



Research article

Mechanical degradation of biomass wood pellets during long term stockpile storage



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ABSTRACT

This paper quantifies and assesses the mechanical degradation of white wood and steam exploded wood pellets in indoor and outdoor stockpile storage over a twenty-one month period in the UK. The indoor stored steam exploded wood pellets on the surface of the pile only exhibited a 3% decrease in durability after twenty months in storage. The outdoor stored pellets demonstrated much higher levels of mechanical degradation. In the summer period with high relative humidity and temperature, the durability of pellets sampled from the surface of the pile dropped from 92 to 22% after three months in storage with a durability of 10% measured after nine months in storage. The degradation of the pellets from the middle of the pile was more gradual and less severe with a maximum durability drop of 34%. The impact on mechanical properties was significant for the indoor stored white wood pellets with pellets quickly degrading to dust. This study shows that while steam exploded pellets could be stored in covered storage, white wood pellets require a fully enclosed storage environment. Short term outdoor storage of steam exploded pellets could be considered if extended periods of low rainfall and relative humidity can be reliably predicted.

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1. Introduction

The large scale use of biomass worldwide in decarbonising power generation is predicted to grow in order to meet the EU 2030 emissions targets of 40% below 1990 levels and renewables target of providing at least 27% of EU's energy requirements [1]. Densified pelletized forms of biomass fuel are preferred as they have higher energy density and hence provide an economic advantage in the areas of transport, storage and handling. However, compared to coal, wood pellets bring a number of challenges in areas of supply [2], storage and transport [3–6], conveying and milling [7] and combustion [8]. Burning wood pellets can also result in changes in the ash and emissions composition which will have to be considered in treatment processes downstream of the burner [9,10]. Occupational health and environmental considerations are also important [11].

One of the challenges in storage and transport is the loss of pellet mechanical integrity. A significant loss of mechanical strength can lead to high levels of dust, which increases the risks of fires and explosions [12,13], as well as posing a health hazard to workers [14]. Higher dust levels also potentially cause heat generation in stockpiles by microbial attack as explained by Lehtikangas in [15].

There are studies reported investigating the changes in the pellet mechanical properties as a result of storage [15–17], however these are at much smaller scale than typical utility industry fuel stores. Lehtikangas [15] investigated the small scale storage of nine different types of pellets made from fresh and stored sawdust, bark and logging residues. Storage took place in large plastic bags in an unheated barn for 5 months from December to May in Sweden. The range of tests carried out included moisture and ash content, heating value, pellet length, bulk density, durability, water absorption resistance and particle size distribution. The changes in the chemical properties of the pellets were not significant but storage resulted in break-up of the pellets, as reflected in the reduced pellet length and pellet durability. Chico-Santamarta et al. [16] also reported on pellet length reduction when storing canola straw pellets in airtight bags in a storage shed at Harper Adams University College, UK for 48 weeks while Kymalainen et al. [17] observed a decrease in the pellet durability of untreated wood pellets, torrefied pellets and steam exploded pellets stored over a period of five months in 0.5–1 l mesh bags in both outdoor uncovered and covered storage in Finland.

The work reported here differs from these previous works in that the storage was at a significant scale (~6 tonnes/metric tons) and in stockpiles and replicated the potential storage scenarios being considered by power generators within the UK – i.e. outdoors and in covered facilities. This comprehensive study investigated the impacts of relative humidity, ambient temperature and rainfall separately and collectively on the

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moisture uptake and mechanical degradation of white wood and steam exploded wood pellets in stockpile storage. Pellets from both the surface and middle of the different piles were sampled at regular intervals with photographs and SEM images of the degraded pellets generated and presented within this paper. Mechanical tests performed on the samples enabled axial and diametrical compression strengths and the inter-laminar shear modulus to be determined as well as durability. The range of laboratory tests undertaken also included the determination of the pellets' volatile and ash content and net calorific value as well as the fungal count and identification on fresh and degraded samples. However, the analysis and results for these aspects are not included here, more information can be found in Graham [18]. As part of this long term study, a short term project was carried out in the laboratory to investigate the effects of relative humidity and temperature on wood pellet degradation as reported by the same authors in [19].

2. Material and methods

Two different pellet types and two different storage scenarios were studied over different periods as listed below:

- Steam exploded wood pellets (20 months, spring to the following winter) indoor (covered roof) and outdoor storage
- Steam exploded wood pellets (12 months, winter to winter.) outdoor storage – this was a different batch of pellets to the one above
- White wood pellets (10 months, autumn to autumn) indoor (covered roof) storage.

The steam exploded wood pellets (made from a mixture of softwood and hardwood chips) were sourced by E.ON from an American supplier. Storage trials were carried out promptly upon delivery of the pellets to the UK. The white wood pellets were manufactured from softwood material (again originally supplied from North America) and sourced by E.ON from Ironbridge power station, it should be noted that they had previously been stored at Ironbridge for a few months in a fully enclosed warehouse. The properties of the fresh steam exploded pellets as received in the first and second batches for storage in the spring and winter respectively and the fresh white wood pellets for autumn storage are listed in Table 1.

The pellet stockpiles were constructed at Leyfields farm in Retford, UK, owned by Coppice Resources Ltd. [20]. All of the stockpiles had the same size 2.4 × 2.4 m base by 1.5 m high, corresponding to approximately 6 t (metric tons) with the perimeter being established by a permeable porous membrane enclosure. The pile height was restricted by the angle of repose of the pellets, which was <45°. In the first spring, two steam exploded wood pellet piles were constructed, one indoor (Fig. 1a), and one outdoor (Fig. 1b), both on concrete bases; these were monitored over twenty months in storage. The indoor pile was constructed in an open barn which had a roof and two walls, being open on the remaining two sides. This constituted Phase 1 of the project. In the autumn, a white wood pellet pile was set up for indoor storage in the open barn and studied for 10 months. In the winter, a new outdoor steam exploded wood pellet pile was also built and studied for 12 months. This constituted Phase 2 of the project.

The temperatures within the stockpiles were continually monitored and logged as were the ambient temperature, rainfall and relative

humidity using a weather station at the site [18]. The total rainfall was measured as height in mm per unit area captured at the storage site. A tipping bucket rain gauge was used which registered a pulse of 0.13 mV for every 3 cm³ of water collected in the bucket, which corresponded to 0.091 mm depth of water per unit area. The rainfall in mm per unit area could therefore be calculated from the voltage recorded.

Fuel samples (approximate sample size of 500–600 g) were extracted from the surface and middle of each storage pile on a monthly basis for the first six months and then less frequently thereafter using a graded sampling probe (Fig. 2) which was specially designed for this task [18].

The probe was made of a polycarbonate material and 2 m in length with internal and external diameters of 9.4 cm and 10 cm respectively. As shown in Fig. 2, the sampling section only constituted a small part of the probe and was designed as a fully enclosed section with a trap door. It had an aperture of 6 cm wide and 14 cm long. A stainless steel rod and handle were connected to the sampling section. After the probe had been inserted to the right location inside the pile where sampling could take place, the handle was turned to open the trap door and allow sample to fall into the sampling section. The trap door was then closed again prior to the sampling probe being extracted out of the pile. The probe was also graded so that the depth reached within the pile could be monitored. The surface sample was taken on the surface of each pile and 75 cm from the ground (halfway up pile) and the middle sample was taken 75 cm from the ground and approximately 1.2 m (halfway) into the pile horizontally. The collected samples were not pre-treated prior to the analysis and testing mentioned in this article.

The pellet % moisture content was determined using the oven drying method using British Standard DD CEN/TS 15414-2:2010 [21]. The moisture content reported in this paper is on a wet basis. Drying at 105 °C [21] was only carried out on 300 g of each monthly sample once. The weight of each sample taken from the piles monthly was kept at around 500–600 g to try and avoid too much material being removed from the piles, potentially causing movement of material within the piles. However sample variation for the moisture test was determined at the start and end of the storage period and the maximum sample variation range was 1%.

2.1. Pellet images

Photographs of the pellets from both the surface and middle of each pile were taken at regular intervals. Scanning electron microscopy (SEM) was carried out on the cross section of the pellets to better understand crack formation and propagation within. SEM images were acquired at the point of receipt of pellets (denoted as 'fresh' throughout) and after 3 and 6 months in storage. The microscope used was a Quanta 600 by FEI [22]. Before SEM analysis, samples were set in epoxy resin and polished [18].

2.2. Measurement of mechanical properties

2.2.1. Pellet durability

The pellet durability of fresh and stored samples was measured using a Dural (II) tester [23]. A 100 g sample of pellets was tumbled at 1600 rpm for 30 s and then sieved through a 4.75 mm sieve. Typically

Table 1
Properties of fresh pellets at the start of storage.

Pellet	Bulk density kgm ⁻³	Average diameter mm	Average length mm	Net calorific value kJ/kg	Moisture content %	Volatile content %	Ash content %
Steam exploded batch 1 Phase 1	780	5.8	17.1	18,710	2.7	72.6	2.9
Steam exploded batch 2 Phase 2	750	6.2	21.1	19,247	3.2	73.5	1.1
White wood pellets Phase 2	615	8.2	16.3	17,375	9.2	72.0	1.6

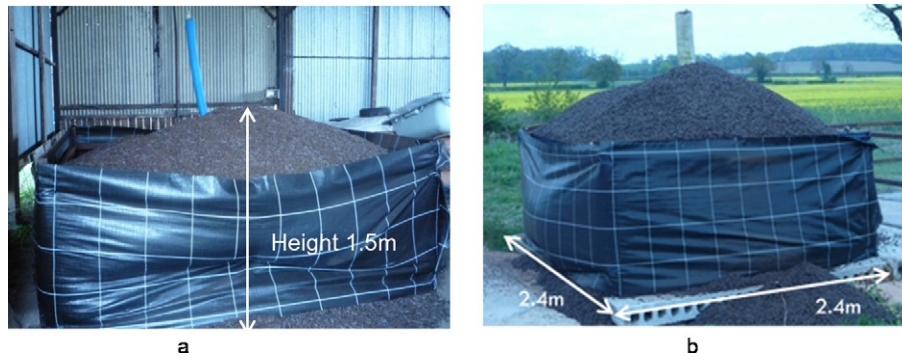


Fig. 1. Phase 1 steam exploded wood pellet indoor (a) and outdoor (b) pile 2.4 m × 2.4 m base by 1.5 m height.

a single durability test was performed on the monthly samples to avoid having to extract too much material from the stockpiles on each sampling visit. However, triplicates carried out on fresh and stored samples yielded a variation in sample durability result values of 1–4%.

The durability is calculated as the weight percentage in the oversize fraction >4.75 mm.

$$\text{Durability (\%)} = 100 \times \frac{\text{oversize mass after test g}}{\text{original mass g}} \quad (1)$$

The standard test for durability, standard BS EN-15210 (superseded by [24]), is different to the Dural (II) tester employed here. However, the Dural (II) tester has been shown to better differentiate the impact of degradation on durability [18] due to its more vigorous tumbling action returning a wider spread of numeric values, allowing a better differentiation of results.

2.2.2. Shear and compression tests

Shear and compression tests of pellets were introduced in the ninth month of Phase 1 (where it was noticed that changes in pellet durability were starting to be significant) in order to provide more detailed information of the impact of pellet degradation mechanisms on mechanical properties. An INSTRON dual column table top universal testing system (model 5969) [25] was used to carry out three point flexure (shear), axial compression and diametrical compression tests; using a setup similar to ASTM D143 14 [26]. The INSTRON mechanical tester was operated at a load cell capacity of 5 kN at a ramp rate of 1 mm per minute. The material used in the standard [26] is raw wood of dimensions 50 × 50 mm where for this work a pellet is utilised. However as the focus of this study is to understand the impact of degradation on mechanical properties over time, rather than a direct comparison to a

standard value, this approach is deemed appropriate and returns observable differences in compression strengths and shear moduli for fresh and stored pellets.

The axial and diametrical compression strengths were determined as the minimum force at which the pellet cracks, similar to the method used in [18] and showed the resistance of the pellets to deformation and breakage when compressed vertically and horizontally, which are likely scenarios in storage. The flexure test yielded the Young's modulus (E) of the pellet, which is a measure of the pellet stiffness or resistance to elastic deformation; and it was performed based on a 3-point flexural test setup similar to [18].

The axial and diametrical compression tests were carried out in five replicates and the flexure test in ten replicates, to provide a variability analysis. In Section 3 of this paper, the average of each of the mechanical properties is presented in Table 3 for fresh pellets and Table 4 for stored pellets (after nine months in storage), with the range included to show the minimum and maximum values.

3. Results and discussion

3.1. Physical appearance of pellets

The steam exploded wood pellets stored indoors (Phase 1) did not exhibit a significant change in appearance throughout their storage period, although there was evidence of small cracks developing on the surface which did not penetrate into the structure of the pellet. However the outdoor pellets showed visible signs of degradation as illustrated in Fig. 3 below.

A significant change in appearance was noticed in the pellets from the surface of the Phase 1 outdoor pile after three months. The fresh pellets (Fig. 3a) had a smooth and shiny/glassy outer surface which was dark coloured in nature. Fig. 3c shows the outdoor stored pellets (surface sample) after three months in storage where major cracks are evident that appear to propagate through the pellet structure, leading to a rough and fractured surface appearance. The pellet degradation was caused by continuous exposure of the pellets to weather conditions as explained in Section 3.3. The pellets sampled from the middle of the outdoor pile appeared less degraded and this is also discussed in Section 3.3.

The fresh Phase 2 pellets (Fig. 3b) also had a smooth texture and shiny appearance, albeit less 'glassy' and lighter in colour than the Phase 1 pellet (Fig. 3a). The pellets were from two different batches received eight months apart from the supplier and the differences in appearance could be attributed to changes in raw materials and process conditions used in the steam explosion. Lam et al. 2011 [27] in their work on the effects of steam explosion on the properties of ground softwood Douglas Fir reported that the pellets became darker in colour as the severity (residence time and temperature) of the steam explosion increased.



Fig. 2. Sampling probe.



Fig. 3. Fresh and stored pellets after 3 months in storage from Phase 1 (a + c) and Phase 2 (b + d) outdoor steam exploded pellet piles, where fresh is used to denote pellets at the start of the storage period.

The Phase 2 pellets from the surface of the outdoor pile at 3 months storage (Fig. 3d) also had started to develop cracks and a rougher texture, but appeared less degraded compared to Phase 1 for the same length in storage. It was speculated this could be because the two batches of pellets were made from different raw materials or the thermal treatment processing technique had been altered between the two pellet batch production dates. As noted above, the physical appearance and colour of the two batches of steam exploded pellets was quite different, so a different behaviour on storage might be expected. Despite requests, no further information on what had caused the batches to be different was obtained from the supplier.

The Phase 2 white wood pellets, stored indoors, showed signs of severe and rapid mechanical degradation (see Fig. 4).

After one month in storage, swelling and disintegration of the white wood pellets could be observed. Very few pellets had retained their original shape and many pellets had significant cracks developing. After four and six months in storage (Fig. 4b), pellet degradation was even worse, with most pellets having disintegrated to what appears to be the original particle size prior to pelletisation. This very high level of pellet degradation in an open barn environment illustrates that

white wood pellet is very susceptible to degradation, even in a covered environment. The fact that the pellets used for these tests had already been subjected to a period of storage at Ironbridge power station probably exacerbated their deterioration during these tests. White wood pellets are best stored in a fully enclosed environment and whenever possible storage time should be minimised with a first-in, first-out usage policy.

3.2. Scanning electron microscopy (SEM) images of pellets

Fig. 5a shows the SEM image of the circular cross section of a fresh Phase 1 steam exploded pellet at the start of storage and Fig. 5b that of an equivalent pellet from the surface of the outdoor pile after six months in storage.

While the SEM image of the fresh pellet (Fig. 5a) shows a few small cracks highlighted by the white circles mostly towards the edge of the pellet, the image of the stored pellet from the surface of the outdoor pile (Fig. 5b) shows a large extent of crack formation and propagation. There were multiple large cracks right across the pellet diameter and the pellet showed signs of its edge becoming uneven. The SEM images

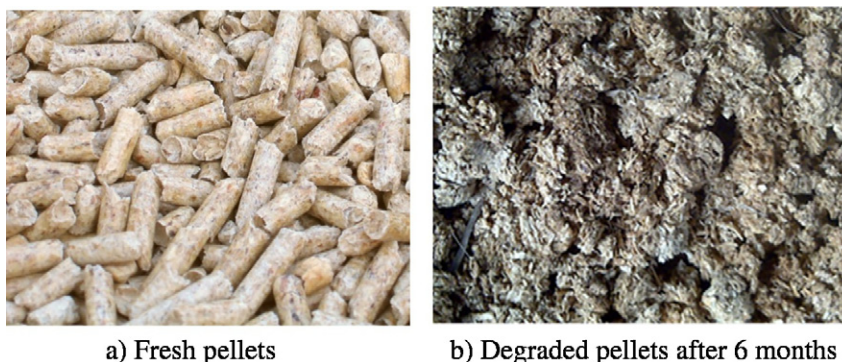


Fig. 4. Fresh (a) and degraded pellets after 6 months in storage (b) from Phase 2 indoor white wood pellet pile.

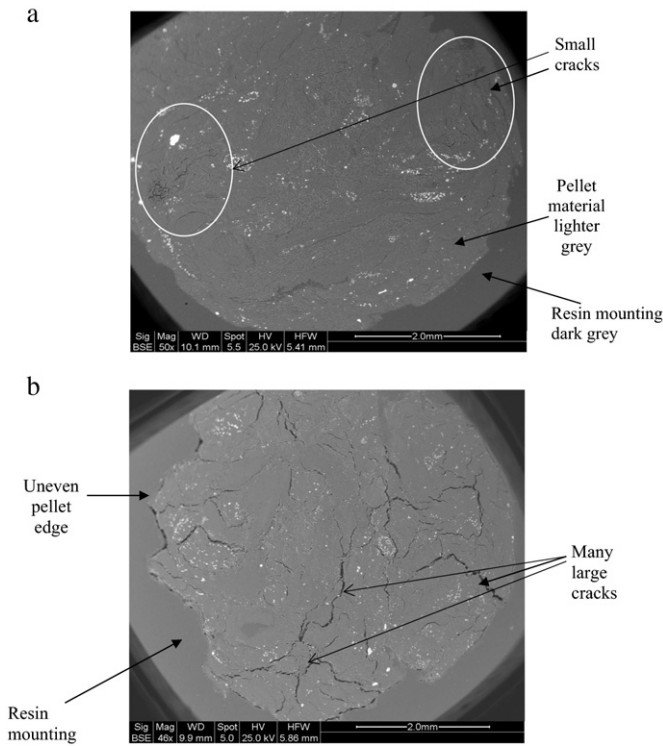


Fig. 5. a. Circular cross section of fresh Phase 1 steam exploded pellet, where the full pellet is shown in Fig. 3a. b. Circular cross section of stored Phase 1 steam exploded pellet from surface of outdoor pile after 6 months.

of the fresh and stored Phase 2 steam exploded outdoor surface pellets show similar degradation behaviours. For the pellets taken from the middle of the outdoor storage pile and samples taken from the indoor pile, the extent of degradation and crack propagation were less evident from SEM images.

The SEM image of a fresh white wood pellet showed that cracks were present throughout the pellet at the start of storage, unlike the fresh steam exploded pellets [18]. After six months in storage, very few whole pellets could be identified from the white wood pellet pile.

3.3. Durability

The durability of the pellets is defined in Eq. (1) (see above). Durability of samples taken from the surface and middle of the Phase 1 indoor steam exploded pellet pile did not change significantly (up to 3% change) throughout the storage period (Fig. 6a). The fresh Phase 1 steam exploded pellets had a moisture content of 2.7% (wet basis) and after twenty months in storage, the pellets on the surface of the indoor pile had a moisture content of 9.6% while pellets taken from the middle of the pile were at a moisture content of 6.2%. The increase in moisture content can be attributed to continuous exposure to a high relative humidity ranging between 70 and 90%.

For the pellets stored outdoors the changes in durability were significantly larger (Fig. 6a, b), following the large increases in moisture content caused by exposure to high relative humidity and rainfall [18]. Fig. 6a shows the durability of the pellets from both the Phase 1 indoor and outdoor steam exploded wood pellet piles plotted against pellet moisture content while Fig. 6b shows the durability of the Phase 1 steam exploded wood pellets from the surface and middle of the outdoor pile plotted against time in storage alongside the monthly total rainfall.

The exposure of the pellets on the surface of the outdoor pile to high relative humidity and rainfall in the first three months of storage resulted in a 20% increase in the moisture content of the pellets and a 70% reduction in pellet durability (data point A on Fig. 6a). The observed

changes in structure and cracks described in Sections 3.1 and 3.2 obviously made the pellet more susceptible to breakage during the durability test and also during handling and conveying. From the third month until the end of testing, the step changes in moisture content were not as large as the one seen during the first three months of storage and no further large step decreases in durability were observed, instead a gradual drop was seen (Fig. 6b). In contrast, the pellets in the middle of the outdoor pile exhibited a different behaviour to the pellets on the surface. The first nine months of storage saw a decrease in pellet durability of 7% (data point B in Fig. 6a) while the moisture content of the pellets only increased from 2.7 to 10.7% during that time. But as the relative humidity and more significantly rainfall increased from January 2012, the pellets saw two step increases in moisture content (reaching 20% and 26% respectively), with durability decreasing by 16% (data point C in Fig. 6a) and 34% (data point D in Fig. 6a) respectively, from their initial values. The pellets in the middle of the pile were obviously protected from continuous exposure to weather changes and saw smaller increases in the moisture content which would explain the higher resistance to mechanical degradation compared to surface pellets. The pellets on the surface of the outdoor piles were directly exposed to changing rainfall, relative humidity and temperature and are likely to have undergone cyclic expansion and contraction. Pellets in the middle were more protected and hence less vulnerable to mechanical degradation when moisture increased. This shows that in a short term outdoor storage scenario (3 months), the outer layers of the pile will degrade dependent on the environmental conditions but the middle pellets are likely to be protected and less susceptible to mechanical degradation.

In the first three months of Phase 2, the total rainfall was 55 mm per unit area compared to 80 mm in Phase 1, and the pellets on the surface of the outdoor steam exploded pellet pile in Phase 2 only suffered a 5% decrease in durability following a rise in the moisture content from 3 to 8%. From then onwards, the rainfall increased and remained consistently high for up to eight months (35–75 mm per unit area). This led to a significant step increase in the moisture content of both the surface (22%) and middle (24%) pellets with corresponding durability drops of 40 and 10% respectively from initial durability. Table 2 provides a comparison between the moisture and durability behaviours of the Phase 1 and Phase 2 outdoor steam exploded pellets.

Table 2 shows that the pellets tested during Phase 2 demonstrated less reduction in durability for a similar moisture content compared to the pellets from Phase 1. The reduction in durability of the Phase 1 pellets (both on the surface and in the middle of the outdoor pile) is more than twice that of the Phase 2 pellets. As mentioned in Section 3.1, it is speculated this could be because the pellets were made from different raw materials or the processing (thermal treatment) technique had been altered between the two production batches.

For the white wood pellets in indoor (covered) storage, the durability of both the surface and middle pellets decreased over time, as shown in Fig. 7.

For the white wood pellets on the surface of the pile, the moisture content increased from 9 to 12%, yielding a 40% drop in durability after six months. Because of significant pellet degradation and dust formation as storage progressed, it was not possible to retrieve samples from the middle of the pile using the sampling probe. At the end of the trial after ten months in storage, the pile was carefully deconstructed in order to obtain a middle sample. The moisture of that sample was 9% with a drop in durability of 15%. As the pile was protected from rain, this moisture increase came from the high relative humidity. However as the storage barn was open with two open walls (as opposed to a fully enclosed storage environment), some rain might have reached the pellets depending on the wind direction, and this might have contributed to the rapid mechanical degradation of the pellets.

The trends observed in this work of the higher mechanical strength of fresh and stored steam exploded wood pellets (by steam explosion)

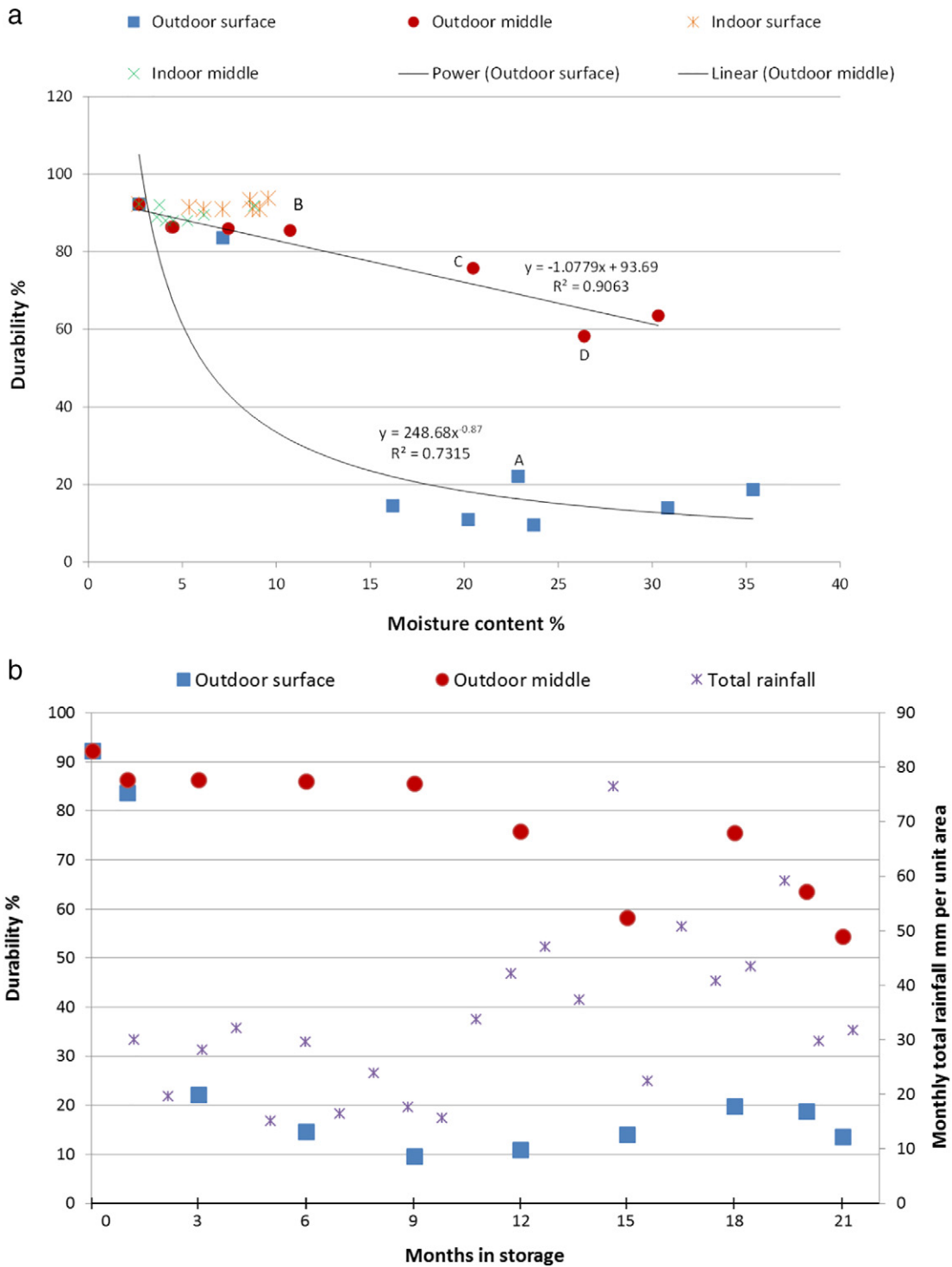


Fig. 6. a. Durability % (Eq. (1)) of Phase 1 steam exploded wood pellets against pellet % moisture content. b. Durability % (Eq. (1)) against time in storage of Phase 1 outdoor steam exploded wood pellets including total monthly rainfall.

Table 2
Comparison between the maximum durability drops of Phase 1 and 2 steam exploded pellets stored in outdoor stockpiles.

Project phase	Sample	Maximum durability drop% from initial value	Moisture content %	Length of time in storage for maximum durability drop in months
Phase 1	Surface	82	24	9
Phase 1	Middle	34	26	15
Phase 2	Surface	42	24	10
Phase 2	Middle	12	28	12

compared to untreated white wood pellets were also observed by [17] during outdoor uncovered and outdoor covered storage for five months. Graham et al. [19] investigated the degradation of steam exploded and white wood pellets in a laboratory environment with exposure to high relative humidity at a range of temperatures and also reported on the higher durability of the steam exploded pellets throughout the tests. According to the work of [27,28], pellets made from steam exploded wood had a breaking strength 1.4 to 3.3 times larger than t pellets made from untreated wood with the same pelletisation conditions. It was suggested that a modified structure of lignin after steam explosion

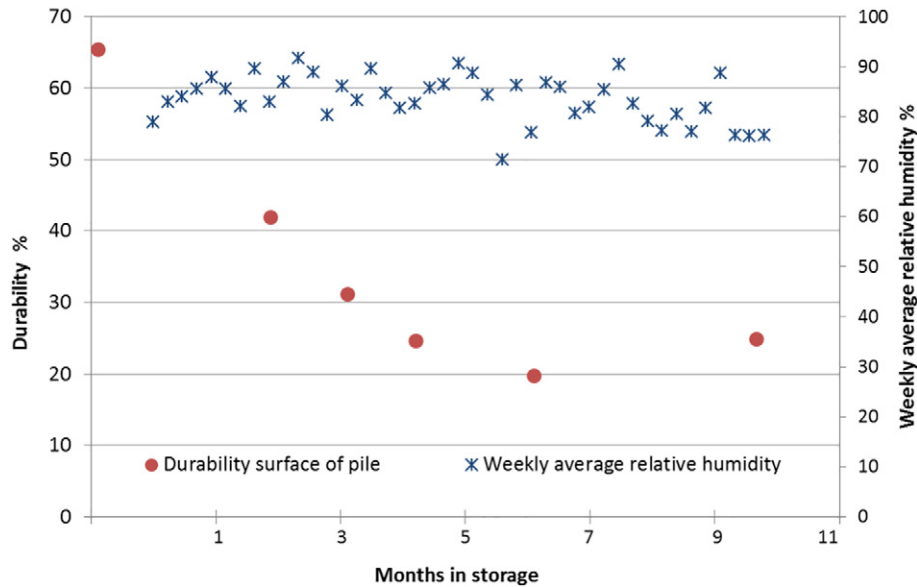


Fig. 7. Durability % (Eq. (1)) of pellets from the surface of indoor white wood pellet pile from creation against time in storage including weekly average relative humidity (%).

contributed to the increase in breaking strength. Lam et al. [29] reported that the improvement in hardness and mechanical stability of steam exploded pellets can also be explained by the binding role of mono-sugars released during hydrothermal treatment.

In the doctorate thesis of S Graham [18], the full results of the chemical analysis carried out on the steam exploded and white wood pellets is reported. The dry ash content, dry ash free volatile content and dry ash free calorific value graphs showed no clear trends with time in storage. Any changes were found to lie within the normal range of fuel variability. However the net calorific value of the pellets showed an overall decreasing trend as storage progressed due a gradual increase in moisture content. The pellets stored outdoor suffered a larger drop in net calorific value compared to the pellets in indoor storage.

3.4. Pellet compression strength and Young's modulus

Pellet compression and shear tests were introduced to the experimental scope in the ninth month of the Phase 1 testing, after pellet durability was observed to have been significantly impacted by outdoor storage. The compression strength and Young's modulus of the fresh and stored Phase 1 and Phase 2 pellets are compared in Tables 3 and 4. Table 3 shows the mechanical properties of the different 'fresh' pellet types at the start of storage. The mean values for axial and diametrical compression strength and Young's modulus are given with the values in brackets showing the minimum and maximum variation based on five samples for the compression tests and ten samples for the Young's modulus test. The variation is expected due to the inhomogeneity of biomass and potential differences in pelletisation conditions.

The fresh Phase 1 steam exploded pellets had the highest axial and diametrical compression strengths and shear modulus, with the fresh Phase 2 white wood pellets having the lowest, with the moisture content following the reverse sequence. The largest variation was observed

in the Young's modulus results, especially for the Phase 1 steam exploded pellets.

Table 4 shows the compression strength and Young's modulus of the different pellets after nine months in storage, with the changes in moisture content and pellet durability from starting values highlighted.

The Phase 1 steam exploded pellets stored indoors retained the highest Young's moduli after nine months in storage, which matches the trends in pellet durability. However the 56% and 23% drop in the Young's modulus of the indoor surface and middle-sampled pellets respectively are much higher than the corresponding durability changes of 1 and 4% indicating that the potential for pellets to fail through shear forces is significantly in storage scenarios. The % changes in axial and compression strengths were also higher than those seen in durability tests. Durability tests showed no significant change for pellets stored indoors whereas reductions from a minimum of 20% to a maximum of 30% were seen for the axial compression strength. The Instron tests (compression and inter-laminar shear) are very different in nature to the durability test. In the durability test, the pellets are tumbled at high speed and although they experience forces as they rotate around and bounce against each other, the forces are not continuous and of increasing magnitude. In each of the three Instron test, a force of increasing magnitude is applied to the pellet continuously until the pellet fractures, providing a value which is checked across multiple pellets in a repeatable manner. While the Instron tests represent storage loads, durability attempts to represent some of the forces the pellets experience during handling and conveying.

The Phase 1 steam exploded pellets stored outdoors saw larger drops in compression strength and Young's modulus after nine months compared to the indoor pellets, with the surface pellets showing a larger extent of mechanical degradation than the pellets sampled from the middle of the pile. This trend was also reflected in the durability data.

While the compression strengths and Young's moduli of the stored Phase 2 outdoor steam exploded pellets are similar in value to those

Table 3
Mechanical properties of 'fresh' pellets at the start of storage.

Pellet type	Moisture content %	Durability (Eq. (1)) %	Average axial compression strength MPa (min–max)	Average diametrical compression strength MPa (min–max)	Average Young's modulus MPa (min–max)
Phase 1 steam exploded	2.7	92	20 variation: (17–22)	57 variation: (44–70)	417 variation: (280–550)
Phase 2 steam exploded	3.2	86	13 variation: (8–19)	50 variation: (43–58)	192 variation: (110–270)
Phase 2 white wood	9.2	64	6 variation: (4–9)	19 variation: (16–21)	37 variation: (28–48)

Table 4
Percentage changes in the moisture content and mechanical properties of pellets after nine months in storage where surface and middle refer to the location samples were taken from within the stockpile.

Pellet type	Increase in moisture content from starting value %	Decrease in durability from starting value %	Average axial compression strength MPa (min–max)	% dec from fresh	Average diametrical compression strength MPa (min–max)	% dec from fresh	Average Young's modulus MPa (min–max)	% dec from fresh
Phase 1 steam exploded indoor surface	8.7	1	14 variation: (12–16)	30	31 variation: (25–42)	46	187 variation: (124–250)	56
Phase 1 steam exploded indoor middle	4.5	4	16 variation: (14–19)	20	56 variation: (34–67)	2	322 variation: (239–454)	23
Phase 1 steam exploded outdoor surface	23.7	82	2 variation: (0–4)	90	33 variation: (28–36)	42	4 variation: (1–7)	99
Phase 1 steam exploded outdoor middle	10.7	6	7 variation: (4–10)	65	36 variation: (26–57)	37	110 variation: (27–243)	76
Phase 2 steam exploded outdoor surface	22.3	40	9 variation: (8–19)	31	11 variation: (9–13)	78	24 variation: (16–37)	88
Phase 2 steam exploded outdoor middle	24.1	6	6 variation: (8–19)	54	6 variation: (5–7)	88	44 variation: (27–70)	77
Phase 2 white wood indoor surface	12.2	39	2 variation: (1–4)	67	11 variation: (9–19)	42	13 variation: (3–34)	65
Phase 2 white wood indoor middle	9.5	15	3 variation: (3–4)	50	7 variation: (4–12)	63	36 variation: (18–62)	3

of the Phase 1 outdoor steam exploded pellets after nine months, the % change from the starting properties of the fresh pellets was larger in Phase 1 than in Phase 2. This higher resistance to mechanical degradation of the Phase 2 pellets compared to the Phase 1 pellets was also seen in the durability test results, as discussed in Section 3.3.

The white wood pellets started with the lowest mechanical strength (Table 3) and after nine months in indoor storage, their durability, compression strength and Young's modulus were lower than the indoor stored steam exploded pellets. As explained in Section 3.3, this reflects the superior mechanical nature of the steam exploded pellets.

3.5. Significance of results

The fresh Phase 1 steam exploded pellets had the highest mechanical strength with the Phase 2 white wood pellets having the lowest. This indicates that during initial handling and conveying upon delivery at the storage site/power station, the fresh Phase 1 pellets are likely to undergo the least breakage and dust formation, with the fresh Phase 2 white wood pellets having the greatest likelihood to break down to fragments and dust during the same operations.

The mechanical degradation results show that for the steam exploded pellets at the surface of the pile, outdoor storage strongly impacts on pellet degradation with significant moisture uptake and decrease in durability. Within the storage pile the effects are less pronounced, but are still measureable. The local climatic conditions will often determine the outcome - in countries with long periods of low relative humidity and rainfall, long term outdoor storage of steam exploded wood pellets would be viable. In the UK the weather is unpredictable. Therefore it would be more risky to store steam exploded wood pellets in outdoor stockpiles in the longer term. However, short term outdoor stocking (e.g. up to 1 month) might be feasible in moderate weather conditions. Exposure to moderate relative humidity alone does not result in significant pellet degradation and fresh pellets do exhibit resistance to light rainfall. This may also benefit operators as short exposure of steam exploded pellets at ports and during loading/unloading on ships and rail wagons should be less of an issue than when dealing with white wood pellets, where unloading of vessels has to stop during rainfall. White wood pellets degrade severely upon exposure to moderate relative humidity and need stored in a fully enclosed environment.

4. Conclusions

This study enabled the mechanical degradation of white wood pellets and steam exploded wood pellets during long term indoor and outdoor storage to be assessed and compared.

For the steam exploded wood pellets stored outdoors, both the relative humidity and rainfall contributed to an increase in the moisture content of the pellets which resulted in pellet swelling and mechanical weakening. In both Phases 1 and 2, the drop in mechanical strength was greater for the pellets taken from the surface of the outdoor piles with

the Phase 1 pellets seeing a maximum durability drop of 82% and the Phase 2 pellets a drop of 42%. The pellets taken from the middle of the storage piles showed higher resistance to mechanical degradation with the Phase 1 pellets seeing a 34% decrease in durability. Throughout storage, the outdoor Phase 2 steam exploded pellets exhibited higher resistance to mechanical degradation than the equivalent Phase 1 pellets - this is suggested to be due to different raw material potentially treated at different thermal conditions.

For the Phase 1 steam exploded wood pellets stored indoors, the extent of mechanical degradation was very low (3% drop in durability). Therefore long term storage of these pellets in an open barn with roof would be a viable option.

The mechanical degradation observed for the Phase 2 white wood pellet indoor pile was severe on both the surface (39% drop in durability) and in the middle (15% drop in durability) of the pile, with pellet disintegration commencing as early as after one month in storage. This shows that continuous exposure to ambient UK relative humidity causes the pellets to weaken through moisture absorption. Although this rapid deterioration was probably exacerbated by the fact that the white wood pellets had already been stored at Ironbridge power station for some time, it is clear that white wood pellet is very prone to degradation and it is advisable to store such material in a fully enclosed environment.

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