Fuel Processing Technology 179 (2018) 229–237

Contents lists available at ScienceDirect

Fuel Processing Technology

journal homepage: www.elsevier.com/locate/fuproc

Research article

Mechanical strength and combustion properties of biomass pellets prepared with coal tar residue as a binder

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ARTICLE INFO

Keywords:
Coal tar residue
Biomass pellets
Binder
Mechanical strength
Combustion properties

ABSTRACT

To reutilise the hazardous waste material coal tar residue (CTR) to bring environmental and economic benefits, CTR was first used as a binder to prepare biomass pellets with enhanced mechanical strength and heating values. CTR, which mainly contained asphaltenes (40.06%), aliphatics, aromatics and non-hydrocarbon components, had a high viscosity (72,276 mPa·s) and heating value (27.46 MJ/kg). When the CTR percentage increased from 0 to 40 wt%, the abrasive resistance of wheat straw, sawdust and moso bamboo pellets significantly increased from 10.62–69.20% to 95.66–98.24%, while their water resistance time increased from 6 s to > 30 min and their heating value increased by 20.62–25.96%. The ignition temperature of wheat straw pellets increased from 275.7 to 280.7 °C as the CTR content increased from 0 to 30 wt%, whereas the maximum burning rate decreased from 1.28 to 0.82 mg/min and the burnout temperature increased from 465.33 to 563.33 °C.

1. Introduction

Coal tar residue (CTR) is a type of toxic, hazardous industrial solid waste generated in the process of coal gasification or coking and composed of heavy tar oil, pulverised coal and other solid particles entrained in gases produced by coal pyrolysis. According to previous studies, CTR contains 2–6 aromatic rings, some of which are carcinogenic polycyclic aromatic hydrocarbons (PAHs) such as naphthalene and benzo[*a*]pyrene, and its direct discharge would cause serious pollution to soil, groundwater and the surrounding air [1–4]. Moreover, CTR is a secondary energy source with high calorific value and should be handled carefully. As a result of the relatively high viscosity of CTR at room temperature, it can be used as a binder in certain conditions. Shi et al. [5] utilised CTR as an additive for the production of coke and as an adhesive for fabricating briquettes. Both provided good experimental results.

As a type of biofuel, biomass is advantageous because it is clean, sustainable and carbon-neutral. However, biomass is not utilised directly because of its low energy density, unstable combustion rate, high particle emissions and difficulties in storage and transportation [6,7]. Pelletisation is considered to be an effective method of improving the storage and transport properties of biomass. Many investigations into biomass pelletisation have been reported in the literature. These investigations have revealed that the properties of the raw material (moisture content, particle size and components) and pelletising conditions (compression velocity, compression pressure, die temperature and die size) have a direct effect on pellet quality (density, calorific value, durability, compression strength and hydrophobicity) [8,9]. Stelte et al. [10] observed that the pelletising pressure increased exponentially with the pellet length, and the rate of increase was dependent on the type, temperature, moisture content and particle size of the biomass. Kirsten et al. [11] studied the influence of particle size reduction on the physical and mechanical qualities of the pellets and the energy demand during production. A hammer mill with a 4 mm mesh yielded hay pellets with the required bulk density and durability while minimising the specific energy input ($E_{spec,\ total}$ = 157 W h/kg). Ishii et al. [12] discovered that rice straw pellets were formed with a high yield ratio and high durability with an optimal moisture content of between 13% and 20% at a formation temperature of 60 °C or 80 °C.

Usually, in the production of densified biomass pellets high pressures (70–250 MPa) and hot-pressing temperatures (100–250 °C) are employed to increase their durability and soften the point components so as to increase the attractive forces between the small biomass particles. However, pelletising at high pressures and hot-pressing temperatures consumes much more energy. Therefore, specific binders are added to improve the mechanical durability of biomass pellets under conditions of ambient temperature and low pressure. Kong et al. [13] studied the effect of waste wrapping paper fibre used as a 'solid bridge'

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https://doi.org/10.1016/j.fuproc.2018.07.011
Received 28 April 2018; Received in revised form 5 July 2018; Accepted 11 July 2018
0378-3820/

Table 1
Proximate and ultimate analysis of coal tar residue, biomass and lignite.

Samples	Proximate analysis (air-dried)				Net calorific value (air-dried) (J/g)	Ultimate analysis (air-dried)				
	Moisture (%)	Ash (%)	Volatile matter (%)	Fixed carbon (%)		Carbon (%)	Hydrogen (%)	Nitrogen (%)	Sulfur (%)	Oxygen (%)
Coal tar residue	14.64	5.58	66.76	13.02	27,462	56.46	6.01	1.12	1.94	14.25
Wheat straw	12.20	7.42	64.75	15.63	15,340	38.38	4.31	0.40	0.29	37.00
Sawdust	15.62	0.21	72.35	11.82	17,388	45.96	4.54	0.21	0.64	32.82
Moso bamboo	9.54	0.98	75.24	14.24	17,407	44.22	5.15	0.49	0.22	39.40
Ximeng lignite	37.37	13.77	23.47	25.39	13,523	32.39	1.89	0.86	0.41	13.31

Table 2
Organic, ash and heavy metal compositions of coal tar residue.

Organic compositions	Aliphatic hydrocarbon (%)	Aromatic hydrocarbon (%)	Non- hydrocarbon (%)	Asphaltene (%)	Moisture (%)	Solid particle (%)
Coal tar residue	11.37	11.85	17.30	40.06	14.64	4.78

Ash compositions	SiO_2 (%)	Al_2O_3 (%)	Fe_2O_3 (%)	CaO (%)	MgO (%)	K_2O (%)	Na_2O (%)
Coal tar residue	2.16	0.60	0.79	0.57	0.15	0.04	0.30

Heavy metal compositions	Fe (ppm)	Ca (ppm)	Na (ppm)	V (ppm)	Zn (ppm)	Pb (ppm)	Cu (ppm)	Ni (ppm)
Coal tar residue	88.19	42.93	41.54	0.27	6.47	5.87	0.17	0.10

on the physical characteristics of biomass pellets made from sawdust. The results showed that the addition of wrapping paper fibre to waste wood sawdust greatly reduced the negative effects of resiliency on the density and mechanical properties of biomass pellets during storage. Peng et al. [14] indicated that torrefied sawdust particles prepared under typical torrefaction conditions (280–300 °C for 10–30 min) could be formed into strong pellets by compression at a die temperature of higher than 220 °C or by introducing biomass binders such as untreated sawdust, starch or lignin at a lower die temperature. Mišljenović et al. [15] studied the feasibility of an alternative method of producing wood pellets with the addition of waste vegetable oil and examined how the oil affected the physical quality and surface properties of the pellets, as well as the pelletising process. The results showed that the addition of oil significantly increased the energy content of the wood pellets, although the pellet strength was reduced. Jiang et al. [16] investigated the effects of process parameters on the properties of the pellets in the co-pelletisation of sludge and biomass materials. The results showed that the pellet density increased with increases in parameters such as the pressure, sludge ratio and temperature. An increase in the sludge ratio in the pellet would slow the release of volatile substances. The synergistic effect of proteins and lignin may be the mechanism involved in the co-pelletisation of sludge and biomass. Lu et al. [17] investigated the use of crude glycerol, bentonite, lignosulphonate and softwood residues as binders in biomass fuel pellets used for thermochemical conversion to enhance the quality of the pellets for transportation and storage. The results showed that the specific energy consumption in the pelletisation of wheat straw decreased significantly on the addition of lignosulphonate, bentonite, wood residues and wood residues pretreated with crude glycerol. Craven et al. [18] proposed an approach for creating moisture-stable wood pellets via the addition of hydrophobic coatings. No appreciable reduction in pellet strength was recorded after 1800 s after pellets were treated with paraffin oil, castor oil, mineral oil and linseed oil. Treatment with oil also increased the energy density of wood pellets.

Binders such as waste vegetable oil, bentonite, lignosulphonate, starch and lignin have been examined extensively in the literature with respect to their effectiveness for pelletising. However, the use of CTR as a binder has rarely been investigated. Therefore, in the present paper the physical and chemical properties of CTR have been studied. Three representative biomass wastes (wheat straw, sawdust and moso bamboo), which are very abundant resources in China, and Ximeng lignite were employed as raw materials to assess the feasibility of using CTR as a binder to prepare biomass/lignite pellets. The three biomass wastes, which are rich in cellulose, hemicellulose and lignin compositions, are often used to produce biomass pellets in industry. Ximeng lignite from the largest lignite producer in Inner Mongolia of China was used as a comparative condition to produce pellets with a CTR binder, because lignite has lower volatile matter and higher fixed carbon and moisture than biomass. The effects of different proportions of CTR on the mechanical strength of the pellets, which was exemplified by abrasive resistance, impact resistance and water resistance, were studied, and the optimum proportion of the binder for transportation and storage is proposed in this paper. In addition, thermogravimetric (TG) experiments were conducted to investigate the effect of CTR on the ignition and combustion characteristics of wheat straw pellets and sawdust pellets.

2. Materials and methods

2.1. Physical and chemical properties of CTR

Proximate and ultimate analyses of CTR were carried out and the amounts of the ash components of CTR were measured using the GB/T 1574-2007 test method. Inductively coupled plasma–atomic emission spectroscopy was used to investigate the heavy metal content in CTR. The viscosity was measured using a rotary viscometer (HAAKE VT550) with an SV2 rotor and a corresponding measuring cup at intervals of 5 °C as the temperature was increased from 25 °C to 95 °C. Furthermore, the shearing rate was increased from 0 to 100 s^{-1}. After water and solid particles were removed, the remaining CTR components were separated into four fractions by column chromatography according to the SY/T 5119-1995 standard. Gas chromatography–mass spectrometry (GC–MS) (Finnigan, San Jose, CA) was used to investigate the components of CTR. Chromatographic separation was performed using a DB-5 ms capillary column (30 m × 0.25 mm × 25 μm). The inlet temperature was 250 °C and the oven temperature was increased from 50 °C (held for