Physical Characteristics and Energy Content of Biomass Charcoal Powder

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Abstract- The objective of this study is to investigate potential biomass materials for charcoal briquette production by comparing physical properties and energy content. The charcoal powder was obtained from 3 sources. The first group was charcoal from industrial factories which is charcoal from biomass power plant (CBPP). The second group was charcoal from a by-product of agricultural products, consisting of rice husk coal (RHC), coconut-shell coal (CSC), corn cob coal (CCC), cassava stump coal (CStC) and eucalyptus bark coal (EuBC). The third group was charcoal from recycling vegetal coal, consisting of recycling eucalyptus coal (REuC) and recycling assorted wood coal (RAWC). The results showed the physical properties of charcoal powder with an average bulk density of 189.19–563.73 kg/m$^3$ and average angle of repose of 35.05°–43.21°. The material flowability was ranged between fair to passable flow and free-flowing with average particle size of 0.31–1.29 mm. The static coefficient of friction on the material surface was 0.46–0.66 on mild steel, 0.39–0.57 on stainless steel, 0.45–0.59 on zinc sheet, 0.43–0.61 on galvanized steel, and 0.52–0.66 on rubber. The energy content of charcoal powder revealed the HHV to range from 3,393.78–7,303.86 cal/g, the commercial briquettes charcoal range value from 5,205.34–5,382.62 cal/g. The results of the physical properties of the charcoal powder provide useful data for engineering design. Whilst, the comparison between the commercial briquette charcoal and the biomass charcoal powder shows the potential of biomass as a raw material to produce charcoal briquettes to replace woody biomass, thereby increasing the value of that material.

Keywords Biomass Charcoal, Physical characteristics, Energy content of biomass charcoal, Charcoal briquettes.

1. Introduction

According to the energy crisis that caused by the drastically increasing of global energy demand due to expanding of population and industrial section, global warming situation, and environmental pollution, green and renewable energy sources become more favourable approach as for a replacement of fossil fuel [1,2]. Currently, biomass energy source, which accounts for 14% of the world energy consumption, is prioritized at the fourth place after petroleum, gas, and coal [3]. The biomass is a sustainable energy source that can be found anywhere in the world [4] and restored to their original form and multiply in quantity. There are several methods converting biomass into energy[5,6] such as direct combustion, gasification or pyrolysis, anaerobic digestion, hydrolysis, hydrogenation or fermentation and briquettes which the later is preferable for household use for direct combustion.

In Thailand, the high energy consumption in the year 2019 was 85,7088 ktoe, an increased 2.1% from the previous year. The total value of final energy consumption was 1,245 Billion Bath. Refined oil is the highest consumption energy source at 49.1% of the total consumption [7]. Although LPG (liquid petroleum gas) is generally used in household as for cooking fuel [8], it also requires substantial subsidies of importation because the LPG production in Thailand is insufficient for the
domestic demand. Besides, natural gas is not a renewable resource[9,10]. Charcoal and firewood are major fuel sources for household cooking in developing countries [11-13]. However, they have a great impact on forest resources and environment, including health issues caused by smoke pollution [14] which later discourages the usage of firewood. Regardless of the impact, demand for wood charcoal and charcoal briquettes in the household is still high both nationally and internationally because of the charcoal-grilled food culture and popularity of barbecue business that rise a high demand of charcoal fuel. Moreover, charcoal usage reduces the smoke pollution issues due to its less smoke during cooking [15]. The firewood provides calorific value or heating value of 4,539-4,778 kcal/kg with 70% volatile content, 28% fixed carbon content, and 2% ash content [16]. After undergone the heating process in the absence-air condition to remove the volatile compounds but left fixed carbon content, the firewood turns into charcoal with a higher calorific value of about 7,167 kcal/kg but lower volatile content of 15–20%. At present, biomass briquettes are majorly used for household fuel in the developed countries [17] because of wood charcoal depletion [18]. As for raw material resource for firewood and charcoal, forest area declined to 25.6% which implies an increasing rate of deforestation. For this reason, the utilization of biomass is an urgent need. Thailand generally produced a wide variety of agricultural products and is one of the world's top exporters of agricultural and food products [19]. Thus, variety of biomass sources are available for biomass fuel production, especially by-products or wastes from harvesting and processing of agricultural products such as coconut shell, palm shell, corn cob, rice husk, rice straw, cassava stems and rhizomes, bagasse, and sugarcane leaves, rubberwood chips, etc. Moreover, the energy generated by these biomass materials each year is equivalent to 54 million tons of lignite coal. The biomass fuel is a sustainable supply for energy consumption and is an advantageous approach to replace fossil fuel in the future [20]. In any case, a crucial part is what process and how to enhance the heating value/weight unit of these biomass materials [21]. Higher heating value (HHV) is a factor affecting an increase in biomass energy utilization in the energy industry. The biomass utilization is not only meeting the energy demand but also help people to protect forest resources and maintaining the ecological balance including environment friendly because the biomass contains a low N and S composition. The biomass material has the potential to reduce the greenhouse effect by releasing an estimate of zero CO₂ emission [22] and lower acidic gas emission compared to fossil fuel [23].

Charcoal briquette type is an optimal format for the management because the briquette type helps the producer to reduce transportation cost, storage space, and charcoal dust issue [24], but to enhance the heating value and combustion period. Considering biomass material as for fuel purpose, physical properties, and energy content of the substrates must be verified and determined to prioritize their quality and value [25,26]. However, the raw material or biomass are generally obtained from various sources of production, biomass species, harvesting periods and methods, product processing, and storage process that affecting the changing of internal properties. [27] Therefore, the study of these factors is needed and should thoroughly be examined.
The research aims to study physical properties and energy content of biomass charcoal powder to provide basic information on characteristics and types of biomass powder for the charcoal briquette production. In this study, types of charcoal were selected from manufacturing scrap for material reuse and adding value. The testing charcoal consisted of 3 groups, group 1 was charcoal from a biomass power plant (CBPP) (Figure 1), group 2 was charcoal from a by-product of agricultural products (Figure 2a) which were coconut-shell coal (CSC), corn cob coal (CCC) (i.e., corn stalks or maize cobs), cassava stump coal (CStC) (i.e., Cassava rhizome charcoal), eucalyptus bark coal (EuBC), and rice husk coal (RHC) (Figure 2b), whilst group 3 was manufacturing scrap/waste (Figure. 3) which were recycling eucalyptus charcoal (REuC) and recycling assorted wood coal (RAWC). The charcoal material from group 1 and 3 must be grided to reduce particle size before compressed by briquettes machine.

2. Materials and methods

2.1 Preparation of biomass charcoal powder sample

As for charcoal powder preparation, biomass materials were collected from plantations and production sites in the northeast region of Thailand. Corn Cob was collected from Khon Kaen Province, whilst, Cassava Stump was collected from Sakon Nakhon Province. Coconut-shell, Rice Husk, and Charcoal from a Biomass Power Plant (CBPP) were collected from Nakorn Phanom Province. Eucalyptus Bark was obtained from wood chip factory in Nakorn Phanom Province. The Recycling Eucalyptus Coal (REuC) and Recycling Assorted Wood Coal (RAWC) were collected from Kalasin Province. The biomass raw materials (corn cob, cassava stump, coconut-shell, eucalyptus bark) were stored to reduce the moisture content to less than 20% before carbonized in a 200-litre tank. (Figure 2a) Rice husk in production of coal by igniting heaps around traditional chimneys. (Figure 2b) The obtained all charcoals were not suitable for the process. They had to be ground converting the charcoal into fine particles. The materials were grinded by a hammer mill with sieve size 6 mm, at 1,000 rpm of drum speed, using an electric motor of 3 horsepower, before storing in a sealed plastic container.

2.2 The study of physical properties of charcoal powder

The physical properties of the material are important keys for a designing of management systems such as transportation, handling, and storage etc.[28,29]. This study investigated several physical properties which were moisture content, average particle size, bulk density, angle of repose, and static coefficient of friction.

2.2.1 The study of moisture content

It is a parameter for engineering applications, design for drying method, handling, storage, and feeding facilities and conversion process. [25]. In this study, the moisture content was measured by Halogen Moisture Analyzer (Model MB45, OHAUS, Corporation., Parsippany, NJ 07054 USA) at temperature condition of 105 °C using the powder weight of 1 gram per sample, then recorded the constant moisture content value every 1 minute [28].

2.2.2 The study of particle size

The particle size and size range of the charcoal powder influence options for conveying system as well as combustion behaviour of biomass briquette. Homogeneity of the particle size has an impact on the size and shape of the briquette that could be a marketable product [30,31]. Whilst, the particle size affects the quality and performance of flowability, density, and strength of the charcoal briquettes [32,33]. The smaller the particle size, the higher the density and strength. Accordingly, the bulk density of each charcoal type impact directly on performance, strength value, and density of the charcoal briquettes product [34,35]. Sieve analysis is a method to evaluate solid particle size or fineness by sieve known-weight solid matter through a set of test sieves based on the testing standards of ASAE S319.1 [36–40]. The vibratory sieve shaker (Retsch; AS 200 control, Germany) which consisted of different sieve sizes were used and arranged following the Canadian series sieve numbers as 4, 8, 16, 30, 50, 100, and 200 with the mesh size of 4.75, 2.36, 1.18, 0.60, 0.30, 0.15, and 0.075 mm, respectively (Table 1). Sieve trays were weighed and recorded all data, then put 100 ±5 g of each charcoal powder type on the topmost tray before shaking by the vibratory sieve shaker for 10 minutes, before weighing the trays and calculate the remaining percentage of the charcoal powder on the trays. The particle size and size range were evaluated by geometric mean diameter (d_{gw}) using equation (1) and by geometric standard deviation (S_{gw}) using equation (2) from data collection of 5 testing replications. The charcoal powder sample must contain less than 10 % (w.b.) of moisture content, [26] if not, the samples must be dried up at 50 °C prior the testing to prevent sieve obstruction.

\[
d_{gw} = \log^{-1} \left[ \frac{\sum_{i=1}^{n} (w_i \log d_i)}{\sum_{i=1}^{n} w_i} \right] \tag{1}
\]

\[
s_{gw} = \log^{-1} \left[ \frac{\sum_{i=1}^{n} (\log d_i - \log d_{gw})^2}{\sum w_i} \right]^{1/2} \tag{2}
\]

where,

- \( d_{gw} \) = geometric mean diameter (mm.)
- \( s_{gw} \) = geometric standard deviation
- \( w_i \) = weight fraction on i’th sieve
- \( d_i \) = diameter of sive openings of the i’th sieve
- \( d_{i+1} \) = diameter of the opening in next larger than i’th sieve (just above in a set)
- \( \bar{d}_i \) = geometric mean diameter of particles on i’th sieve

\[
\bar{d}_i = (d_i \times d_{i+1})^{1/2}
\]
Table 1. Sieve number, mesh number and mesh size.

<table>
<thead>
<tr>
<th>Sieve number</th>
<th>Mesh number</th>
<th>Mesh size (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>4.75</td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>2.36</td>
</tr>
<tr>
<td>3</td>
<td>16</td>
<td>1.18</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>0.60</td>
</tr>
<tr>
<td>5</td>
<td>50</td>
<td>0.30</td>
</tr>
<tr>
<td>6</td>
<td>100</td>
<td>0.15</td>
</tr>
<tr>
<td>7</td>
<td>200</td>
<td>0.075</td>
</tr>
<tr>
<td>pan</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

\[
\rho = \frac{m}{V}; \quad \text{kg m}^{-3} \tag{3}
\]

where \( \rho \) is the bulk density, \( m \) is the mass of charcoal powder and \( V \) is the volume of measuring cup.

2.2.4 Angle of repose

The angle of repose is an angle of material piling on flat ground, which is the steepest angle of material pile holding up and does not fall due to gravity. The angle of repose is an indicator for flowability of a material [26]. The angle depends on the internal friction among particles and the flowability of that material, which are influenced by the moisture, density, particle size and shape of that material, as well as environmental factors such as gas aggregation and adsorption, relative humidity. The angle of repose is useful information for the transportation management and designing of hopper and feeder devices [41] and indicating the cohesive force of the particles and flowability of each material. The material flowability was characterized by Carr for 5 levels from \(<30^\circ\) as a very free-flowing, \(30-38^\circ\) as a free-flowing, \(38-45^\circ\) as a fair to passable flow, \(45-55^\circ\) as cohesive, to \(>55^\circ\) as very cohesive (non-flowing).

The angle of repose was measured using the test kit of the Seedburo filling hopper and stand (Seedburo Equipment Co., Chicago, IL.60607) by setting the distance between the hopper bottom and the measuring cup at 17.2 cm (Figure 4). Then, The charcoal powder was placed inside the hopper before open the funnel orifice valve and let the charcoal powder flow rapidly into the measuring cup until it exceeds the rim of the cup, then remove the excess powder in a zigzag stroke by a smooth wood, length over the cup’s diameter [42,43]. The testing procedure was repleted for 20 replications, then calculated the bulk density of the charcoal powder using the equation (3).

Figure 4. Seedburo filling hopper and stand for bulk density Measurement.

Figure 5. Seedburo filling hopper and stand for angle of repose(fixed-base) measurement.
was calculated from the testing data of 20 replications using the equation (4).

\[ \beta = \tan^{-1} \left( \frac{y}{x} \right) \]  

(4)

where \( \beta \) is the angle of repose, \( y \) is the height of slope and \( x \) is the radius of a base (d/2)

2.2.5 Static coefficient of friction

Before testing for the static coefficient of friction, the moisture content must be re-tested because the moisture conditions before the testing must be less than 10% (w.b.) as same as the study of the particle size. The static coefficient of friction was evaluated by the method of tilting plane as shown in Figure 6. The charcoal powder was stored in a cylindrical container (50 mm-diameter and 50 mm-height) at the top end of the testing plane. In this study, the coefficient of friction was tested on 5 surface materials, stainless steel, mild steel, zinc sheet, rubber, and galvanized steel. The cylindrical container was placed 2 mm above the material surface plane before slowly adjusting a rotating rope to lift the plane until the charcoal powder begins to slide, then stop and record the friction angle[44][45][46]. The static coefficient of friction was calculated from the testing data of 20 replications using the equation (5).

\[ \mu = \tan \theta \]  

(5)

where \( \mu \) is the static coefficient of friction and \( \theta \) is the angle of a plane when charcoal powder began to slide.

Figure 6. Tilting plane and different surface materials for Static coefficient of friction measurement

2.3 Energy content of charcoal

Heating value or calorific value is an indicator of the energy content of biomass material. It is the quantity of energy stored in a unit of biomass, usually measured by using the heat of combustion which energy will be released as heat when it is completely burned with oxygen under standard conditions [30,46,47]. Heating value demonstrated as higher heating value (HHV) according to the condition of the sample as-determined basis ASTM D 3180-89. It can be calculated from the analysis of the sample and has the same moisture remaining at the time of testing.

From 8 types of charcoal powder with higher heating value potential. (Figure 1,2, and 3) The charcoal from a biomass power plant (CBPP) was reduced moisture content by sun-dried, so that all 8 types of charcoal powder had a moisture content of <10% (w.b.). HHV was determined according to ASTM D5865 standard by using the PARR Bomb Calorimeter Meter, Model 1341 of the Agricultural Machinery Department, Faculty of Agriculture and Technology, Nakhon Phanom University. Samples from commercial charcoal briquettes in Thailand were tested and compared.

3. Data Analysis

Data of physical properties was calculated the mean value, standard deviation and analysis of variance as well as compared the differences among the samples by using Least Significant Difference (LSD) at a significant level of 0.05. Data of heating properties were analyzed for variance between the type of charcoal powder and compared the mean by using Duncan's Multiple Range Test (DMRT) method. Charcoal with the same level of heating value was grouped. The heating value of the commercial charcoal in Thailand as compared to obtain information about the mixing ratio for producing charcoal briquettes.

4. Results and Discussion

4.1 The result of physical properties of charcoal powder

4.1.1 Moisture Content

From the study of the moisture content of 8 types of charcoal powder found that Corn cob coal (CCC), Cassava stump coal (CStC), Coconut-shell coal (CSC), Eucalyptus Bark coal (EuBC), Rice husk coal (RHC), Charcoal from a biomass power plant (CBPP), Recycling Eucalyptus coal (REuC) and Recycling assorted wood coal (RAWC) had average moisture content (w.b.) between 5.78%–15.33% (Table 2). Charcoal from a biomass power plant (CBPP) contained high moisture content due to the charcoal obtained from the process of temperature reduction by soaking in water, it was stored in a storage shed without drying.

4.1.2 Particle size analysis

The study of mean particle size and standard deviation of the charcoal particle size found that charcoal from a biomass power plant (CBPP) had the coarsest particle size, followed by coconut-shell coal (CSC), the mean particle size of 1.29 and 1.26 mm. Other charcoal powders had a mean particle size of less than 1 mm. The finest mean particle size was rice husk coal (RHC) of 0.14 mm (Table.2 and Figure 7). When charcoal from a biomass power plant (CBPP) and coconut-shell coal (CSC) was ground to reduce the size, it becomes pellets due to the strength of charcoal. While corn cob coal (CCC) became charcoal flakes that similar to the powder after the ground process, due to the coagulation structure of the corncob. Rice husk coal (RHC) was more powdery than other charcoals. The charcoal particle size has a direct effect on the density of charcoal briquettes [43]. Small particle size can increase the density of charcoal briquettes, increase the surface area of bonding material that increase strength and reduce shattering from impact or falling [44]. Abdul-Razzak et al. [45] found that medium particle size of charcoal powder (2.36 mm) enhanced water temperature, fine particle (0.59 mm) raised combustion time and large particle (2.41 mm) increased specific gravity or relative density. Therefore, hammer mill grinder with 6mm sieve size can produce suitable fineness of charcoal powder for making
charcoal briquette. Using a sieve size of 6 mm instead of 3 mm can increase the working performance of miller.

4.1.3 Bulk density

The study on physical properties of 8 charcoal powder types with average moisture of 5.78–15.33% (w.b.) found that average bulk density ranged from 189.9-563.73 kg/m$^3$. Coconut-shell coal (CSC) had highest bulk density, followed by eucalyptus bark coal (EuBC), recycling assorted wood coal (RAWC), rice husk coal (RHC), charcoal from a biomass power plant (CBPP), recycling eucalyptus coal (REuC), cassava stump coal (CStC) and corn cob coal (CCC); bulk density of 563.73 (8.73), 385.66 (7.13), 371.59 (8.46), 362.05 (2.88), 351.33 (15.33), 275.34 (6.84), 207.16 (4.99) and 189.19 (9.95) kg/m$^3$ respectively (Table 2).

The analysis of variance (ANOVA) showed that type of charcoal had a significantly different effect on the bulk density ($P < 0.01$). Mean values of 8 types of charcoal were significantly different when compared using LSD method at 5% significance level (Table 2).

Table 2. Moisture content (as-determined basis), Mean of geometric mean diameter; $d_{gw}$ (geometric standard deviation; $S_{gw}$), Density and Angle of repose of charcoal powder.

<table>
<thead>
<tr>
<th>No.</th>
<th>Type of Charcoal</th>
<th>Moisture Content (average) ; % (w.b.)</th>
<th>geometric mean diameter (mm.) ; $d_{gw}$($S_{gw}$)</th>
<th>Density (kg.m$^{-3}$)</th>
<th>Angle of repose</th>
<th>Carr Classification of flowability</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CCC</td>
<td>9.47-10.48 (9.95)</td>
<td>0.79 (1.92)</td>
<td>189.19$^a$</td>
<td>39.83$^c$</td>
<td>Fair to passable flow</td>
</tr>
<tr>
<td>2</td>
<td>CStC</td>
<td>5.44 - 6.76 (6.19)</td>
<td>0.46 (1.98)</td>
<td>207.16$^b$</td>
<td>38.15$^b$</td>
<td>Fair to passable flow</td>
</tr>
<tr>
<td>3</td>
<td>CSC</td>
<td>7.85 – 9.34 (8.73)</td>
<td>1.26 (1.70)</td>
<td>563.73$^h$</td>
<td>38.95$^c$</td>
<td>Fair to passable flow</td>
</tr>
<tr>
<td>4</td>
<td>EuBC</td>
<td>6.51 – 7.64 (7.13)</td>
<td>0.31 (3.38)</td>
<td>385.66$^d$</td>
<td>43.21$^d$</td>
<td>Fair to passable flow</td>
</tr>
<tr>
<td>5</td>
<td>RHC</td>
<td>5.45 – 6.23 (5.78)</td>
<td>0.14 (1.58)</td>
<td>362.05$^a$</td>
<td>35.05$^a$</td>
<td>Free flowing</td>
</tr>
<tr>
<td>6</td>
<td>CBPP</td>
<td>14.59 – 16.48 (15.33)</td>
<td>1.29 (1.28)</td>
<td>351.33$^d$</td>
<td>43.50$^d$</td>
<td>Fair to passable flow</td>
</tr>
<tr>
<td>7</td>
<td>REuC</td>
<td>6.33 - 7.18 (6.84)</td>
<td>0.35 (3.04)</td>
<td>275.34$^c$</td>
<td>42.64$^d$</td>
<td>Fair to passable flow</td>
</tr>
<tr>
<td>8</td>
<td>RAWC</td>
<td>7.62 – 9.27 (8.46)</td>
<td>0.31 (3.20)</td>
<td>371.59$^f$</td>
<td>39.97$^c$</td>
<td>Fair to passable flow</td>
</tr>
</tbody>
</table>

P - value < 0.01, LSD(0.05) = 5.84

$^a$-f Mean values with different letters for each column are a significant difference (LSD)

Figure 7. Particle size distributions of charcoal powder
4.1.4 Angle of repose

The result of the angle of repose of charcoal powder (Table 2) found that the angle of repose of charcoal powder ranged from 35.05 degrees to 43.50 degrees. Charcoal from a biomass power plant (CBPP) had the highest angle of repose, followed by eucalyptus bark coal (EuBC), recycling eucalyptus coal (REuC), and eucalyptus bark coal (EuBC) at 5.89% (w.b.) moisture had higher mean static coefficient of friction on the rubber sheet than on mild steel, zinc sheet, galvanized steel and stainless steel (0.61, 0.58, 0.53, 0.52 and 0.42, respectively). Recycling assorted wood coal (RAWC) at 9.36% (w.b.) moisture had higher mean static coefficient of friction on the rubber sheet than on mild steel, zinc sheet, galvanized steel and stainless steel (0.61, 0.56, 0.51, 0.49 and 0.47, respectively). Rice husk coal (RHC) at 5.97% (w.b.) moisture had a mean static coefficient of friction on the rubber sheet equal to mild steel but found higher than galvanized steel, zinc sheet and stainless steel (0.66, 0.61, 0.59 and 0.57, respectively). Charcoal from a biomass power plant (CBPP) at 7.76% (w.b.) moisture had higher mean static coefficient of friction on the rubber sheet than on mild steel, zinc sheet, galvanized steel and stainless steel (0.61, 0.58, 0.53, 0.52 and 0.42, respectively). Recycling assorted wood coal (RAWC) at 9.36% (w.b.) moisture had higher mean static coefficient of friction on the rubber sheet than on mild steel, zinc sheet, galvanized steel and stainless steel (0.61, 0.56, 0.51, 0.49 and 0.47, respectively). The results of this study conformed to the study of Kittipong Laloon [33] and Barry EA. [46]. This study also found that the stainless sheet had a low static coefficient of friction (Figure 9) due to its glossy and slippery surface. The result conformed to the report of Singh KK and Goswami TK. [47]

The analysis of variance (ANOVA) showed that the type of charcoal had a significantly different effect on the angle of repose (P < 0.01). Mean values were significantly different when compared using LSD method at 5% significance level (Table 2). Rice husk coal (RHC) had the lowest angle of repose and was significantly different from other charcoal. Coconut-shell coal (CSC) and cassava stump coal (CSC) were not significantly different. Recycling assorted wood coal (RAWC), corn cob coal (CCC) and coconut-shell coal (CSC) were not significantly different on the angle of repose. As well as eucalyptus bark coal (EuBC), recycling eucalyptus coal (REuC) and charcoal from a biomass power plant (CBPP) were not significantly different on the angle of repose.

4.1.5 Static coefficient of friction

The static coefficient of friction of charcoal was shown in Table 3 and Figure 8. Corn cob coal (CCC) at 9.83% (w.b.) moisture had a mean static coefficient of friction on rubber sheet higher than on mild steel, zinc sheet, galvanized steel and stainless steel (0.61, 0.51, 0.50, 0.44 and 0.41, respectively). Cassava stump coal (CSC) at 6.21% (w.b.) moisture had higher mean static coefficient of friction on the rubber sheet than mild steel, zinc sheet, galvanized steel and stainless steel (0.57, 0.52, 0.50, 0.47 and 0.44, respectively). Coconut-shell coal (CSC) at 9.25% (w.b.) moisture had higher mean static coefficient of friction on the rubber sheet than on mild steel, zinc sheet, galvanized steel and stainless steel (0.52, 0.46, 0.45, 0.43 and 0.39 respectively). Eucalyptus bark coal (EuBC) at 5.89% (w.b.) moisture had higher mean static coefficient of friction on the rubber sheet than on mild steel, zinc sheet, galvanized steel and stainless steel (0.56, 0.55, 0.54, 0.49 and 0.43 respectively). Rice husk coal (RHC) at 5.97% (w.b.) moisture had a mean static coefficient of friction on the rubber sheet equal to mild steel but found higher than galvanized steel, zinc sheet and stainless steel (0.66, 0.61, 0.59 and 0.57, respectively). Charcoal from a biomass power plant (CBPP) at 7.76% (w.b.) moisture had higher mean static coefficient of friction on the rubber sheet than on mild steel, zinc sheet, galvanized steel and stainless steel (0.61, 0.58, 0.53, 0.52 and 0.42, respectively). Recycling eucalyptus coal (REuC) at 7.21% (w.b.) moisture had higher mean static coefficient of friction on the rubber sheet than on mild steel, zinc sheet, galvanized steel and stainless steel (0.66, 0.54, 0.53, 0.48 and 0.42, respectively). Recycling assorted wood coal (RAWC) at 9.36% (w.b.) moisture had higher mean static coefficient of friction on the rubber sheet than on mild steel, zinc sheet, galvanized steel and stainless steel (0.61, 0.56, 0.51, 0.49 and 0.47, respectively). The results of this study conformed to the study of Kittipong Laloon [33] and Barry EA. [46]. This study also found that the stainless sheet had a low static coefficient of friction (Figure 9) due to its glossy and slippery surface. The result conformed to the report of Singh KK and Goswami TK. [47]

The analysis of variance (ANOVA) showed that the type of charcoal had a significantly different effect on the static coefficient of friction (P < 0.01). Mean values were compared using the LSD method at 5% significance level (Table 3). The static coefficient of friction of charcoal made from woods such as recycling eucalyptus coal (REuC), eucalyptus bark coal (EuBC), recycling assorted wood coal (RAWC) and charcoal from a biomass power plant (CBPP) was not significantly different on the various surface.

Table 3 The static coefficient of friction of charcoal powder at the moisture content (as-determined basis; adm)

<table>
<thead>
<tr>
<th>No.</th>
<th>Type of Charcoal</th>
<th>Moisture Content (average) ; % (w.b.)</th>
<th>Static coefficient of friction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mild steel</td>
</tr>
<tr>
<td>1</td>
<td>CCC</td>
<td>9.07 – 10.46 (9.83)</td>
<td>0.51&lt;sup&gt;c&lt;/sup&gt;&lt;sub&gt;c&lt;/sub&gt;</td>
</tr>
<tr>
<td>2</td>
<td>CStC</td>
<td>5.84 – 6.61 (6.21)</td>
<td>0.52&lt;sup&gt;c&lt;/sup&gt;&lt;sub&gt;c&lt;/sub&gt;</td>
</tr>
<tr>
<td>3</td>
<td>CSC</td>
<td>8.72 – 9.96 (9.25)</td>
<td>0.46&lt;sup&gt;c&lt;/sup&gt;&lt;sub&gt;c&lt;/sub&gt;</td>
</tr>
<tr>
<td>4</td>
<td>EuBC</td>
<td>5.49 – 6.78 (5.89)</td>
<td>0.55&lt;sup&gt;c&lt;/sup&gt;&lt;sub&gt;c&lt;/sub&gt;</td>
</tr>
<tr>
<td>5</td>
<td>RHC</td>
<td>5.18 – 6.97 (5.97)</td>
<td>0.66&lt;sup&gt;c&lt;/sup&gt;&lt;sub&gt;c&lt;/sub&gt;</td>
</tr>
<tr>
<td>6</td>
<td>CBPP</td>
<td>7.08 – 8.05 (7.76)</td>
<td>0.58&lt;sup&gt;c&lt;/sup&gt;&lt;sub&gt;c&lt;/sub&gt;</td>
</tr>
<tr>
<td>7</td>
<td>REuC</td>
<td>6.73 – 8.17 (7.21)</td>
<td>0.54&lt;sup&gt;d&lt;/sup&gt;&lt;sub&gt;c&lt;/sub&gt;</td>
</tr>
<tr>
<td>8</td>
<td>RAWC</td>
<td>8.97 – 9.73 (9.36)</td>
<td>0.56&lt;sup&gt;d&lt;/sup&gt;&lt;sub&gt;c&lt;/sub&gt;</td>
</tr>
</tbody>
</table>

<sup>P - value</sup> < 0.01

<sup>A – D</sup> Mean values with different letters for each row are significantly difference (LSD) at P < 0.05, 0.02

<sup>a – c</sup> Mean values with different letters for each column are significantly difference (LSD) at P < 0.05, 0.02
4.2 Higher Heating Value of Charcoal

The study of higher heating value (HHV) of charcoal was conducted by comparing the heating value at residual moisture (As-determine basis) (Table. 4). Commercial charcoal briquettes sample no. 1-3 had to mean higher heating value of 5,301.66, 5,382.62 and 5,205.34 cal/g, respectively, and qualified for the Thai Community Product Standards of Charcoal Briquettes (TCPS No.238/2004) [48]. Recycling eucalyptus coal (REEuC) had highest HHV, followed by Coconut-shell coal (CSC), Corn cob coal (CCC), Recycling assorted wood coal (RAWC), Charcoal from a biomass power plant (CBPP), Rice husk coal (RHC), Eucalyptus bark coal (EuBC) and Cassava stump coal (CStC) produced the lowest HHV (7,303.86, 7,154.16, 6,526.38, 6,805.04, 5,991.17, 4,863.29, 3,779.97 and 3,393.77 cal/g, respectively). The HHV of charcoal was then compared by statistical method. It was found that the HHV of Cassava stump coal (CStC), Eucalyptus bark coal (EuBC) and Cassava stump coal (CStC) was found similar than coconut shell charcoal in the study of Nitipong Soponpongpipat. et al. [50]. The static coefficient of friction of charcoal was processed through the Torrefaction at temperature 200 °c for 60 minutes, its heating value was 5,045.57 cal/g (21.12 0.34 MJ/kg). Rice husk charcoal (RHC) had higher HHV than the standard of Bionic Charcoal Briquette (TCPS No.946/2005) [49] and standards of Charcoal briquette (TCPS 238-2004). However, the Cassava stump coal (CStC) had HHV potential as reported by Sunardi et al. [51]. They also had HHV that equivalent to and higher than HHV of wood charcoal. The reported HHV of wood charcoal was 4,468–7,955 cal/g [51–53]. The study of Michael Lubwama et al. [44] reported that biochar briquette had HHV of 3,965–5,255 cal/g. Moreover, the result of HHV of Corn cob coal in this study was higher than Corn cob charcoal that was processed through the Torrefaction, as reported in the study of Nitipong Soponpongpipat. et al. [50], J.J. Lu and W.H.Chen.[51]. Nakasorn K. et al. [54] The HHV of Corn cob charcoal in this study was also higher than corn cob coal briquette that reported by Sunardi et al. [52]. Although the HHV of Rice husk coal (RHC) in this study was lower than the standards of Charcoal briquette (TCPS 238-2004) that indicate the HHV of more than 5,000 cal/g. However, the HHV of Rice husk coal was found to be higher than the heating value of Rice Husk Biochar and Rice Husk Biochar Pellets that reported by Hu Q. et al. [53], Rice Husk Charcoal that reported by Suryaningsih S. et al. [55], and Rice husks briquettes that reported by Michael Lubwama and Vianney Andrew Yiga. [11]. The Recycling eucalyptus charcoal (REEuC) and Charcoal from a biomass power plant (CBPP) that contained eucalyptus woods as one of the material, had HHV higher than eucalyptus woods that was processed through the Torrefaction in the study of S. de O. Araújo. et al. [56] and the HHV of Coconut-shell coal (CSC) was found similar than coconut shell charcoal in the study of D. P. Biswas [57].

Except for the Cassava stump coal (CStC) and Eucalyptus bark charcoal (EuBC), most of the charcoal samples qualified the standard of Bionic Charcoal Briquette (TCPS No.946/2005) and the standard of Charcoal briquette (TCPS 238-2004) that defined the HHV of more than 4,000 cal/g and 5,000 cal/g, respectively. They were also had HHV higher than commercial briquettes charcoal as shown in Table 7, and

![Figure 8. The static coefficient of friction of charcoal powder](image-url)
higher than the heating value of commercial briquettes charcoal, 5,447 cal/g, that reported by Michael Jerry Antal JR. et al. [58]. Moreover, the HHV of charcoal samples were higher than sawdust charcoal briquette, 4,820 cal/g, in the study of Akowuah JO. et al. [59], of which similar to the HHV of Rice husk coal (RHC) in this study. Eucalyptus bark coal (EuBC) had HHV of 3,996 cal/g, which was lower than the report of Juizo CGF, et al. [60] at 4,669.67 cal/g. According to the report of Lubwama M. et al. [44], it can be used as household cooking fuels as compared to the heating value of firewood. The Eucalyptus bark coal had the potential to be used as the secondary ingredient in charcoal briquettes production, due to its large amount, especially in the Eucalyptus wood ships factory areas. Moreover, eucalyptus bark is not a major material for industry, nor is Bionic Charcoal Briquette (TCPS No.946/2005) production. The Cassava stump coal (CStC) had mean HHV of 3,393.78 cal/g. According to the study of Nakasorn K. et al. [54], it was found that the combustible component (volatile substance + fixed carbon) and the higher heat value (HHV) was 89.17–95.05% and 4,310–6,025 cal/g, which conformed to the study of Sen R. et al. [23] and Tippayawong N. et al. [61]. Therefore, Cassava stump has the potential to be used as raw material for charcoal briquette production. It could be used as secondary material in charcoal briquettes production or Bionic Charcoal Briquette (TCPS No.946/2005) as well as Eucalyptus bark coal (EuBC). However, the materials must be collected before material decay or destroyed by pests.

**Table 4. Higher Heating Value of Charcoal (As-Determined Basis, adm)**

<table>
<thead>
<tr>
<th>Type of Charcoal</th>
<th>Moisture content (%)</th>
<th>Higher Heating Value; HHV, (cal/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TISI; Charcoal Briquette (TCPS No.238/2004)</td>
<td>≤ 8</td>
<td>≥ 5,000</td>
</tr>
<tr>
<td>TISI; Bionic Charcoal Briquette (TCPS No.946/2005)</td>
<td>≤ 8</td>
<td>≥ 4,000</td>
</tr>
<tr>
<td>Commercial Briquettes Charcoal 1, (CBC 1)</td>
<td>4.91</td>
<td>5,301.66 ±48.34</td>
</tr>
<tr>
<td>Commercial Briquettes Charcoal 2, (CBC 2)</td>
<td>5.98</td>
<td>5,382.62 ±298.86</td>
</tr>
<tr>
<td>Commercial Briquettes Charcoal 3, (CBC 3)</td>
<td>5.67</td>
<td>5,205.34 ±71.35</td>
</tr>
<tr>
<td>CCC</td>
<td>9.83</td>
<td>6,526.38±±265.38</td>
</tr>
<tr>
<td>CStC</td>
<td>6.21</td>
<td>3,393.78±±480.12</td>
</tr>
<tr>
<td>CSC</td>
<td>9.25</td>
<td>7,154.16±±448.73</td>
</tr>
<tr>
<td>EuBC</td>
<td>5.89</td>
<td>3,779.98±±106.00</td>
</tr>
<tr>
<td>RHC</td>
<td>5.97</td>
<td>4,863.29±±153.80</td>
</tr>
<tr>
<td>CBPP</td>
<td>7.76</td>
<td>5,991.18±±197.59</td>
</tr>
<tr>
<td>REuC</td>
<td>7.21</td>
<td>7,303.86±±159.58</td>
</tr>
<tr>
<td>RAWC</td>
<td>9.36</td>
<td>6,085.04±±208.18</td>
</tr>
</tbody>
</table>

* ± Mean values with different letters for each row are significantly different (DMRT) at *P* < 0.01

### 5. Conclusion

Charcoal powder in this study had a mean moisture content of 5.78–15.33 % (w.b.), mean bulk density of 189.19–563.73 kg/m², angle of repose 35.05–43.21 degrees. The flowing ability of material was fair to passable flow and free-flowing. The mean particle size was 0.31–1.29 mm, at the mean moisture content of less than 10% (w.b.). At the mean moisture content of 5.89–9.83% (w.b.), static coefficient of friction on mild steel was 0.46–0.66, on stainless steel was 0.39–0.57, on zinc sheet was 0.45–0.59, on galvanized steel was 0.43–0.61 and on a rubber surface was 0.52–0.66, at the average moisture content of 5.97–13.21% (w.b.). The higher heating value of 8 charcoal samples had an average higher heating value of 3,393.78–7,303.86 cal/g. While 3 commercial briquette charcoal samples had higher heating value was 5,205.34 – 5,382.62 cal/g, followed the standard of Charcoal briquette (TCPS 238-2004) that defined the HHV of more than 5,000 cal/g.

The results of physical properties of charcoal powder benefits for the engineering design. Higher heating value compared between commercial briquettes and charcoal from biomass materials demonstrated the potential of biomass that can be used as raw material for charcoal briquettes production and substitute biomass from trees. Thereby the value of such material can be increased (Zero Waste).
Acknowledgements

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References


