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Investigation into the applicability of Bond Work Index (BWI) and Hardgrove Grindability Index (HGI) tests for several biomasses compared to Colombian La Loma coal

Orla Williams [a,*], Carol Eastwick [a], Sam Kingman [a], Donald Giddings [a], Stephen Lormor [b], Edward Lester [a]

[a] Energy and Sustainability Research Division, Faculty of Engineering, The University of Nottingham, University Park, Nottingham NG7 2RD, UK
[b] EDF Energy plc., Production Performance Team, Cottam Power Station, Outgang Lane, Retford DN22 0EU, UK

HIGHLIGHTS

- Bond Work Index (BWI) & Hardgrove Grindability Index (HGI) tests for biomass & coal.
- BWI can predict the potential for mill choking of biomass in a tube and ball mill.
- HGI is a poor method of predicting grindability of biomass in vertical spindle mills.
- Pellets should be composed of pre-densified particles close to the target size.
- Approximate correlation between HGI and BWI found for some biomass samples.

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ABSTRACT

With increasing quantities of biomass being combusted in coal fired power stations, there is an urgent need to be able to predict the grindability of biomass in existing coal mills, but currently no standard biomass grindability test exists. In this study, the applicability of the Hardgrove Grindability Index (HGI) and Bond Work Index (BWI) as standard grindability tests for biomass were investigated for commercially sourced wood pellets, steam exploded pellets, torrefied pellets, sunflower pellets, eucalyptus pellets, miscanthus pellets, olive cake and Colombian La Loma coal. HGI predicts the behaviour of fuels in vertical spindle mills and BWI for tube and ball mills. Compared to La Loma (HGI of 46), all biomasses tested performed poorly with low HGI values (14–29). Miscanthus pellets had the highest BWI or W_i at 426 kW h/t. Despite similar HGI values, some untreated biomasses showed lower BWI values (Eucalyptus pellets W_i 87 kW h/t, HGI 22) compared to others (sunflower pellets W_i 366 kW h/t, HGI 20). Torrefied pellets had the lowest W_i (16 kW h/t), with La Loma coal at 23 kW h/t. Wood, miscanthus and sunflower pellets exhibited mill choking during the BWI test, as the amount of fines produced did not increase with an increasing revolution count. An approximate correlation between HGI and BWI was found for the biomass samples which did not experience mill choking in the BWI test. Milling results in this paper suggest that biomass pellets should be composed of pre-densified particles close to the target size in order to minimise the energy use in mills and possibility of mill choking. Our findings would also suggest that the BWI is a valid test for predicting the potential for mill choking of biomass in a tube and ball mill. HGI, however, appears to be a poor method of predicting the grindability of biomass in vertical spindle mills. A new standard grindability test is required to test the grindability of biomasses in such mills.

1. Introduction

Global coal consumption by power generators is growing annually [1]. With increasing legislation to reduce emissions from coal fired power stations in Europe [2,3], biomass combustion is playing an increasing role in the UK, Europe and beyond [4]. In order to minimise costs, biomass is often ground in existing coal mills when used in coal fired power stations, but the fracture mechanics in conventional mills were optimised to exploit the brittle structure of coal which contains pre-existing macro and micro flaws [5]. This type of breakage does not occur in biomass, which possesses a more orthotropic structure [6]. Standard grindability tests have been developed for coal, with the Hardgrove Grindability Index

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* Corresponding author. Tel.: +44 7815289720.
E-mail address: enxow@nottingham.ac.uk (O. Williams).

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(HGI) being the standard test for vertical spindle mills [7,8], and the Bond Work Index (BWI) for tube and ball mills [9,10]. No standard grindability tests currently exist for biomass, and there have only been limited studies on the use of standard grindability tests for coal on biomass, which have mainly focused on torrefied materials [11–16]. This paper aims to analyse the applicability of the standard HGI and BWI as a standard test for grindability on a wide variety of commonly used biomasses in the power sector compared to a known coal.

The Hardgrove Grindability Index (HGI) test is based on Rittinger's theory that "the work done in grinding is proportional to the new surface produced" [17,18]. The index varies from 20 to 110, with a lower HGI indicating a coal is harder to grind and more energy will be required to reach the required degree of fineness. The test is conducted on a standardised laboratory scale ball-and-race mill and is covered by BS 1016-112:1995 [8]. A strong, hard coal will often have a high rank and be difficult to reduce in size; a weak, soft coal of lower rank will be easier to grind; but very low rank coals can also be difficult to reduce in size. For coal, HGI correlates to compressive and tensile strength measurements which roughly correlate with coal rank, and increasing bulk modulus [5]. However, Kendall [19] showed that crack propagation becomes impossible via compression once a critical particle size is reached, the length of which is material dependant, and particles below this size are ductile in compression. Zuo et al. [20] showed that the relationship between coal size reduction and energy input is a nonlinear curve, so it is difficult to represent coal grindability with a single numerical value. Rubiera et al. [21] showed that the HGI of binary coal blends cannot be predicted from the weighted average of the individual coals in the blend, which has important implications in the co-milling and combustion performance of biomass and coal blends, as the actual performance may be quite different to the predicted behaviour for a blend due to the interactions between the blends. Vassilev et al. [22] noted that biomass composition and properties varied significantly from coal. The observation by Agus and Waters [23] that mills are volumetric devices and that the traditional HGI method favours denser coals with small volumes has led to the HGI test to be modified to use a volume (rather than mass of coal), and this method is commonly used to analyse biomass and coal HGI values experimentally [12,14,24], although industry uses the standardised mass based method [7,8].

The Bond Work Index (BWI or W_i) is defined as the calculated specific energy (kW h/t) applied in reducing material of infinite particle size to 80% passing 100 μm [25]. The higher the value for W_i, the more energy is required to grind a material in a ball mill [10,26]. The BWI test is used extensively in the mining industry to analyse the absolute resistance of different materials to ball milling, the energy consumption for ball milling, and scale up [27]. The test itself contains 5 major components: a standard grindability test of a material; an empirical equation that converts the test results to the observed results of a commercial mill; an empirical equation to allow for the overall size ratio reduction; scale up equations to predict the results for larger mills; and a series of empirical correction factors based on experience for varying milling conditions. While the BWI has been used extensively on brittle materials [10,28–34], limited testing (using modified forms of the theory) of biomass has been conducted in planetary ball mills [11] and hammer mills [35]. As the BWI and the HGI are both measures of the grindability of a material, it might be expected that results from the two tests could be correlated. Studies have shown an approximate correlation of HGI and BWI based on the findings of several studies for a wide range of materials, but biomass was not amongst the materials tested [9,36]. Bond proposed the following equation for finding the equivalent wet grinding work index (W_i) from the Hardgrove Grindability Index [26]:

$$W_i = 435/(HGI)^\wedge 0.91 \tag{1}$$

As McIntyre and Plitt noted [34], no data was provided to support this correlation. They modified the correlation based on the testing of a wide range of brittle materials, including limestone, subbituminous, and bituminous coal, and for materials with a BWI value above 8.5 kW h/ton, the correlation between HGI and BWI was found to be:

$$W_i = 1622/HGI^\wedge 1.08 \tag{2}$$

However, these correlations have not been tested on biomass samples commonly used in the power sector.

An increasing number of legacy coal fired power stations are being converted to burn biomass. There is an urgent need to understand the grinding behaviour of a wide range of biomasses in all types of mills, not least because incorrect operation of existing coal mills during biomass milling increases the risk of fires in biomass mill hoppers [37]. This study aims to investigate the applicability of the HGI and BWI tests for a wide range of commonly used biomasses used in the power generation sector and analyse which biomass characteristics influence the milling behaviour, and the suitability of the test for analysing the grindability of biomass.

2. Materials and methods

2.1. Materials

The samples used in this work are either routinely co-fired in coal fired power plants or have been used in biomass co-firing trials, as illustrated in Fig. 1. Portuguese wood pellets (mainly pine with a small amount of eucalyptus), Spanish olive cake (a residual waste mix from olive oil production formed of powdered olive pulp (0–850 μm), olive pips (850–3350 μm) and olive pellets/self-formed lumps (3350 μm+) [38]), Russian sunflower husk pellets and Colombian La Loma coal were provided by EDF Energy plc. South African eucalyptus pellets, American steam exploded white wood chip pellets, miscanthus pellets, and torrefied white wood chip pellets were provided by E.ON UK plc.

The particle size range of the biomass particles (prior to densification) was obtained using the British standard BS EN 16126:2012 [39]. 2 litres of boiling deionised water was poured over 300 ± 1 g of each pellet sample and then soaked for 24 h. The samples were then dried at 35–60 °C until they reached 5–15% moisture content. The samples were then split into two portions; 150 g was used to obtain the moisture content via BS EN 14774-1:2009 [40], and the other 150 g portion was split and sieved according to BS 15149-2:2010 [41] to obtain a particle size distribution.

2.2. Thermal characterisation

Limited information was available on the source and species of the material, for commercial reasons. Thermal profiles were produced using TA Instruments Q500 Thermogravimetric Analyser (TGA). TGA runs used 10–15 mg of milled sample with a particle size range of 75–300 μm. The method used was based on the slow pyrolysis method developed by Lester et al. [42] for analysing the composition of biomass. The sample was heated in a furnace at 5 °C/min in 100 ml/min of Nitrogen from atmospheric temperature to 900 °C, after which the gas was switched to air at 100 ml/min. The results were processed and analysed in Matlab® 2014a in order to establish the sample composition and peak volatiles release rate on a dry weight basis. The composition of the samples is given by moisture, volatile, fixed carbon, and ash contents. The peak volatile release rate and corresponding temperature were obtained from the derivative thermogravimetric curves. TGA was used to analyse

Fig. 1. (top left to right) Spanish olive cake, torrefied pellets, wood pellets, South African eucalyptus pellets, (bottom left to right) Colombian La Loma coal, steam exploded pellets, miscanthus pellets, sunflower husk pellets.

any changes in composition during the BWI test. The gross calorific values (H) on a dry weight basis of the samples were found using an IKA C5000 Bomb Calorimeter (Staufen, Germany) in accordance with BS ISO 1928:2009 [43]. Certified Benzoic Acid tablets were used as a standard, and the sample weight was calibrated to give the same temperature rise as the standard.

2.3. Hardgrove Grindability Index (HGI) test

The HGI test used followed BS 1016-112:1995 [8] and was conducted at Environmental Scientific Group, Bretby, UK for the biomass samples, and at Alfred H Knight, Ayrshire, UK, for the coal, both on a standard Hardgrove testing machine. The samples were dried in accordance with BS EN 14774-1:2009 [40], then crushed and sieved to a size fraction of 1180–600 μm. 50 g ± 0.01 g of the 1180–600 μm size fraction was disbursed evenly into the Hardgrove machine bowl with evenly spaced balls and then secured into the apparatus. The apparatus was then run for 60 ± 0.25 revolutions. The sample was then removed from the bowl and sieved in a 75 μm sieve size for 10 min. Mass m (g) is calculated based on the of the test portion passing through the 75 μm sieve, using the formula:

$$m = 50 - m_1 \tag{3}$$

where m_1 is the mass, in grams, of test portion retained on the 75 μm sieve. The HGI index was found using the calibration chart in Annex A of BS 1016-112:1995 [8]. The process was then repeated and the mean of the two determinations, rounded to the nearest whole number, is the HGI rating for the sample.

2.4. Bond Work Index (BWI) theory & test

The BWI is determined using a dry grinding test in a standardised testing machine, the Bico Ball Mill [44] at the University of Nottingham. The mill contains 285 steel balls of total weight 20.13 kg with a drum size of 305 mm in diameter by 305 mm in length which rotates at a constant speed of 70RPM. The coal sample was crushed in a Retsch Jaw Crusher (Hann, Germany) to 3.35 mm and (prior to testing) a full cumulative size distribution was performed on the coal and olive cake to obtain the 80% passing size of the feed (F_{80}), while the average pellet diameter of 100 measured pellets was used as F_{80} for the pellets in accordance with BS EN ISO 17829 [45]. The La Loma coal and olive cake were sampled using a riffle type splitter to provide representative sampling of the materials for the tests. The BWI test used 700 ml of dry sample [25] run for 100 revolutions in the mill, following which the contents were sieved to a set target equilibrium sieve size (P_1). While the normal Bond Work Index test is defined on ascertaining the energy consumption in comminuting material to pass 100 μm, the target sizes used in full scale coal mills for biomass and coal are different and based on the burner requirements. The target size was set to 1 mm for biomass based on pulverised fuel (PF) burner requirements for biomass [46,47] and 90 μm for the La Loma coal based on the operating requirements for this coal in a tube and ball mill at EDF Energy plc coal fired power station in Cottam, UK. The fines from the sieving were weighed and placed to one side, and new product was added to the oversized milled material to bring it back to its original weight. The new number of revolutions required was calculated from the results of the previous test to produce sieve undersize equal to 1/3.5 of the total charge of the mill. This process was repeated until the gram per revolution (G) reaches a constant value for a minimum of three cycles. A full sieving analysis was performed on the last three cycles and the 80% passing size of the product (P_{80}) was determined to calculate the BWI. All work indices are derived from the general comminution energy equation proposed by Walker et al. [48] which relates the net specific energy E, the characteristic dimension of the product x, the exponent n, and a constant C related to the material:

$$dE = -C\ dx/x^\wedge n \tag{4}$$

In addition there are the three theories of comminution which describe empirical size reductions, these being Rittinger's [18], Kick's [49] and Bond's [10] theories of comminution which state that:

1. The energy required for size reduction is proportional to the new surface area generated [18].
2. The equivalent relative reductions in sizes require equal energy [49].
3. The net energy required in comminution is proportional to the total length of the new cracks formed [10].

The application of Kick's and Rittinger's theories has been met with varied success and are not realistic for designing real size reduction circuits [50]. However the BWI can be applied to ball and rod mills, and is the most commonly used method of sizing these mills. The general form of the BWI Equation is:

$$W = 10W_i \cdot (1/\sqrt{P_{80}} - 1/\sqrt{F_{80}}) \tag{5}$$

where W is the work input (kW h/t), W_i is the Bond Work Index (kW h/t) which expresses the resistance of the material to crushing and grinding, and F_{80} and P_{80} are the 80% passing size of the feed and product (μm) respectively. W_i can therefore be found through the following equation:

$$W_i = 44.5/P_1^{\wedge}0.23 \cdot G^{\wedge}0.82 \cdot (10/\sqrt{P_{80}} - 10/\sqrt{F_{80}}) \tag{6}$$

where P_1 is the closing sieve size (μm), G is the grindability (net g/rev). The Bond Work Index (W_i) expresses the resistance of the material to grinding to a specified product size, and the higher the value of W_i, the more difficult the material is to grind to the required product size. The Work Input W, gives the power required by the mill to grind the product to the required product size. In addition, the higher the value, the more power will be required to reduce the material to the required product size for a given mass flow rate. The non-linear regression analysis of the BWI and HGI correlations was performed on IBM SPSS Statistics 22.

2.5. Particle size characterisation

The Rosin–Rammler distribution equation was originally developed to describe the distribution of coal fines from coal mills [51], and it has been shown that the Rosin–Rammler distribution equation is a good fit for biomass comminution in hammer mills [52,53]. The Rosin–Rammler equation is:

$$R(d) = 100(1 - exp - (d/d')^{\wedge}n) \tag{7}$$

where R is cumulative percentage undersize mass (%), d is particle diameter (μm), d' is the characteristic particle size (μm), defined as the size at which 63.2% ($1 - 1/e = 0.632$) of the particles (by weight) are smaller, and n is the Rosin–Rammler size distribution parameter (dimensionless). The Rosin–Rammler parameters were found using the Matlab® GUI Tool developed by Brezáni and Zelenak [54]. The particle size distributions of percentage retained mass against particle size were plotted on semi-logarithmic plots. Geometric mean diameter by mass d_{gw} and geometrical standard deviation S_g was calculated according to BS ISO 9276-2:2014 [55]. The pre-densified particle size 80% passing particle size (FPP_{80}) was obtained via the particle disintegration test described in Section 2.1. The resultant Bond Work Index for FPP_{80} is defined as WPP_i, and the Work Index is WPP.

3. Results and discussion

3.1. HGI test

Table 2 shows the HGI results for La Loma coal, Spanish olive cake, eucalyptus pellets, wood pellets, steam exploded pellets, and sunflower pellets. Miscanthus and torrefied pellets were not tested due to limited quantities of material being available. On average, coals used in UK power stations have a HGI around 40–60; the La Loma coal tested in this work falls within this range with a HGI of 46. The biomasses tested performed very poorly (HGI of 14–22), indicating a high resistance to grinding. Even the steam exploded pellets showed only a nominal improvement (HGI of 29) in comparison to non-treated biomasses. The majority of samples showed the same result in the repeat test, or varied by ±1 HGI value.

Ohliger et al. [12] found very high HGI values for torrefied beech wood, but the crushing ratio (the average particle size before milling divided by the average particle size after milling) for the same samples were lower than that of lignite, indicating that the high HGI values can be misleading when analysed by themselves. A HGI equivalent using a Retsch PM100 planetary ball mill was developed by Bridgeman et al. [14], and has been used by Ibrahim et al. [15] to find HGI values as high as 86.4 for torrefied willow. These figures have been compared to coals tested as per international HGI testing standards [7,8] by Li et al. [56], and superficially appear to show a vast improvement in grindability, with the potential to be better than some coals. However the HGI figures reported by Bridgeman and Ibrahim are not from the same method (and apparatus) and caution is required when comparing HGI values that are not derived from a Hardgrove machine. Hardgrove testing machines use compression breakage modes similar to those in a vertical spindle mill, whereas planetary ball mills use high impact breakage modes [57]. The HGI test was developed for coal fired power plants, and the target 75 μm size is based on what is required for combustion in pulverised fuel coal burners [46]. However biomass has a target particle size closer to 1000 μm for pulverised fuel burners. For a 150 kW pilot burner, the optimal burn conditions for wood feed stocks was 95% of particles (by weight) were smaller than 1000 μm with a moisture content lower than 15% [47]. Therefore a grindability test which aims to analyse the grindability of biomass to 75 μm is inappropriate, as the target size for optimal combustion of biomass and the setting for the classifier output from full scale mills is an order of magnitude of higher than this. In addition, the critical particle size for compressed fracture should be ascertained for biomasses to be milled in coal mills, as below this size the biomass will behave as a ductile material and mills which use compression and impact forces will not be able to further reduce the particle size. Coal has a critical particle size of 5 μm, while polystrene's is 4.48 mm [19], but the critical crack length of biomasses used in PF combustion is unknown.

Table 1 compares the BWI and HGI tests. The HGI test is very constricted in its setup compared to the BWI test. The feed sample is already within the target size range (600–1180 μm) and the mass size is small in comparison to the BWI test. Even with the modified HGI test the volume is still limited to a small unrepresentative volume (50 cm^3) [12,14,15,23,58]. The BWI test has the advantage of being based on a larger volume (700 ml) and with a variable target size, so the impact of target particle size on the grindability of materials can be investigated. The output of the BWI test is also in a more useable form of energy consumption per ton (kW h/t), which allows the method to be compared to other

Table 1
Comparison of HGI & BWI test conditions.

	BWI	HGI
Mill comparison	Tube & ball mill	Babcock & Wilcox mill (ring–ball)
Target particle size	Any size below 3.35 mm	75 μm
Particle size range	<3.35 mm (powder) or pellet size	1.18–600 μm
Mass constriction	Volume – 700 ml	Mass – 50 g
Output	kW h/ton	HGI index
Suitable materials	Brittle materials	Good quality coals

Table 2
Summary of HGI and BWI data for all samples; Hardgrove Grindability Index HGI, 80% passing feed size F_{80}, 80% passing product size P_{80}, grindability per revolution G, final revolution count R_F, bond work index W_i, work input W, gross calorific value on dry basis H, bond work index-gross calorific value ratio (W/H).

Sample	HGI	F_{80} (μm)	P_{80} (μm)	G (g/rev)	R_F	W_i (kW h/t)	W (kW h/t)	H (J/g)	W/H (%)
Wood pellets	18	8400	786	0.053	2141	413	102	20405	1.80
Miscanthus pellets	–	6290	811	0.057	2168	426	96	18571	1.86
Sunflower pellets	20	8620	764	0.059	1699	366	93	20238	1.66
Eucalyptus pellets	22	8390	757	0.340	411	87	22	19810	0.40
Steam exploded pellets	29	5910	355	0.283	556	64	26	20049	0.46
Torrefied pellets	–	8000	758	2.655	60	16	4	21772	0.07
Olive cake	14	3712	590	0.202	390	136	34	19318	0.63
La Loma coal	46	2709	77	0.664	242	23	22	30004	0.26

forms of milling such as hammer mills [35] or planetary ball mills [11] which already have modified work indicies based on the theories of comminution. Therefore, it can be concluded that HGI is a poor method of testing the grindability of biomass in vertical spindle mills and a new standard grindability test is required to test the grindability of biomasses. A larger, more representative, volume of material and a target particle size close to that required for the PF burners and mill classifiers is important. It is also important that the grindability test identifies the failure mechanism in use and subsequent impact on particle characteristics.

3.2. BWI test overall results

Table 2 shows the results of the BWI tests. The biomasses all had the same equilibrium sieve size of 1000 μm, while coal was set to 90 μm in order to achieve a particle size close to the 70% passing at 75 μm. Miscanthus pellets had the highest W_i at 426 ± 29.5 kW h/t (high variability due to mill choking), with wood pellets (413 ± 3.7 kW h/t) and sunflower pellets (366 ± 0.5 kW h/t) showing similar results. Olive cake had a W_i of 136 ± 3.6 kW h/t. Surprisingly, eucalyptus pellets showed a much lower W_i at 87 ± 8.7 kW h/t, which was close to that of the steam exploded pellets (64 ± 0.8 kW h/t). The lowest W_i for the biomasses was for the torrefied pellets (16 ± 1.1 kW h/t), with the La Loma coal having a similar W_i at 23 ± 0.1 kW h/t with a target size of 90 μm. Table 2 also shows the heating value (H) of the samples on a dry basis and what percentage the Work Input (W) represents of this value (W/H). As expected, the La Loma coal has the highest calorific value (30,044 J/g). The torrefied pellets had a higher heating value than the steam exploded pellets, which was on a par with the other wood pellets. The heating values for the samples found in this study corresponded to similar samples tested in literature (14,000–21,000 J/g for biomass [59,60] and 26,000–33,000 J/g for coal [9]). The milling energy represents a low percentage of the heating value of the samples, with values ranging from 0.07% for the torrefied pellets, up to 1.86% for miscanthus pellets.

The work input W and the grindability per revolution G showed a similar order of results. Wood pellets had the highest W and lowest G at 102.29 kW h/t and 0.053 g/rev, followed closely by miscanthus and sunflower pellets (95.85 kW h/t, 0.057 g/rev and 93.08 kW h/t, 0.059 g/rev respectively). This reversal of order between these samples is due to the difference in feed size (F_{80}) used in the calculations; miscanthus pellets are approximately 6 mm in diameter, while wood and sunflower pellets diameter was approximately 8 mm. Miscanthus also had a higher P_{80} value than wood and sunflower pellets, which means the difference between F_{80} and P_{80} is lower for miscanthus than for wood and sunflower pellets.

The results from the BWI tests show a wide spread of BWI values amongst the biomass samples. As expected the wood, miscanthus and sunflower pellets had W_i values an order of magnitude greater than that of the coal, and the olive cake was five times greater than coal. However the eucalyptus, which is an untreated biomass, performed almost as well as the steam exploded pellets. The torrefied pellets had a significantly higher BWI than the others indicating that the torrefaction process used produced pellets which are more grindable in a tube and ball mill compared to the steam exploded process.

3.3. Bond work index mill behaviour

Fig. 2 shows the mass per size fraction and revolution count for each run of each sample. For wood, miscanthus and sunflower pellets the trend is very similar. The mass size fraction below the target size of 1 mm stabilises quickly to a constant mass, especially for the wood pellets. Even though the revolution count increases from 260 to 2104, the mass produced below 1 mm remains around 100 g after the second run. Therefore the increase in revolutions is not producing any more fines, which indicates that the forces within the mill are not sufficient to break down the material. This is indicative of mill choking, which is a known issue with biomass in full scale mills, where increasing the revolutions appears to have no impact on the amount of fines produced. The decrease in the 3.35 mm+ size fraction indicates that the pellets are breaking down into smaller sizes, so the forces are sufficient to break down the pellets, but the increase in the 1–1.7 mm size in particular shows that the mill is struggling to break down the pellets beyond their pre-densified particle size (FPP_{80} is 1446 μm for wood, 1311 μm for miscanthus, and 1757 μm for sunflower pellets), and therefore the breakage mechanisms within a tube and ball mill are not suitable for the comminution of ductile materials. This test highlights that fundamentally mills that use impact, compression and attrition will struggle to breakdown ductile materials such as biomass to sizes required for PF systems.

Eucalyptus shows a different behaviour to the other untreated biomasses. It has a FPP_{80} of 1279 μm, which although smaller than the other samples, is still above the target equilibrium size of 1 mm. The pattern of mass per size fraction and revolution count for eucalyptus indicates that the forces within the mill are sufficient to break down the material beyond its pre-densified particle size, and as the FPP_{80} is close to P_1, less energy is required to comminute compared to sunflower pellets whose FPP_{80} is far from P_1. The percentage of mass produced below 1 mm follows the same pattern as the revolution count, and thus it can be deduced that the revolution count has a direct impact on the amount of fines produced, and that mill choking is not experienced in the same manner as for the other untreated biomasses. Olive cake is made of 3 sections: olive pulp (0–850 μm), olive pips (850–3350 μm) and olive pellets/self-formed lumps (3350 μm+) [38], and 43% of the feed sample fell into the sub 1 mm category. The graph for olive cake in Fig. 2 does not show a linear or smooth trend compared to the other samples due its heterogeneous nature despite splitting the sample to try to reduce this issue. Two distinct patterns emerged; while the revolution count does impact the amount of fines produced, the mass percentage in the 1–1.7 mm size range continually increases as the run count increases. This shows that

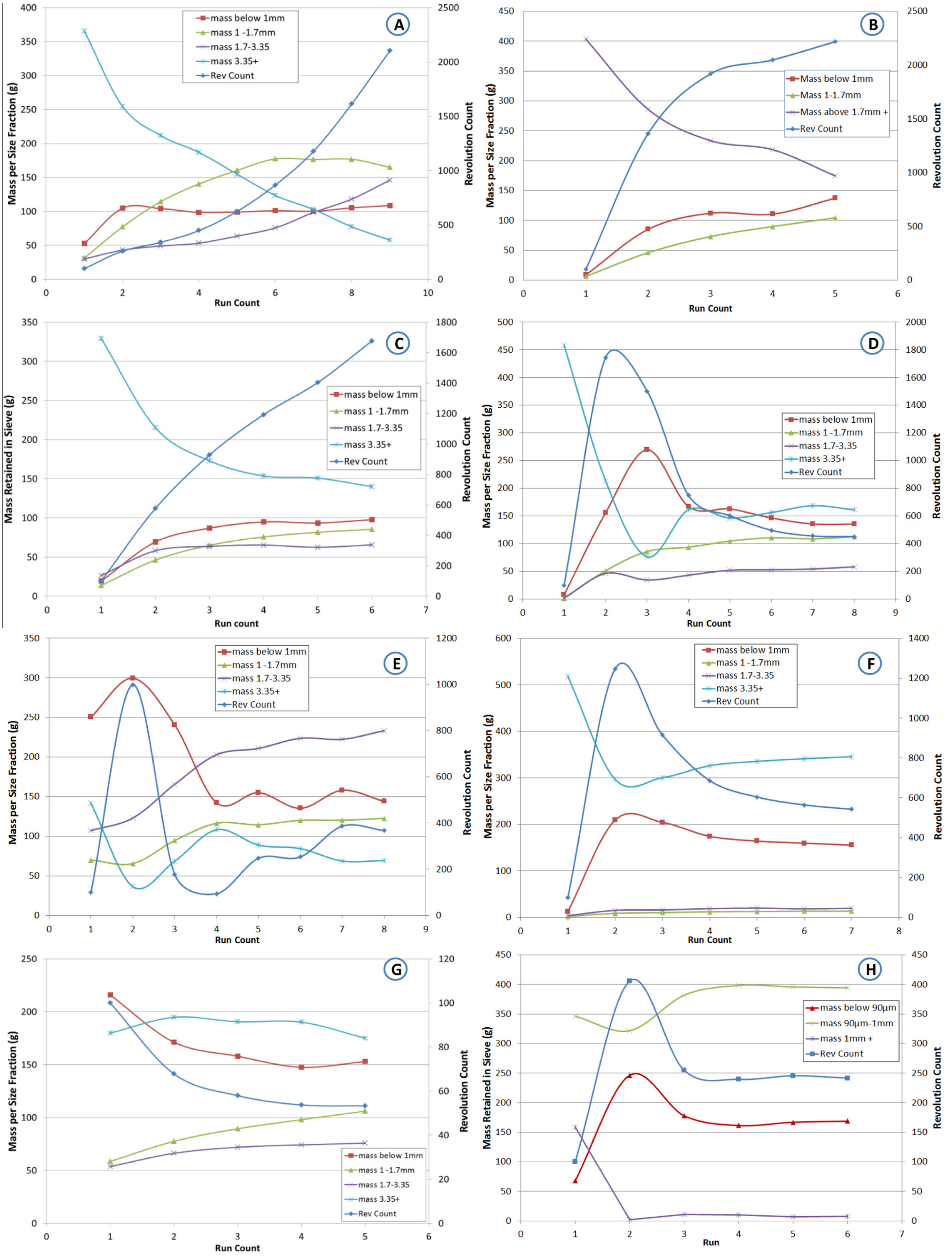

Fig. 2. Mass per size fraction & revolution count against run count for BWI test: (A) wood pellets, (B) miscanthus pellets, (C) sunflower pellets, (D) eucalyptus pellets, (E) olive cake, (F) steam exploded pellets, (G) torrefied pellets, and (H) La Loma coal.

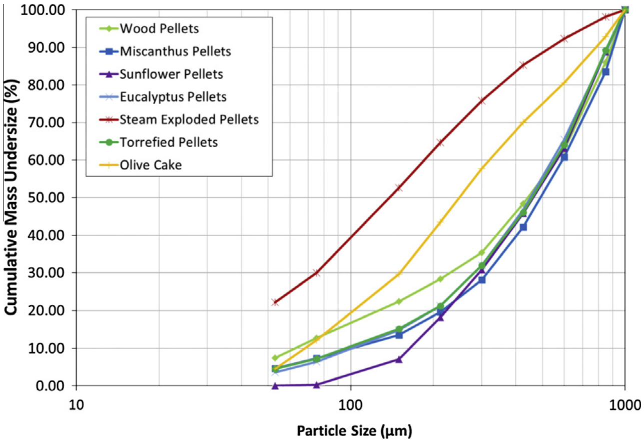

Fig. 3. Cumulative distributions for the final 3 runs for biomass samples.

Table 3
Rosin–Rammler and geometric mean diameter analysis of cumulative distributions of product from final 3 runs; 80% passing product size P_{80}, Rosin–Rammler characteristic particle size d', Rosin–Rammler size distribution parameter n, Rosin–Rammler coefficient of determination R^2, geometric mean diameter d_{gw}, geometric standard deviation S_g.

Sample	P_{80} (μm)	d' (μm)	n	R^2	d_{gw} (μm)	S_g
Wood pellets	786	530	1.28	0.989	412	1.86
Miscanthus pellets	811	582	1.64	0.994	451	1.72
Sunflower pellets	764	557	1.82	0.997	409	1.72
Eucalyptus pellets	757	541	1.62	0.997	410	1.76
Steam exploded pellets	355	210	0.97	0.999	141	2.89
Torrefied pellets	758	544	1.61	0.996	420	1.72
Olive cake	590	360	1.22	0.997	276	2.60
La Loma coal	77	59	2.81	0.983	50	1.62

the forces in the mill are sufficient to break down a portion of the olive cake, but not all of it, which could lead to mill choking in a full scale mill over time.

The La Loma coal showed adequate grindability in the mill for its much finer target size of 90 μm. The target for La Loma coal in a tube and ball mill at EDF Energy plc coal fired power station in Cottam, UK, is 70% passing at 75 μm, and from this study the 70% passing from the 90 μm equilibrium size was 68 μm, showing a close approximation to the full scale targets. Fig. 2 shows that the mill behaviour for La Loma was similar to that of the olive cake, eucalyptus and steam exploded pellets. The two treated biomasses showed very different milling behaviours to the untreated biomasses as well as each other. The steam exploded pellets showed a vast improvement on milling performance compared to the untreated pellets and olive cake, but the results were comparable to the eucalyptus pellets. The steam exploded had one of the lowest FPP_{80} at 1286 μm, but also had the finest P_{80} at 355 μm. As with olive cake, eucalyptus pellets and La Loma, the first 100 revolutions led to a high second run revolution count, which quickly reduced as the runs proceeded and the material started to break down. For the steam exploded pellets there is virtually no sample in the 1–3.35 mm size range, indicating that the pellets either remain intact or break up into fines during the milling process. The torrefied pellets had the highest FPP_{80} of 1537 μm but interestingly a P_{80} of 758 μm, which was comparable to the untreated biomasses. Fig. 3 shows that the forces within the mill are sufficient to easily break down the pellets, but some remain in the 1–3.35 mm range unlike the steam exploded pellets.

3.4. Bond index test particle size distributions

Fig. 3 shows the combined cumulative distributions for the product of last 3 runs of the BWI test for the biomass samples. Apart from olive cake and the steam exploded pellets, the cumulative distributions of the biomass samples were very similar, which is reflected in the P_{80} values for the samples in Tables 2 and 3 of around 750–800 μm. Olive cake had a finer distribution due to the inclusion of 43% of the feed being fines below 1 mm, while the steam exploded produced the finest cumulative distribution of all the biomass samples, which is reflected in its P_{80} value of 355 μm and in Fig. 3 which shows that the pellets break down into fines rather than larger particles. Table 3 shows the Rosin–Rammler data and mean geometric diameter data for the samples. There is a good fit for the samples with the Rosin–Rammler distributions ($R^2 > 0.995$), but quite a spread in the Rosin–Rammler distribution parameter n, varying between 0.97 for the steam exploded pellets up to 1.81 for the sunflower pellets. Lower n represents a wider distribution, and thus a higher diversity of particle sizes. This is also reflected in the higher geometrical standard deviations, S_g, with steam exploded and olive cake having highest values (2.89 and 2.60 respectively). This indicates that the product output is very dependent on material type, but for most untreated biomasses the output will be similar in product size and distribution, regardless of the W_i values obtained. As expected from other biomass milling studies [52,53] and mathematically, the geometric mean diameter from the ball milling is smaller than the Rosin–Rammler size parameter for all samples.

3.5. Impact of pre-densified pellet particle size on bond work index

Table 4 shows the impact of changing the feed size from pellet diameter (F_{80}) to the 80% passing size for the pre-densified pellet particle size (FPP_{80}) on the W_i. By using FPP_{80}, the value of BWI is significantly higher than for the pellet diameter, as the FPP_{80} creates a lower denominator in the BWI Eq. (6). This implies that less energy is required to break the pellets back down to their pre-densified particle size than is involved in breaking the particles into smaller particles. The implication is that for biomass pellets there are two stages of milling occurring. The first is the breaking down of the pellets into smaller parts or back to the pre-densified particle sizes, and the cohesive forces involved in holding together the pellets are weak and easy to overcome in the mills. The second stage of milling is the breaking down of the pre-densified particles into smaller particles. This suggests that to reduce energy consumption and potential for mill choking, the pellets should be formed of particles close to the required target size. This would reduce the milling to solely the pellet comminution phase and minimise mill choking by eliminating the particle comminution stage.

Table 4
Pellet particle size FPP_{80}, and revised bond work index WPP_i, work input WPP for pellet particle size FPP_{80}.

Sample	Wood pellets	Miscanthus pellets	Sunflower pellets	Eucalyptus pellets	Steam exploded pellets	Torrefied pellets	Olive cake	La Loma coal
FPP_{80} (μm)	1446	1311	1757	1279	1286	1537	3712	2709
WPP_i (kW h/t)	1086	1271	756	263	102	38	136	23
WPP (kW h/t)	102	95	93	22	26	4	33	22

Table 5
Thermal composition data for the samples from TGA on wt.% of dry fuel (standard deviation across all runs are shown in brackets).

Sample	Moisture (%)	Volatiles (%)	Fixed carbon (%)	Ash (%)	Peak vol. release temperature (°C)	Peak vol. release rate (%/°C)
Eucalyptus pellets	8.2 (0.1)	85.2 (2.0)	11.6 (1.8)	3.2 (0.4)	338 (0.5)	1.1 (0.03)
La Loma coal	7.1 (1.2)	40.3 (1.1)	53.8 (0.9)	5.9 (1.0)	419 (0.5)	0.3 (0.01)
Miscanthus pellets	7.9 (0.3)	71.6 (1.0)	15.9 (1.3)	12.6 (1.8)	285 (1.0)	0.6 (0.03)
Olive cake	7.5 (1.3)	71.4 (1.7)	18.4 (1.3)	10.3 (0.7)	288 (1.9)	0.5 (0.02)
Sunflower pellets	9.1 (0.2)	78.5 (0.5)	15.7 (0.6)	5.8 (0.9)	310 (0.5)	0.8 (0.04)
Torrefied pellets	6.6 (0.2)	72.4 (1.2)	23.9 (1.3)	3.7 (0.1)	327 (0.2)	1.0 (0.02)
Wood pellets	8.4 (0.3)	82.6 (1.9)	13.3 (1.9)	4.1 (0.4)	337 (0.6)	0.8 (0.02)
Steam exploded pellets	5.7 (0.3)	78.5 (1.1)	17.3 (1.5)	4.3 (0.6)	330 (0.5)	1.0 (0.03)

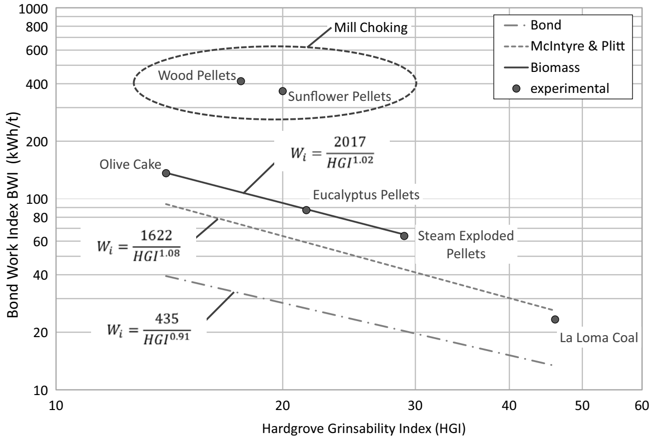

Fig. 4. Bond Work Index (BWI) versus Hardgrove Grindability Index (HGI).

3.6. Thermal composition of the samples

Table 5 shows the thermal characterisation of the samples on a dry basis across all the BWI runs. There is no appreciable difference in the composition of the samples during the test based on the standard deviations shown for each value. The highest fixed carbon for the biomasses was for torrefied pellets at 23.9%, followed by olive cake (18.4%) and the steam exploded pellets at 17.3%. Both treated biomasses had higher fixed carbon than the other untreated woody biomasses. The percentage component values for the samples in this study corresponded to similar samples tested in literature [59]. Eucalyptus, torrefied, wood and steam exploded pellets showed a similar peak volatile release rate (0.8–1.1%/°C) and peak volatile release temperature (327–338 °C). Olive cake and miscanthus pellets showed a much lower peak volatile release rate (0.5 and 0.6%/°C respectively) and peak volatile release temperature (288 and 285 °C respectively), which is an important consideration in coal mills, which can introduce preheat air between 200 and 300 °C. La Loma showed the highest peak volatile release temperature (420 °C), but lowest peak volatile release rate (0.3%/°C).

3.7. HGI & BWI correlations for biomass

Fig. 4 shows BWI plotted against HGI for the biomass and coal samples. In addition to the experimental data, the Bond (1) and McIntyre and Plitt (2) correlations are plotted for the sample HGI data. The wood and sunflower pellets show no relation to the other points due to the mill choking experienced during the BWI test. While none of the experimental results are close to the Bond correlation, the La Loma coal does lie near the McIntyre and Plitt correlation. This is to be expected as this correlation was based on similar materials with a W_i above 8.5 kW h/ton [34]. While the olive cake, eucalyptus and steam exploded pellets do not sit close to the Bond or McIntyre and Plitt correlations, they do show a similar trend of decreasing BWI with increasing HGI. Using non-linear regression analysis, the biomass best fit line was determined by Gauss–Newton method is defined as:

$$W_i = 2017/HGI^{\wedge}1.02 \tag{8}$$

However it should be noted that this correlation is based on a very limited number of samples and is only applicable for the test equipment and experimental conditions used to obtain the W_i and *HGI* values.

4. Conclusions

The applicability of two standard grindability methods for coal; Hardgrove Grindability Index and Bond Index test, have been tested on several biomasses and one coal commonly used in the power sector. For the BWI test, particle size characterisation, thermal composition and analysis of mill behaviour were used to analyse mill phenomena such as mill choking.

HGI is a poor indicator of the grindability of biomass in a vertical spindle mill, and can give misleading results when analysed alone. Grindability tests which aim to analyse the grindability of biomass to 75 μm are flawed, as the target size for optimal combustion of biomass and the setting for the classifier output from full scale mills is an order of magnitude of higher than this. The BWI test can be used to analyse the mill behaviour of biomass in a tube and ball mill. Wood, miscanthus and sunflower pellets exhibited mill choking during the BWI test, as the amount of fines produced did not increase with an increasing revolution count. Thus the BWI can be used to see if biomass samples are likely to encounter mill choking prior to full scale mill trials.

The BWI results show that there are two stages of milling occurring in biomass pellets. The first is the breaking down of the pellets into smaller parts or back to the pre-densified particle sizes, where the cohesive forces involved in holding together the pellets are weak and easy to overcome in the mills. The second stage of milling is the breaking down of the pre-densified particles into smaller particles. However, the forces involved in this second stage are much greater than the initial pellet breakage stage. Therefore, to optimise milling in a coal mills, biomass pellets should be composed of particles close to the required size so that only the pellet comminution stage occurs.

Whilst it has been shown that the BWI test is a useful test for analysing and predicting the mill behaviour of biomass in a tube and ball mill, the HGI test is not suitable for predicting the grindability of biomass in vertical spindle mills. A new standardised grindability test is therefore required to test the grindability of biomasses in these types of mills.

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