce equivalent physical and mechanical properties of clay bricks. Furthermore, this study found that different heating rates affect the properties of clay brick although not critically. The advantages of using higher heating rates are shorter firing duration, greater energy efficiency and lower gas emissions.

Nonetheless, slow heating rates produced a better product in terms of appearance (Fig. 3). Clay bricks can only survive up to about 2 °C min$^{-1}$ to produce a good quality brick. At 5 °C min$^{-1}$, good results for compressive strength, dry density and water absorption properties were obtained. However, only the brick and cube samples survived with minor disintegration effects and visible cracks as the beam samples disintegrated into pieces during the firing process. Up to 10 °C min$^{-1}$, even the brick samples hardly survived with most of the surface disintegrating during the firing process. This situation is due to the sudden release of trapped gas or the expansion of trapped water in brick samples that have poor pore systems.

---

**Table 4**

<table>
<thead>
<tr>
<th>Heating rates (°C min$^{-1}$)</th>
<th>Heating time (h)</th>
<th>Firing time (%)</th>
<th>Mixture identification (%)</th>
<th>Estimated Total Emission (ETE) (ppm·hr kg$^{-1}$)</th>
<th>Average dry density (kg m$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CO</td>
<td>Cl$_2$</td>
</tr>
<tr>
<td>0.7</td>
<td>25</td>
<td>3</td>
<td>CB (5.0)</td>
<td>1583.80</td>
<td>2463.90</td>
</tr>
<tr>
<td>2</td>
<td>8.8</td>
<td>3</td>
<td>CB (5.0)</td>
<td>1227.00</td>
<td>3261.90</td>
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<tr>
<td>5</td>
<td>3.5</td>
<td>3</td>
<td>CB (5.0)</td>
<td>670.42</td>
<td>2410.80</td>
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<tr>
<td>10</td>
<td>1.8</td>
<td>3</td>
<td>CB (5.0)</td>
<td>303.66</td>
<td>1751.90</td>
</tr>
</tbody>
</table>

---

**Table 5**

<table>
<thead>
<tr>
<th>Heating rates (°C min$^{-1}$)</th>
<th>Mixture identification (%)</th>
<th>Compressive strength (MPa)</th>
<th>Water absorption (%)</th>
<th>Modulus of rupture (MPa)</th>
<th>Initial Rate of Absorption (IRA) (kg m$^{-2}$ min$^{-1}$)</th>
<th>Average dry density (kg m$^{-3}$)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>CB (0.0)</td>
<td>25.65</td>
<td>5</td>
<td>2.79</td>
<td>0.24</td>
<td>2118</td>
<td>Manufactured samples were good in appearance</td>
</tr>
<tr>
<td>2</td>
<td>CB (0.0)</td>
<td>17.90</td>
<td>7</td>
<td>6.04</td>
<td>1.00</td>
<td>2124</td>
<td>Manufactured samples were good in appearance</td>
</tr>
<tr>
<td>5</td>
<td>CB (0.0)</td>
<td>16.34</td>
<td>7</td>
<td>–</td>
<td>3.57</td>
<td>2134</td>
<td>Control beam samples disintegrated into pieces during firing</td>
</tr>
<tr>
<td>10</td>
<td>CB (0.0)</td>
<td>N/A</td>
<td>5</td>
<td>N/A</td>
<td>3.11</td>
<td>2213</td>
<td>N/A Control beam and cube were not manufactured due to the possible disintegration effect</td>
</tr>
</tbody>
</table>

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- All manufactured samples were good in appearance except for samples fired at 10 °C min$^{-1}$ when small parts of the brick surface disintegrated during the firing process.
3.5. Physical and mechanical properties of CB brick samples

The results for CB bricks by weight are summarised in Table 6. The strength values decreased from 14.25 MPa at 0.7 °C min⁻¹ to 10.05 MPa at 2 °C min⁻¹. There was no significant difference between the compressive strength of bricks fired at 2 °C min⁻¹ and 5 °C min⁻¹, which were 10.05 MPa and 9.40 MPa respectively. However, the strength reduced to 5.03 MPa with 10 °C min⁻¹ firing rate. Tensile strength values slightly decreased from 4.61 MPa at 0.7 °C min⁻¹ to 4.43 MPa and later dropped to 4.30 MPa, followed by 3.08 MPa at 2 °C min⁻¹, 5 °C min⁻¹ and 10 °C min⁻¹ respectively.

On the other hand, water absorption and initial rate of absorption indicate the same increasing trend when results increased from 11% to 14% for water absorption, while the initial rate of absorption increased from 1.32% to 1.45% for water absorption. Moreover, the initial rate of absorption increased from 1% to 4% at 10 °C min⁻¹ heating rates.

Average dry density from 1901 kg m⁻³ to 1853 kg m⁻³ followed by 1736 kg m⁻³ and 1680 kg m⁻³ as higher heating rates were carried out at 0.7 °C min⁻¹, 2 °C min⁻¹, 5 °C min⁻¹ and 10 °C min⁻¹ respectively.

The incorporation of CBs in clay bricks to produce CB bricks also enabled the manufactured samples to be fired and survive high heating rates at up to about 10 °C min⁻¹ without facing any major disintegration effect or cracks, as occurred with the clay brick samples. However, in terms of appearance, the manufactured brick samples with heating rates of 0.7 °C min⁻¹ and 2 °C min⁻¹ were slightly better compared to 5 °C min⁻¹ and 10 °C min⁻¹ in relation to the surface of the samples (Fig. 4). Fig. 5 shows the cross-sections of manufactured samples at heating rates of 0.7 °C min⁻¹, 2 °C min⁻¹, 5 °C min⁻¹ and 10 °C min⁻¹. At higher heating rates, black coring was observed due to incomplete combustion of the organic content provided by the incorporated CBs in the clay brick. The black coring effect was greater as the heating rate increased, especially at 10 °C min⁻¹. Fig. 6 clearly shows that at 10 °C min⁻¹, even the bottom part of the manufactured samples was affected and filled with dark spots.

4. Discussion

The results presented in this paper provide useful information in relation to clay bricks and bricks incorporating cigarette butts (CBs). In particular, it identifies the effect of four different heating rates (0.7 °C min⁻¹, 2 °C min⁻¹, 5 °C min⁻¹ and 10 °C min⁻¹) on the bricks’ estimated total gas emissions (ETEs), and physical and mechanical properties of the bricks.

The clay bricks were observed to have the lowest ETE results at different heating rates. By using one way ANOVA analysis, the results show that CO and Cl₂ were significantly reduced with p < 0.05 at 10 °C min⁻¹, NO at 5 °C min⁻¹, CO₂ and HCN at 0.7 °C min⁻¹ correspondingly. Therefore, it is hard to choose one heating rate that could reduce all emissions while firing the control brick. Conversely, for CB brick, one way ANOVA analysis revealed that most of the ETE emissions significantly obtained the lowest values at 10 °C min⁻¹ for CO, CO₂, Cl₂, NO except for HCN at 0.7 °C min⁻¹ with p < 0.05 respectively compared to other heating rates. Nevertheless, at 0.7 °C min⁻¹ and 2 °C min⁻¹ respectively, significantly higher emissions of CO and CO₂ were observed for CB bricks due to the organic content and porous characteristic compared to the clay bricks. The oxidizing environment in clay brick and CB brick is not analogous as pore systems are better in the CB brick. The improvement of the pore system enables a more complete oxidation process, thus resulting in the release of higher gas emissions. However, significantly lower emissions can be achieved with higher heating rates (5 °C min⁻¹ and 10 °C min⁻¹). Furthermore, many types of filters are available to reduce gas emissions. These filters include primary (focusing on the raw materials and process) and secondary (focusing on the gases released) filters. Others include fabric filters and wet scrubbers. One particularly commonly used filter is limestone (Monfort et al., 2008).

**Table 6**

Physical and mechanical properties of CB brick samples fired at different heating rates.

<table>
<thead>
<tr>
<th>Heating rates (°C min⁻¹)</th>
<th>Mixture identification (%)</th>
<th>Compressive strength (MPa)</th>
<th>Water absorption (%)</th>
<th>Modulus of rupture (MPa)</th>
<th>Initial rate of absorption (IRA) (kg m⁻² min⁻¹)</th>
<th>Average dry density (kg m⁻³)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.7</td>
<td>CB (5.0)</td>
<td>14.25</td>
<td>11</td>
<td>4.61</td>
<td>1.45</td>
<td>1901</td>
<td>Manufactured samples were good in appearance</td>
</tr>
<tr>
<td>2</td>
<td>CB (5.0)</td>
<td>10.05</td>
<td>10</td>
<td>4.43</td>
<td>1.32</td>
<td>1853</td>
<td>Some black coring was observed at the cross-sections of the manufactured samples</td>
</tr>
<tr>
<td>5</td>
<td>CB (5.0)</td>
<td>9.40</td>
<td>15</td>
<td>4.30</td>
<td>3.99</td>
<td>1736</td>
<td>A medium degree of black coring was observed at the cross-section of the manufactured samples</td>
</tr>
<tr>
<td>10</td>
<td>CB (5.0)</td>
<td>5.03</td>
<td>14</td>
<td>3.08</td>
<td>3.97</td>
<td>1680</td>
<td>A large degree of black coring was observed at the cross-section of the manufactured samples and black spots were noticed at the bottom</td>
</tr>
</tbody>
</table>
The comparison between clay bricks and CB bricks also highlighted that different heating rates used during the firing process showed minimal effects on the physical and mechanical properties of the tested samples. Results for clay brick samples reduced gradually but not significantly for strength and water absorption between heating rates of 2 °C min⁻¹ and 5 °C min⁻¹. The initial rate of absorption and dry density increased slightly as the heating rates increased. Findings from the CB brick samples indicated no significant difference between compressive strength and tensile strength measurements for bricks fired at 0.7 °C min⁻¹, 2 °C min⁻¹ and 5 °C min⁻¹. Meanwhile, slightly increased values for water absorption were observed when the heating rate was increased from 2 °C min⁻¹ to 10 °C min⁻¹. Dry density values decreased steadily with the increase of heating rates. In terms of appearance, firing at 0.7 °C min⁻¹ and 2 °C min⁻¹ resulted in a better end product compared to 5 °C min⁻¹ and 10 °C min⁻¹ for both types of fired brick samples. At 5 °C min⁻¹, good results were obtained for dry density, compressive strength and water absorption properties as the properties are still comply with the standards, however the beam samples disintegrated and the tensile strength value was not obtained for the clay brick samples. For CB bricks, because of the incorporation of CBs into the clay bricks, the CB bricks were fired from about 5 °C min⁻¹ to 10 °C min⁻¹ without any major disadvantage, except for the black coring effect inside the brick due to incomplete combustion of the organic content. High heating rates are beneficial in brick manufacture in terms of energy and time consumption as firing bricks at 5 °C min⁻¹ and 10 °C min⁻¹ could reduce the heating time by up to 21 h and 23 h respectively, compared with 0.7 °C min⁻¹ with lower emissions and significantly reduce energy consumption. Therefore, the heating rate is recommended to be increased as it could decrease energy consumption and environmental pollution from gas emissions. This is also supported by the experimental work conducted as the result showed that different heating rates have minimal effects on the properties of CB bricks.

Attempts were also made to solve major drawbacks of firing at high heating rates due to the disintegration effects by incorporating 3% of steel fibre into the clay brick and CB brick samples. The addition of steel fibre worked for the clay bricks as the manufactured samples endured firing at 5 °C min⁻¹ and produced better appearance with similar properties. Further research is strongly recommended, as the incorporation of small amounts of steel fibre could lead to the usage of higher heating rates in brick manufacturing which could significantly reduce emissions, time and energy consumption. For CB bricks, the addition of steel fibre did not significantly improve the properties or the appearance of the manufactured samples.

5. Conclusion

The research carried out in this study has established that higher heating rates could lead to significant reduction of gas emissions as most of the clay brick and CB bricks showed the lowest ETE values at 10 °C min⁻¹ even though few gases shown different results specifically for clay brick samples. Thus, selecting one specific heating rate for clay brick samples to reduce all the gas emissions during firing is difficult. On the other hand, in terms of physical and mechanical properties, clay brick demonstrated acceptable properties up to 2 °C min⁻¹ while CB brick is more resistant to high heating rates as it established acceptable properties up to 10 °C min⁻¹. As for the appearance, lower heating rates produced a better end product compared with high heating rates for both types of fired brick samples. However, building bricks and engineering bricks that is highly in demand focus more on the properties compared to facing brick which require a specific surface appearance and are normally used for aesthetic purposes. In conclusion, CB bricks and high heating rates should be considered as an option or an alternative in the brick industry to minimise the manufacturing cost and time. The changes do not critically affect the properties of fired clay bricks and they significantly reduce environmental pollution, thus offering the potential for greater energy efficiency. The focus of future work is to solve major drawbacks of the manufactured bricks caused by the disintegration effects when firing at high heating rates.

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References


Fig. 5. Cross-sections of beams with 5% CBs fired at 0.7 °C min⁻¹, 2 °C min⁻¹, 5 °C min⁻¹ and 10 °C min⁻¹ heating rates.

Fig. 6. Bottom views of beams with 5% CBs fired at 0.7 °C min⁻¹, 2 °C min⁻¹, 5 °C min⁻¹ and 10 °C min⁻¹ heating rates.


