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INVESTIGATION INTO THE RELATIONSHIP BETWEEN COMPACTION EFFICIENCY AND SUPPORTING LOGISTICS NETWORKS FOR LIGNOCELLULOSIC BIOMASS

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Abstract

This paper presents an investigation into the compaction efficiency and dilation response of lignocellulosic biomass feedstocks. Three common Australian feedstocks; wheat straw, sugarcane bagasse and wattle, and two from the South Pacific; dried coconut shell and the invasive tree species Chinese Albizia were tested. The experiments at variable moisture content and particle cut-size provided evidence to specify favourable conditions for size reduction. The objective of the research is to add to the body of knowledge that informs sustainability benchmarks and alleviates detrimental environmental and societal impacts through consequences associated with meeting global energy and fuel demands. It is part of an evaluation of energy potential of biomass feedstocks and the influence of physical properties on the supporting logistics networks and associated processes. One important goal is to develop the ability to relate physical handling properties to the energy, fuel and chemical yield of the feedstock.

1. INTRODUCTION

Biomass feedstock production and logistics contribute in excess of 35% of the total cost to produce cellulosic ethanol (Hess et al [1]) with 50-75% of those costs attributed to logistics. If chemical or physical pre-processing is included (Miao et al [2]) the percentage of the total costs of producing bioenergy could be as high as 40-60%. Post-harvest, the supply chain and logistics comprises of a number of stages including collection, storage, pre-processing and/or densification, transportation, handling, post-processing (i.e. at the biorefinery or the energy conversion facility), Hess et al [1], Balan [3] and Lamers et al [4].

In the US, an estimated 1 billion tonnes of biomass is required annually to displace 30% of the current petroleum consumption, with the actual cost of biomass comprising approximately one third of the total cost to produce biofuel, Balan [3]. The cost of biomass is directly proportional to yield, while the cost of delivering the biomass to the refinery or conversion facility is dependent on the efficiency of the supporting logistics network. Importantly, the long-term economic viability of a biorefinery is reliant on the magnitude of the logistics network including capital and operational costs, Wang et al [5].

A number of highly variable physical and chemical feedstock characteristics present challenges in the optimisation of these supply logistics networks. These characteristics include moisture content and hygroscopicity (sorption), carbohydrate and ash composition, solid and bulk density, particle size and shape (morphology), compressibility/elasticity, deconstructability (grindability), flowability and the structure at the micro and/or nano scale, Williams et al [6], Cai et al [7]. These factors define economic transport volumes, the viability of conversion processes, guide equipment selection and influence the long-term viability of the biorefinery/energy conversion facility.

Two significant challenges for increasing the efficiency of supplying feedstocks to the refinery (or to the facility converting feedstocks to energy) is to increase the density and to define the optimum particle cut-size (format). Biomass feedstock density depends on the cut-size and individual particle properties such as porosity, elasticity, and shape, moisture content and surface characteristics. The cut-size and distribution for handling is very much dependent on the properties of the as harvested feedstock including the comminution energy required to deconstruct or reduce it. Feedstock size also impacts the economics of the biofuel commercialisation through affecting the conversion yield, Vidal Jr et al [8].

Generally, feedstocks in pellet, briquette or bale form are used in co-firing or combustion processes. To minimise the elasticity/springback and to ensure quality, densification is necessary, in turn also requiring grinding prior to compaction. Springback, related to the particle and bulk elasticity, may be defined as the ability of a bulk material's voids to recover or rebound after the applied pressure has been released, Karamchandani et al [9]. Through densification, an increase in density of 30 times has been reported for products such as wheat straw and grasses, Sokhansanj et al [10]. Due to such high compression, existing densification technology requires significant energy and operating costs. Densification has also been shown to greatly improve transportation efficiency especially if existing storage, handling and transportation infrastructure such as that of coal or grains could be utilised.

In contrast to feedstocks for biomass combustion processes, liquid fuel biorefineries such as lignocellulosic ethanol may require feedstock in uncompressed and loose particulate forms. Compared to bales and densified products, in such applications, feedstocks deconstructed by comminution offer higher digestibility and efficiency in the refining processes such as hydrolysis, fermentation, gasification, pyrolysis and chemical synthesis, Sokhansanj et al [10]. Energy requirement for comminution and optimum particle size also influence logistics design, equipment selection and assessment of overall efficiencies of supplying feedstocks from the farm to the refinery or conversion facility (Miao et al [11]).

To design efficient and durable storage, handling and transportation equipment, biomass compressive/relaxation properties need to be understood. This requires interrogation of existing theoretical descriptions of elasticity, plasticity, and viscoelastic behaviour, isotropic/anisotropic materials assessment spanning the fields of soil mechanics, powder technology and models of granular behaviour. Little research has been conducted in optimising pre-treatment/pre-processing of biomass to improve storage, handling and transportation prior to or in lieu of densification. This paper explores the compaction and dilation behaviour of springy biomass materials as an example of providing the evidence to make an informed decision to influence logistics supply networks and conversion processes through defining criteria for optimum particle size and moisture content.

2. METHODOLOGY

A preliminary testing investigation was undertaken on three biomass feedstocks, sugar cane bagasse, wattle and wheat straw, sourced from a pilot-scale ethanol facility in NSW, Australia. All three materials were tested in the ‘as supplied’ (A/S) state, however, the wheat straw was manually cut to either 5mm pieces or 50mm pieces. The wattle had previously been granulated to a particle size not exceeding 10mm. The same test work, formed part of a different project to evaluate the green waste utilisation for energy potential characteristics of dry coconut waste and an invasive tree Chinese Albizia with an intergovernmental agency in the South Pacific. To enable testing, these samples required size reduction which was undertaken using a conventional shredder (Ryobi Model – RSH2445T). A ‘coarse shred’ (C/S) sample was obtained by passing the ‘as supplied’ (A/S) products twice through the shredder. The size of each of these samples was further reduced by passing each sample through the shredder 10 times. This corresponds to the ‘finely shredded’ (F/S) sample. For a number of tests, each of these materials was also ground to below 0.5mm in a hammer mill.

Experimental testing on all samples was performed at the Centre for Bulk Solids and Particulate Technologies (CBSPT) laboratory, located at the Newcastle Institute for Energy and Resources (NIER) at the University of Newcastle in NSW, Australia. The range of tests included measuring particle density and compressibility in a small-scale tester and a larger cylinder. Particle density was measured using a nitrogen displacement pycnometer. In this test, the relative density of the solid particles within a small volume is measured in a stream of nitrogen. Small cell compressibility tests were performed in a 63.5mm diameter, 19mm deep apparatus, updated from that described in Arnold et al [12] to include a linear variable displacement transducer (LVDT). After filling the cell, an incrementally increasing normal consolidation pressure (up to 51.6kPa) was applied to the bulk sample. Knowing the sample volume, mass and applied load allowed the relationship between bulk density and consolidation pressure to be determined. Compressibility was measured during incremental loading and unloading thereby allowing for the determination of the spring back/relaxation (hysteresis relationship). Finally, loading/unloading tests were also conducted in a 150mm diameter, by 180mm high cylinder. The procedure involved loose filling the cylinder with each biomass sample. Similar to the small cell tests, continuous loading/unloading behaviour was evaluated up to a maximum pressure of 17.6kPa. This allowed for assessment of an increased size of the sample compared to the small cell tests, however, the test was limited to the lower maximum pressure.

3. RESULTS AND DISCUSSION

Particle density for bagasse, wheat straw and wattle were tested in the ‘as supplied’ (A/S) state (moisture content was not measured), however, wheat straw was manually cut to 5mm particle size. The dried coconut shell and Chinese Albizia samples were tested in the ‘finely shredded’ (F/S) cut size at the ‘as supplied’ A/S moisture content. Additionally, particle density was also measured after milling the samples to a size below 0.5mm. The measured particle density of the samples tested is summarised in *Table 1* below. A moisture content of zero corresponds to a totally dried (T/D) sample. Results show that the particle density is very much dependent on the particle size and moisture content. The observed variation is much lower for dried coconut shell compared to Chinese Albizia.

Table 1. Measured Particle or Solids Density

Sample	**Moisture Content (%)**	**Particle Density (kg/m^3)**
Bagasse	A/S	1596
Wheat Straw	A/S	1175
Wattle	A/S	1396
Chinese Albizia	35.7 (A/S)	600
	0 (T/D)	1053
	0 (T/D)*	1383
Dried Coconut Shell	10.2 (A/S)	1374
	0 (T/D)	1321
	0 (T/D)*	1406

**Sample milled to size below 0.5mm*

An example of the relationship obtained during the loading/unloading tests is shown in the left graph in Fig 1, below. A comparison between the results of the small cell and the large cylinder are summarised in the right graph in Fig 1. Compaction is measured as the percentage increase in bulk density with increasing consolidation stress. Springback is calculated as the percentage increase of the sample volume at maximum compaction following full relaxation of the compressive load (i.e. at maximum effective compaction). Compaction efficiency is calculated as the ratio of maximum effective bulk density to the particle density and the void ratio is defined as the free space remaining within the bulk sample at maximum effective compaction.

Results show the ‘as supplied’ wheat straw and bagasse having highest and wattle lowest maximum compaction. During unloading, all samples reduced in compactness, with the (A/S) wheat straw relaxed (dilated) the most. By manually reducing the size of the (A/S) wheat straw to 5mm, maximum compaction reduced, and following unloading, this reduction was not as severe compared to the (A/S) format (or size). Bagasse showed highest maximum effective compaction and (A/S) wheat straw the highest springback. Wattle showed highest compaction efficiency and the lowest voidage, while (A/S) wheat straw showed lowest compaction efficiency and highest voidage. The effective void ratio is very high for all samples tested indicating high porosity (compared to traditional resources such as coal and iron ore). Reducing the size of the wheat straw resulted in reduced springback, increased compaction efficiency and reduced void ratio. Results also show wheat straw has the highest springback and void ratio, along with the lowest compaction efficiency. Wattle showed lowest compaction, springback and void ratio, along with the highest compaction efficiency.

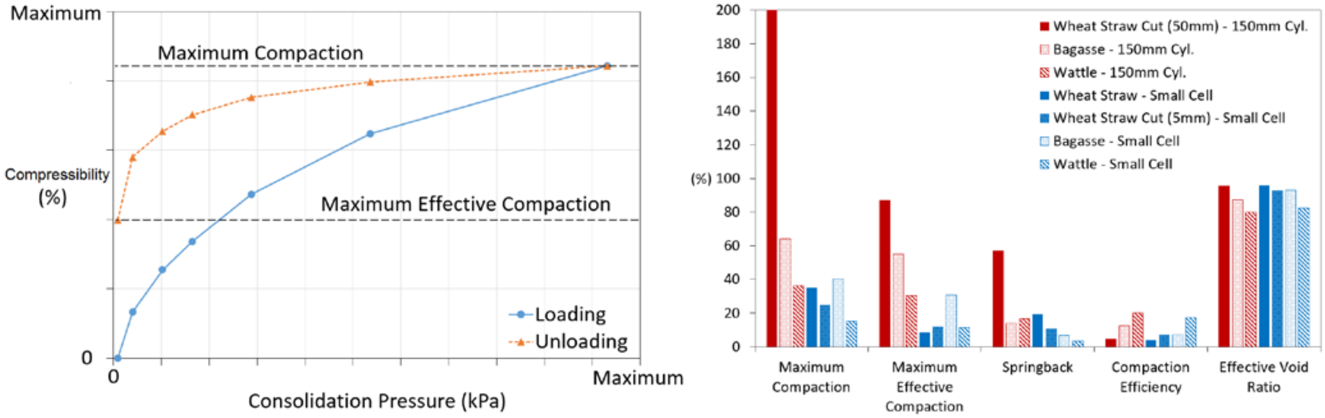

Fig 1 Example of loading/unloading (left) and results comparison (right) for the Australian samples

Results indicated the compressibility of the dried coconut shell increases with a decrease in the cut-size, with moisture content not being of a significant influence. Fig 2 shows dried coconut shell exhibiting steady effective compaction, an increase in compaction efficiency and a decrease in the void ratio with a decrease in cut-size and moisture content investigated. Springback decreased with cut-size, but increased with a reduction in moisture. For the Chinese Albizia, results show opposite behaviour, namely a decrease in compressibility with a decrease in cut-size. Moisture also had an increased influence, and compressibility significantly reduced with a reduction in moisture. The Chinese Albizia increased in maximum effective compaction, springback and void ratio but decreased in compaction efficiency with a decrease in the cut-size. For a constant cut-size, a reduction in moisture was found to result in a lower maximum effective compaction and efficiency as well as an increase in the void ratio. The results indicate that the Chinese Albizia is a highly fibrous and porous material. With respect to selection of particle size for optimising storage, handling and conveying facilities, milling would be more beneficial for this product compared to dried coconut shell, as lower energy would be required.

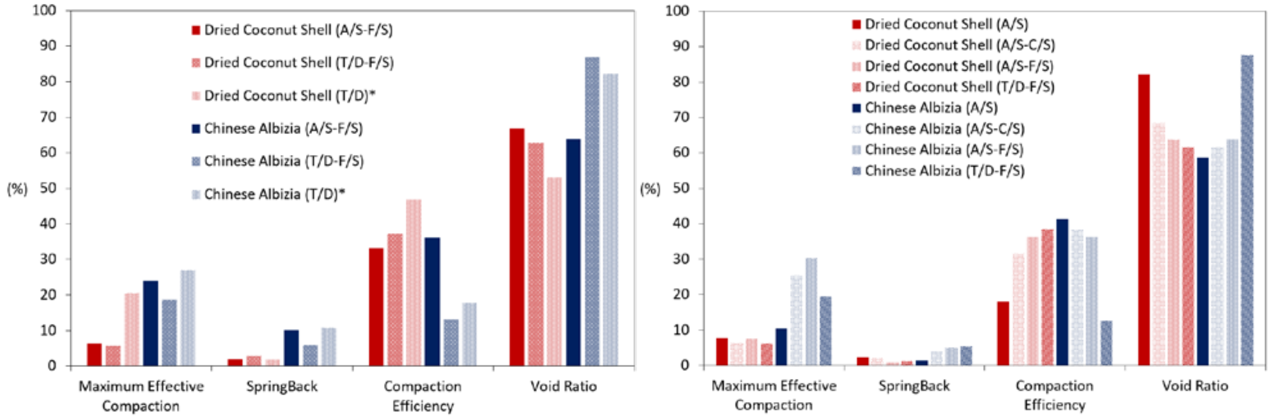

Fig 2 Small cell (left) and large cylinder test results (right) for the South Pacific samples

4. CONCLUSIONS

Experimental work was undertaken which investigated the particle density and compaction/dilation (springback) characteristics of a number of biomass feedstocks during loading and unloading in a small cell and 150mm cylinder apparatus. Results showed the size reduction and moisture characteristics are of significant influence on particle density, compaction and relaxation behaviour, springback and void ratio. Different feedstocks exhibited vastly different behaviour and as such will require different equipment, process flow specification, technique of transportation and feed presentation to a biomass utilisation facility.

This study demonstrates how characterisation tests such as particle density and compaction/dilation may be used to specify criteria for optimum particle size and moisture content for different biomass feedstocks. With additional investigation, such information may be used to better inform the design of logistics supply networks and conversion processes.

5. REFERENCES

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