

Influences of Environmental Humidity on Physical Properties and Attrition of Wood Pellets

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Abstract: Wood pellets have been widely used for power generation and domestic heating recently to substitute fossil fuels. For health and safety reasons, particle degradation and dusts generation in material storage and handling processes are always a serious concern for anyone involved. Also the level of fines in wood pellets can strongly influence fuel milling and combustion. For previous study, wood pellets attrition subjected to its mechanical properties has been reported. However pellet mechanical properties can be inconsistent and influenced by environmental conditions such as humidity, temperature and storage time.

In this paper, attrition behaviour and dust generation of two types of wood pellets have been studied, which the pellets were stored in a constant relative humidity environment for a period of time (4 days). Physical properties such as moisture contents, bulk density and flexural stress of the pellets were measured for the pellets conditioned in a RH chamber, which was believed that equilibrium condition was achieved. Correspondingly, the conditioned pellets for a number of different humidity levels were tested for both impact test and dustiness test. The study shows that the pellets can lose structural strength due to in taking moisture from environment for a high relative humidity. Also a high humidity can result in an increased level of pellet degradation and dusts generated.

Keywords: Wood Pellets, Attrition, Dusts, Humidity influence, Physical properties;

1 Introduction

With attention to a 'green' fuel source to reduce carbon emission, wood pellets have been widely used for two primary sectors: industrial sector (substitute for coal in power plants), and residential sector (for domestic heating). Global usage of wood pellets for both sectors, have had significant growth in the past decade, which reached about 26 million metric tonnes in 2015 [1] and continues to grow.

Compared to other biomass fuels, wood pellets can offer many advantages such as high bulk density, high stability and low moisture contents. In terms of transport costs, wood pellets have less volume to handle, and also facilitate less storage and transportation due to its high energy content than wood chips, logs or other raw biomass. A low moisture content and uniform particle shape also provides better handling ability in storage and transport [2]. However wood pellets still suffer from a number of problems in storage and handling process. Pellet attrition is one major problem, which may produce dust and influence milling and combustion performance [3]. Dust generated in handling and transportation can result in serious health and safety issues in the working environment [4], which requires evaluation and control of the dust and fine contents and their migration in the handling process. Wood pellets flow through multiple handling stages from manufacturers (often overseas) to reach final users, *e.g.*, power stations [5]. Evaluation and control of fines (small part of broken pellets) and dusts (often thought of as those debris so fine they can suspend in air) in the multiple handling stages can be difficult, while the pellets physical properties can be changed through storage and transport in different environments.

To access attrition of wood pellets, a number of evaluation methods including mechanical properties and dust generation have been developed and used in industry such as durability test [6-9]. However

45 these assessments normally evaluate the pellets attrition with constant physical properties for the
46 time when the wood pellets are taken without considering further storage time. In reality, wood
47 pellets are quite often kept in storage for a relatively long period before being moved to the next stage,
48 or sit in transport vehicles (e.g. ship holds) for long distance travel. Storage conditions such as humidity
49 must change from time to time. Some previous research already noted that mechanical properties of
50 wood pellets would change due to exposure to high humidity in stockpiles or severe environmental
51 condition changes [10, 11]. These changes consequently influence the durability of the pellet fuels and
52 the level of fines and dust generated. Varied wood pellet attrition leads to a difficult situation where
53 the material being handled can be from quite clean to extremely high fine (level can be 0% to 40% [12])
54 so the handling characteristics including flowability, dustiness, density and grinding ability may change
55 from hour to hour in the plant, although it also depends upon silo operational status [13].
56 Consequently, it becomes very hard to optimize the systems for reliable, energy efficient operation
57 and safety control [2]. Therefore it is necessary to investigate the influence of environmental humidity
58 on physical properties and attrition of wood pellets to provide a better understanding of the need for
59 humidity control in storage and transport.

60 In this paper, the influence of humidity on physical properties and attrition of wood pellets has been
61 studied include moisture absorption, moisture contents, bulk density and mechanical strength, which
62 can be critical to pellet attrition and dust generation [14]. The pellet attrition has been evaluated using
63 a rotary impact attrition tester for pellet samples conditioned at different relative humidity (RH) levels.

64 2 Physical properties of wood pellets

65 Wood pellets are made of woodchips or sawdust in uniform shapes normally 6 - 8 mm in diameter and
66 3 - 40 mm in length [15]. It gives a bulk density of typically over 600 kg/m³. In the pelletizing process,
67 the wood chips or sawdust is compacted into a uniform cylindrical shape with a polished appearance
68 on the outsides of the pellets, which can prevent absorbing moisture from the ambient environment
69 [16]. Appearance of wood pellets is shown in Figure 1, which are the samples used for current study.



70 Figure 1: The wood pellets being tested, (a) Pine wood pellets, (b) Recycled wood pellets

71 For fuel purposes, physical properties typically of interest with wood pellets are physical dimensions,
72 *i.e.*, pellet lengths, bulk density rather than solid density, moisture contents, pellet strength or
73 mechanical durability, *etc.* Other important specifications may include net calorific value, elemental
74 contents such as nitrogen, sulphur and chlorine, and ash contents, *etc.* [17]. However, these
75 combustion-related properties are not important to the pellet attritions.

76 2.1 Pellet dimensions

77 As mentioned above, wood pellets are made to a uniform diameter of 6 mm or 8 mm with varied
78 lengths of 3-40 mm in standards [15, 16]. Because of pelletizing process, pellet length becomes a
79 critical term for evaluating the quality of wood pellets. In EnPlus A-1 standard [18], fine particles are
80 defined as the particle length is smaller than 3.15 mm, but the size of dust for wood pellets has not
81 been defined in the standards.

82 The meaning of the term “dust” is not universally agreed. With standard durability tests of wood
83 pellets, the dust is particles picked up by an air flow of 175 l/min [19], which gives a maximum size of
84 dust up to 1.0 mm [9]. With the British standard [6], a smaller air flow rate is used, 38 l/min. In this
85 case, it is likely that the dust size of D90 is less than 300 µm. As there is no standard dust size so far
86 for wood pellets, it is sensible to define the dust size for wood pellets as less than 850 µm, which can
87 be easily picked up by an air flow. Therefore the pellet dimensions can be: normal standard wood
88 pellets are 3.15 mm – 40 mm; fines in wood pellets are 0.85 mm – 3.15 mm; and dusts in wood pellets
89 are ≤ 0.85 mm.

90 To assess wood pellet attrition, two categories need to be studied; fines and dust, by different methods,
91 because the mechanisms of pellets attrition are different and may have significantly different
92 influences on pellet attritions with changes in pellet quality. A previous study has reported the
93 influence of pellet dimensions on pellet durability and attrition, which concluded that longer pellets
94 seem more durable with a higher pellet strength [20]. Hence, the pellet dimension can be an important
95 parameter in assessing the quality of wood pellets for attrition of the pellets [14].

96 2.2 Bulk density

97 Bulk density is an important parameter for wood pellets, which directly influences storage and
98 transportation costs [21]. It is defined as weight of bulk pellets in a unit of volume, which can be
99 influenced by a number of factors, including fine contents. Another influence factor is moisture
100 content of the pellets. It is often seen that for clean pellets the bulk density is just over 600 kg/m³.
101 Previous research shows the shorter pellets have a higher moisture content and are less durable [22],
102 which often have a lower bulk density. It has been found that an increased bulk density of the pellets
103 is normally due to a reduced moisture content but also due to increased fines content in pellets [23].

104 2.3 Moisture content

105 Moisture content, usually expressed on a “wet basis” as defined in Eq. 1, has a great impact on bulk
106 density of wood pellets [24]. The moisture in wood pellets is originally from a number of sources. To
107 make the pellets, the raw materials must contain a certain level of moisture [15], which is typically
108 about 7% - 10% [14].

$$109 \quad \text{Moisture content (\%)} = \frac{\text{Mass of water in a unit weight of sample (g)}}{\text{mass of the unit weight pellet sample before drying (g)}} \times 100 \quad (\text{Eq. 1})$$

110 Whittaker [14] gave a detailed discussion of moisture content influence on wood pellet durability. As
111 a summary, for different types of wood pellets previous researches showed completed opposed
112 correlations between moisture content and pellet durability; some research suggested a positive
113 correlation roughly between 7% - 15% moisture contents for scots pine [24], tulip wood [25], and some
114 hardwoods [26]. However a number of studies reported a negative correlation between moisture
115 contents and pellet durability for 5% - 14% moisture in beech [27], and olive pruning residues [28]. A
116 later study showed that there could be an optimum moisture content for pellet durability in sawdust
117 produced pellets at different storage time [23] and the phenomenon was also mentioned by Whittaker
118 [14] and a number of other researchers [29]. Consequently the moisture content of pellets may have

119 a link with pellet attrition and size reduction. Graham’s study showed that a long storage time with
120 high humidity formed cracks and disintegration of the pellets due to reduced pellet strength [10]. Also,
121 Kaliyan [29] concluded that strength and durability of the wood pellets increased with increasing
122 moisture content until an optimum value was reached, although Kaliyan’s conclusion was for making
123 the pellets.

124 2.4 Pellet strength and durability

125 The term “wood pellet strength” is less common than “durability” of pellets, which may refer to both
126 the compressive and impact resistance of a pellet. Compressive resistance testing simulates the
127 loading due to self-weight in storage and the crushing of pellets in (for example) a screw conveyor.
128 Impact resistance testing simulates the impact forces induced on pellets during handling in the filling
129 of silos, bins or storage bays when pellets are dropped either on a hard floor or onto one another [30].
130 Pellet strength is sometimes useful when considering bulk delivery systems, and may be assessed by
131 tensile strength or flexural stress [11].

132 Durability or abrasive resistance is in general defined as the ability to withstand wear and tear, decay,
133 and loss of material through continual use; resistance to change from original appearance; or the
134 ability to resist weathering action or chemical attack [31]. Mechanical durability also means abrasion
135 strength and mechanical strength as compressive and impact resistance [29]. The different tests
136 commonly used measure different aspects of these losses.

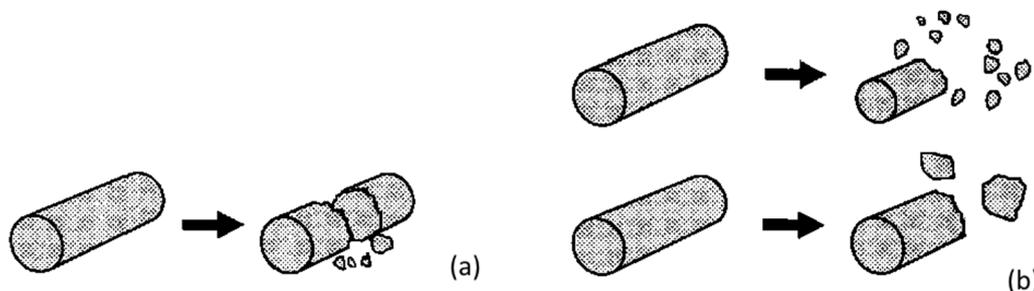
137 Although the tests may be different, durability of wood pellets is usually described by:

$$138 \quad \text{Durability (\%)} = \frac{\text{Mass of the oversized sample after test (g)}}{\text{Original mass of the test sample (g)}} \times 100 \quad (\text{Eq. 2})$$

139 In the standards, the oversize is defined as retained on a 3.15 mm round-hole sieve [6] and this is
140 consistent amongst most standards and users for **durability tests**. But as Frew [9] pointed out, for
141 **dustiness tests** of wood pellets the oversize may have different meanings according to different
142 standards.

143 3 Wood pellets attrition

144 As Thomas indicated [32], when forces were involved that were static or dynamic as a consequence of
145 movement, handling of wood pellets caused attrition that caused small pieces to be broken down from
146 the whole pellets. It is widely recognised that there are essentially two different attrition mechanisms:
147 fragmentation and abrasion shown in Figure 2 [32].



148

149 Figure 2: Two types of wood pellet attritions: (a) Fragmentation; (b) Abrasion [32]

150 3.1 Fragmentation and impact attrition

151 With fragmentation of wood pellets, because of their special shape (cylindrical shape with varied
152 length), the pellets may break in the middle due to impact force acting on one end of the pellet and

153 bending the pellet or causing large cracks. It causes large chunks to fall off from the original pellets
154 and the pellets to break down into smaller size, each of which would be significantly bigger than the
155 nominated dust size. The fragmentation of wood pellets could happen when dropping the pellets at
156 a transfer point, in a pneumatic conveyor or loading pellets into a big silo. Not only dynamic impacts
157 cause pellet fragments, but also does uneven loading stress acting on the pellets in storage.

158 Generally, wood pellets with dynamic impacts have a high chance to break into big pieces due to strong
159 impact force. Pellet fragmentation increases the number of smaller pellets significantly, but relatively
160 less dust is generated compared to abrasion attrition. The cracks can be in any direction, but are more
161 likely through radial direction as a result of small cross-section area compared to pellet length.
162 Therefore pellet fragmentation will depend on pellet strength, impact conditions such as velocity and
163 angle, hardness of the surface collided with and maybe moisture contents.

164 3.2 Abrasive attrition

165 Abrasion of wood pellets is defined as fracture on the edges or surface-unevenness of the pellets [32].
166 Due to manufacture methods of wood pellets, the pellets form a uniform cylindrical shape with varied
167 length from small wood chips by binding process. Pellet strength depends on solid-solid bonds
168 between ingredient particles or the use of specific pellet binders. It may also depend on interactions
169 between the small particles due to particle folding and plying. Therefore pellet strength may not be
170 uniform through each whole individual pellet. The bonding between some of the individual small
171 particles at the surface of a pellet may be relatively weak compared to the whole pellet and these are
172 easy to break off even with gentle rubbing actions such as movement in discharge from storage. So
173 abrasive attrition tends to produce mainly small fines (dust) compared to fragmentation attrition
174 which produces a wider range of particle sizes.

175 3.3 Evaluation methods

176 Many evaluation methods for attrition and dust generation of wood pellets have been developed
177 previously such as durability test [6-9]. Durability of wood pellets is defined in Eq. 2, by determining a
178 ratio between the mass of oversized sample after durability tests and the original sample mass. In
179 published standards, the oversize is defined as 3.15 mm [6] for mechanical durability, however for
180 dustiness tests the oversize of wood pellets is different according to different standards which
181 depends on test method [9].

182 Tumbling method [33] has been widely used to estimate pellet quality in terms of dust number [9] or
183 durability defined in Eq. 2. The test simulates mechanical movement of pellets in handling process and
184 measures fines produced due to the process. During the tumbling, the pellets gently impact and shear
185 over each other or against the wall of the container. According to different standards, dust number
186 can be slightly different because suction air flow rate is different (AS standard is 175 l/min [19] and EN
187 standard is 38 l/min [9]). For the tumbling method, it proposes to measure fugitive dust emissions
188 from the processing, storage, handling and loading/offloading of bulk materials such as wood pellets.
189 However it appears not very effective as an indicator of pellet attrition under dynamic impacts when
190 travelling at a velocity (such as in transfer points and pneumatic conveyor bends), because relative
191 movement of pellets in the tumbler is too small, velocity is very low and the main action is abrasion. A
192 recent study [34] concluded that the forces acting on particles in the tumbling box underestimated the
193 realistic handling conditions assumed such as filling from large heights (up to 21m) and reclaiming at
194 the bottom of a silo.

195 Other than the tumbling method, Oveisi-Fordiie [31] reviewed a number test methods for wood pellet
196 durability. One is the Ligno tester where pellets are exposed to shocks caused by air stream which
197 induces the particles to collide with each other and the wall of equipment. The small sample of 100

grams and lack of air stream control cause a higher variability between experiments and affect the repeatability of the durability measurement. Another one is the Holmen tester where pellets are introduced in a stream of air and pneumatically conveyed in a closed pipeline to simulate a more vigorous treatment of pellets. After treatment, the samples are sieved again with a sieve having an opening of about 80% of the pellet diameter. Similarly the Holmen tester is very restricted to air supply and has similar problems. Another important drawback with the Holmen test is that the acceleration length between impacts is far too short to simulate the effects in a real pneumatic conveying system. The last one mentioned by Oveisi-Fordiie [31] is the drop test, where a five-meter drop tower is used to facilitate dropping the samples onto different test surfaces. Due to the controlled drop heights, drop velocity of pellets is well controlled and the amount of dust generated in handling situation is closer to reality. However the drop velocity is limited by the heights and is not sufficient to simulate the high velocity in pneumatic conveying systems which are very widely used for pellet delivery.

Recently a rotary impact tester has been developed for assessing breakage of large particles (>1.0 mm) under dynamic impacts with a controlled velocity against hard metal surfaces at the Wolfson Centre [12, 35]. Advantages of the rotary impact tester to determine particle attrition for impact attrition are the well-controlled impact conditions such as particle velocity (by adjusting spinning speed of the disc) and impact angles against targets (setting target angles), which are the key factors for estimating degradation level of pellet fragmentation under impacts. However the rotary impact tester may over-estimate pellet attrition compared to that in real pneumatic conveying systems.

4 Experimental study

4.1 Test materials

Two types of sample materials were used; pine wood pellets and recycled wood pellets as shown in Figure 1. The pine wood pellets were made by Forever Fuels to meet high quality standard (ENplus A1). They were produced from virgin wood fibres and stored in a natural environment (water-tight but unheated shed) for about two years before testing. Average moisture of the pine wood pellets was about 5.1% w.b. (wet basis). The recycled pellets were manufactured in the UK (Woody Wood Products) to the ENplus standard, approved by the Forest Stewardship Council (FSC). The recycled pellets were made from 100% waste wood and were specified as 8-10% moisture indicated by the supplier, but was about 5.5% w.b. measured from the received samples. All the pellets are cylindrical of 6 mm in diameter and about 15-40mm long. Typical sizes of the pellets tested are summarised in Table 1.

Table 1: Size distributions of virgin pellets before the tests (percentage in weight)

Length (mm)	Pine wood pellets	Recycled wood pellets
< 10	3%	15%
10 - 20	57%	38%
20 - 30	30%	45%
> 30	10%	2%

229

4.2 Experimental procedures and rigs

4.2.1 Physical properties of the samples

In the tests, a number of physical properties of the pellets have been monitored, such as moisture contents, bulk density and pellet strength.

Moisture contents of pellets defined in Eq.1 were determined by using a moisture analyser (Moisture Analyzer MB35, Ohaus, US), in which 10 grams of each sample was heated at 105°C for 25 minutes

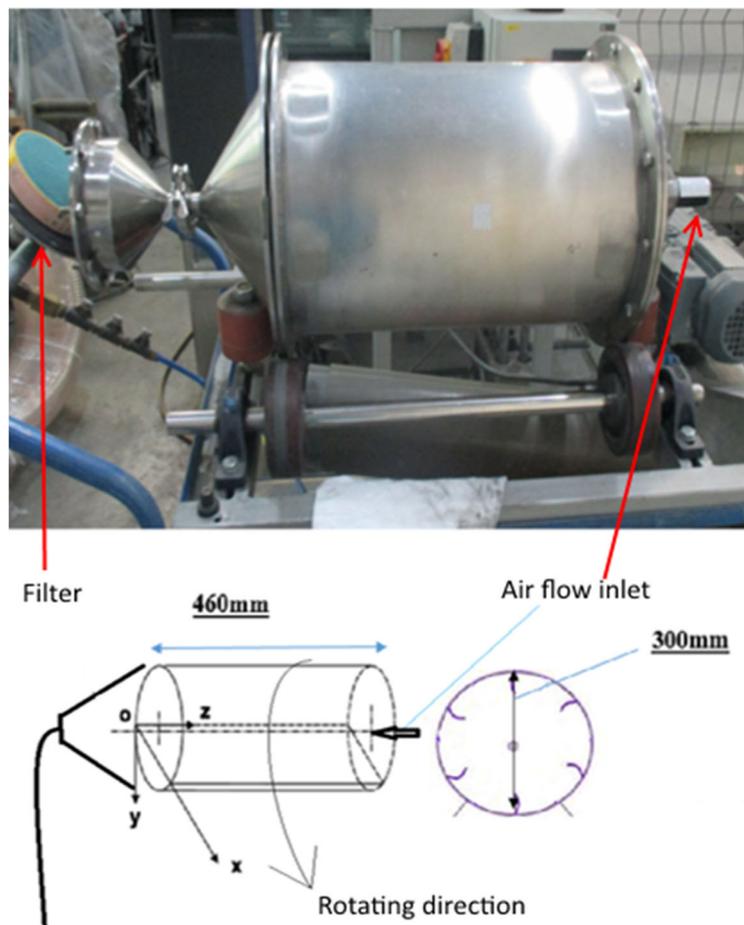
236 and the weight lost as water was measured. Dividing by the sample weight (10g), the wet-basis
 237 moisture content of pellets was given. For bulk density measurement, a standard one-litre container
 238 was used and weight of the pellets in the litre was measured. For pellet strength measurement, a
 239 three-point flexural bending test (bending to failure) was used to measure flexural stress of pellets (σ_f)
 240 as given in Eq. 3. All the measurements were repeated 6 times to obtain an average value and standard
 241 deviation.

242
$$\sigma_f \text{ (MPa)} = \frac{FL}{\pi R^3} \quad \text{(Eq. 3)}$$

243 where L (mm) is support span (for current study, 20 mm was used for all tests), F (N) is the peak load
 244 force at the middle point on the pellet between the supports, and R (mm) is radius of the pellets.

245 **4.2.2 Dustiness test**

246 To determine abrasive attrition and dustiness of wood pellet, a rotary drum tester was used in
 247 accordance with EN 15210 standard [6]. The drum was 460 mm in length and 300 mm in diameter
 248 with 6 of 30 mm lift bars inside (shown in Figure 3).



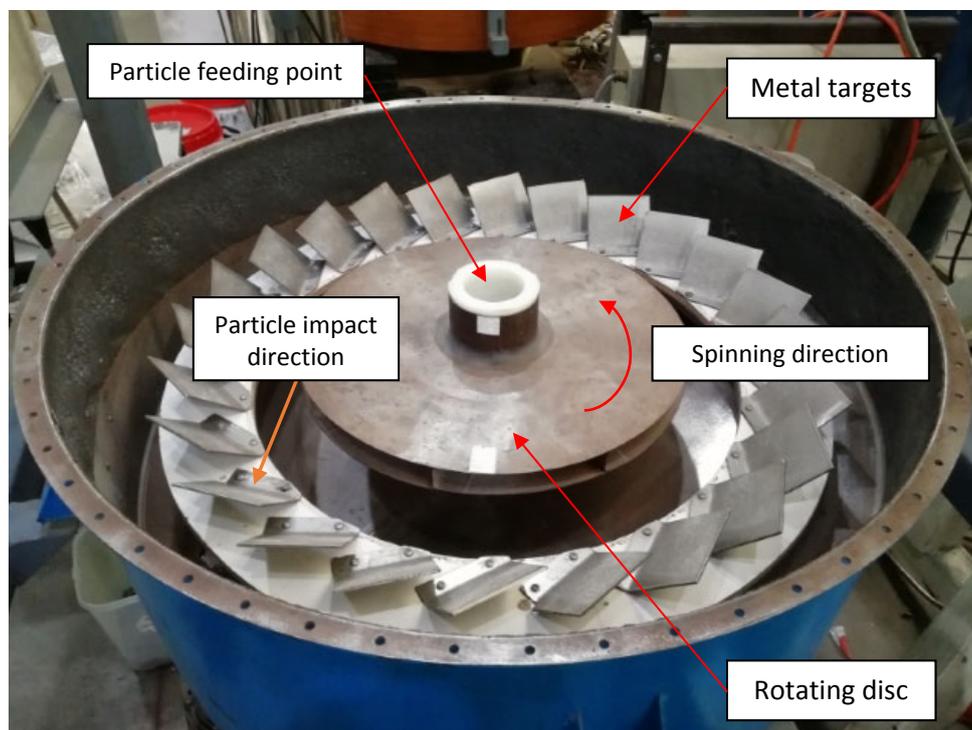
249
 250 **Figure 3: Rotating drum dustiness tester used at the Wolfson Centre**

251 The drum was driven by a speed-controlled motor, running at 40 rpm for a total of 500 revolutions
 252 (12.5 minutes). An airflow of 50 l/min was introduced through one end and ventilated via a filter foam
 253 pad that captured the dust in the air. The dust captured was weighed after tests and mechanical
 254 durability of the pellets in this test was calculated using Equation 1. Also size of the dust was analysed
 255 by a Malvern Mastersizer 2000. In the tests, a sample mass of 500 grams \pm 1.0 g of unconditioned or
 256 conditioned pellets was used for a single test. The slightly higher air flow rate and superficial air

257 velocity inside rotating drum (0.012 m/s) was used (50 l/min instead of 38 l/min specified in the
258 standard) because a larger bulk sample size was applied.

259 4.2.3 Impact attrition test

260 A large scale centrifugal impact attrition tester previously developed at the Wolfson Centre [35, 36]
261 for assessing breakage of large particles (> 1.0 mm), was used for higher velocity impact tests involving
262 more fragmentation. This consisted of a rotating disc (450 mm diameter) and set of equally spaced
263 metal targets fitted onto a ring that surrounded the rotating disc (see Figure 4). The sample material
264 was fed through a hole at the centre of the rotating disc by a feeding hopper. The sample particles
265 were subsequently split evenly and then accelerated radially through eight radial channels by
266 centrifugal forces. The particles were ejected from the channels with a final velocity consisting of a
267 radial and a tangential component, and moved towards the targets. The pellets struck the targets at
268 the designed impact velocity and impact angle. All the tested particles were collected carefully for size
269 analysis and compared to the original particle size for breakage.



270

271 Figure 4: The large scale centrifugal impact attrition tester

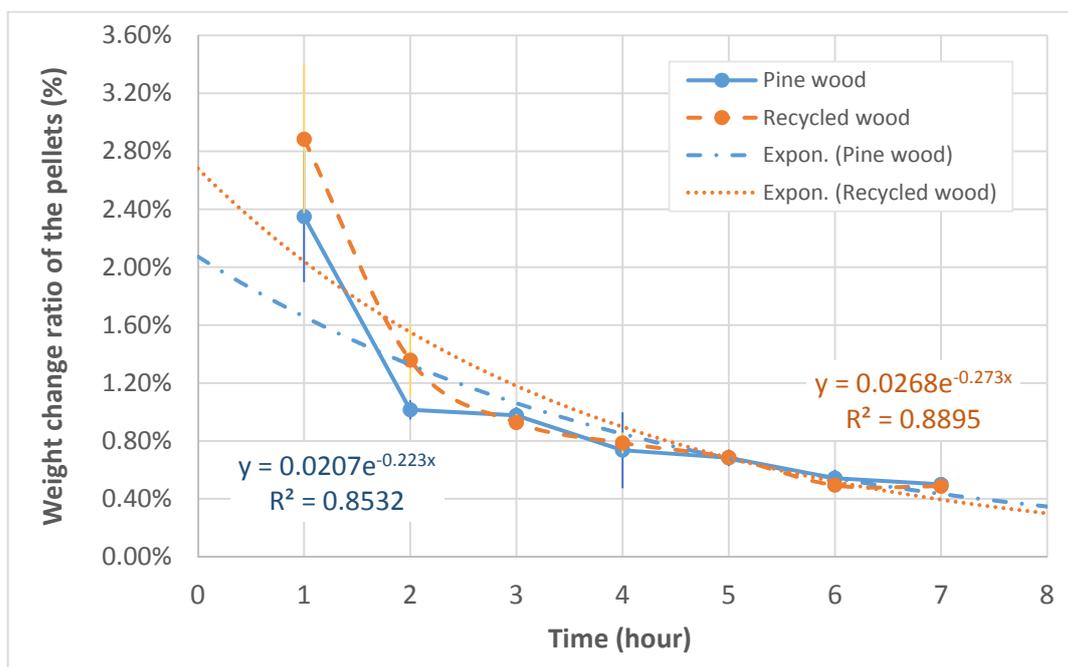
272 The advantage of rotary impact testers is that they enable the determination of particle breakage
273 under well controlled impact velocity and impact angles (by setting the angle of targets), which are
274 the key factors influencing particle degradation under high speed impacts such as in a pneumatic
275 conveying system. Also particle concentration, another influential parameter, can be well controlled
276 by reducing particle feeding rate to the tester so any shielding effect can be avoided. This tester is able
277 to rapidly generate the data by using a small amount of test samples for any size category required or
278 a full size range.

279 In current tests, a 500 gram \pm 1.0 g sample of wood pellets was used for a single test and fed into the
280 tester at a feeding rate of about 10 g/s. The disc rotated at a fixed speed of 578 revolutions per minute,
281 which gave an impact velocity of 20.0 m/s. The targets were rotated at 45° horizontally, which gave
282 impact angle at 45°. A vibrator to the enclosure was used along with manual brushing to collect all
283 samples. The collected sample was subsequently analysed by a 3.15 mm sieve and a vernier calliper.

284 4.3 Test conditions and sample conditioning

285 A test programme was undertaken to study the influence of exposure to various humidities on the
286 pellet attrition properties. Firstly the equilibrium relative humidity of the wood pellets was measured.
287 Five humidity values were selected, which were 20%, 40%, 60%, 80% and 95% RH at a constant
288 temperature of 30°C. These humidity levels were also used for studies of both physical properties and
289 pellet attrition. These humidity values are typical of the range commonly indicated in public
290 meteorology data for the Southern US states where large quantities of these pellets are manufactured,
291 stored and loaded into ships.

292 For pellet attrition, degradation tests of wood pellets were carried out on both dustiness drum tester
293 and rotary impact attrition tester so dust generation and pellet impact degradation can be assessed
294 for the conditioned pellet samples. For conditioning of samples, the pellets were specially conditioned
295 in a Climatic Test chamber (C340/40, Weiss Technik UK Limited) with humidity levels and the
296 temperature for about 4 days. A typical conditioning diagram of pellet rate of weight change (percent
297 change per hour) versus time is shown in Figure 5. An exponential decay curve fitted to this data
298 indicates that the pellets would reach a stable moisture level after 24 hours (weight changes are less
299 than 0.01% after this), so this gave confidence that the pellets would certainly be fully conditioned in
300 4 days. For any conditioned samples, the attrition tests were carried out immediately after the sample
301 was taken out from the chamber so any further environmental influence was minimised. For pellet
302 sizes, the collected test samples were analysed by mechanical sieves and the size ranges used were
303 <3.15 mm, 3.15 - 18.0 mm, and 18.0 - 38.0 mm. Except for the 3.15 mm sieve which was round hole,
304 all others used were square mesh sieves.



305
306 Figure 5: Example pellet weight changes (percent change in weight per hour) in an equilibrium
307 condition of 95% RH with fresh pellet samples, with exponential decay curves fitted

308 5 Results and Discussion

309 5.1 Influences of humidity on pellets physical properties

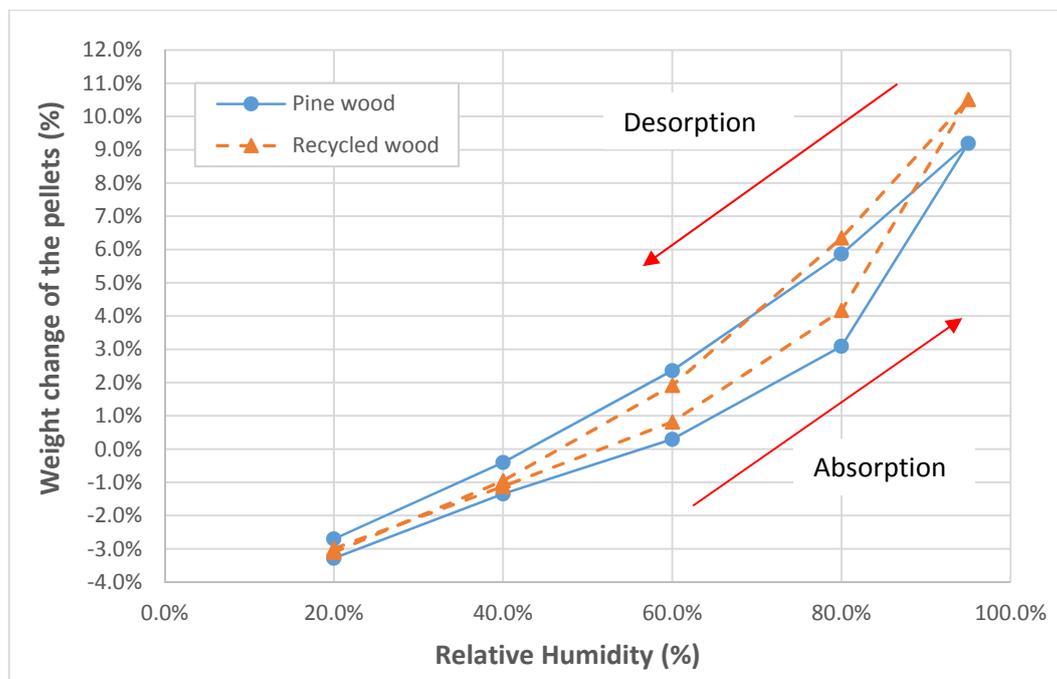
310 It has been reported that many physical properties of wood pellets may change due to humidity
311 changes in storage environment, *i.e.*, moisture contents and bulk density change, *etc.* [37]. Here,

312 influence of humidity on physical properties of wood pellets has been studied in detail, which include
313 moisture absorption, moisture contents, bulk density and mechanical strength.

314 5.1.1 Moisture absorption of wood pellets

315 In Figure 6, equilibrium moisture sorption curves of the pellets (measured using about 20 grams of
316 pellets in a mono-layer on an open tray in the climate chamber) are given, which were measured at a
317 constant temperature of 30°C degrees with 20% to 95% relative humidity (RH) exposure for a 24 hours
318 period for each humidity level continuously. After each period of time, the change of pellet weight was
319 taken. The measurement started from increasing humidity first and decreasing humidity. With the
320 results in Figure 5, it indicates that 24 hours are enough for pellet getting equilibrium. The absorption
321 and desorption curves form a hysteresis loop; this is commonplace for organic materials and is
322 believed to be due to the fact that energy is required to drive moisture into and out of the structure.

323 The samples were originally stored in a natural environment at around 46% RH and already contained
324 some moisture inside, which was 5.1% for the pine wood and 5.5% for the recycled wood pellets. The
325 results showed that there was about 3% weight loss at 20% RH due losing moisture, but a significantly
326 increased mass above 80% RH due to moisture gained. Between 40% and 60% RH, the moisture
327 absorption and desorption were not significant.



328

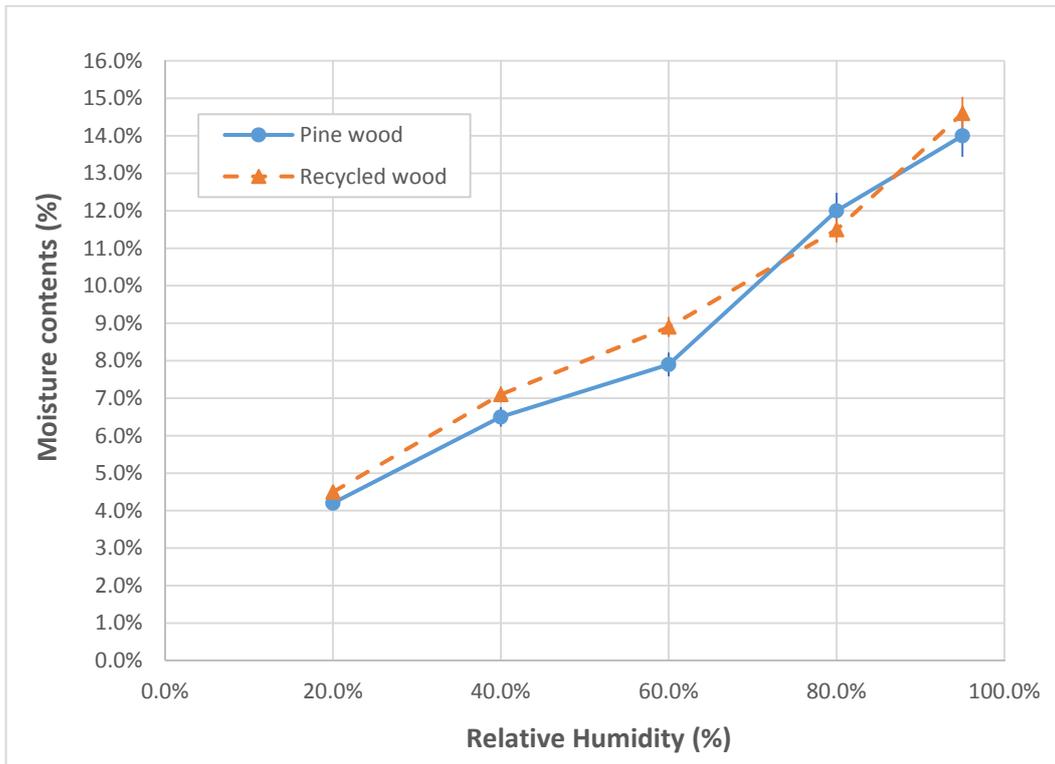
329 Figure 6: Equilibrium moisture sorption curves of the wood pellets with humidity exposure

330 5.1.2 Influence of RH on moisture contents

331 Moisture contents of the bulk-scale test samples of wood pellets after 4 days of conditioning were
332 measured for the samples conditioned at different humidity levels (20% - 95% RH) in trays of approx.
333 1kg in the climate chamber. Results are shown in Figure 7.

334 The results show an approximately linear increase of moisture contents in the pellets with increasing
335 RH, which is in agreement with previous study [38]. The ranges of humidity used in this study were
336 informed by meteorological data covering the Southern US States in which large quantities of wood
337 pellets are manufactured, stored, handled and loaded in large quantities [39]. For the both of samples,
338 it shows a very similar trend of moisture contents according to humidity changes, where appears to
339 have a major effect on the deterioration of pellets. With a humidity of 95% RH, the moisture was 14%

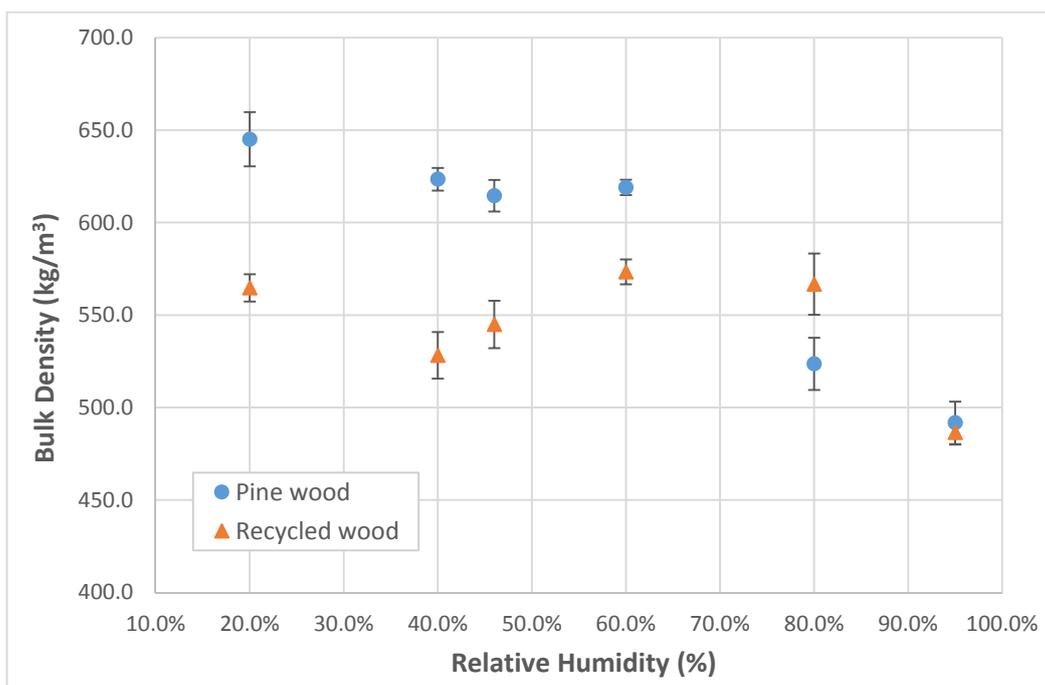
340 for both samples. It means that the pellets can absorb significant moisture, if stored in an extreme
 341 humidity. This may influence the pellet strength and consequently pellets degradation behaviours.



342
 343 Figure 7: Measured moisture contents of the pellets conditioned at certain relative humidity levels

344 5.1.3 Influence of RH on bulk density and mechanical strength

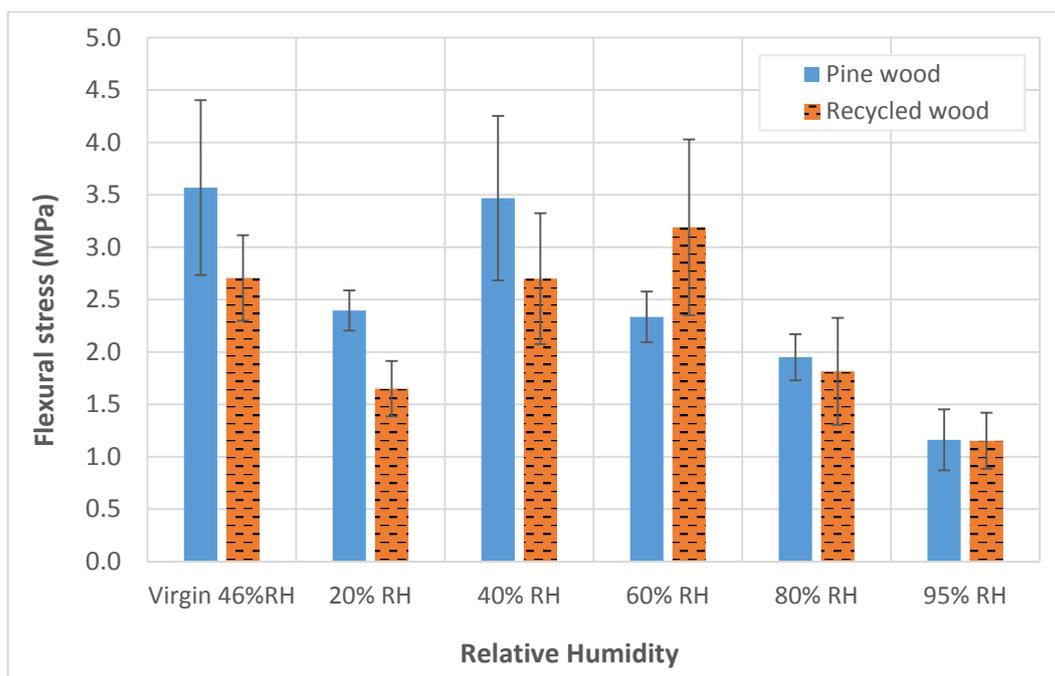
345 Results in Figure 8 give the measured bulk densities of the wood pellets at ambient and different
 346 conditioning RH, and results in Figure 9 give corresponding flexural stresses of the wood pellets.



347
 348 Figure 8: Bulk densities of the wood pellets at ambient and conditioned humidity RH based on 6 tests

349 The results show that both bulk density and pellet flexural stress reduce with an increased relative
 350 humidity. In principle, if volume of the pellets does not change, bulk density of the pellets should
 351 increase when the pellets absorb water. However, decreased bulk density means that the pellets have
 352 expanded and the volume is increased when moisture content is increased. The results of pellet
 353 strength also confirm that the particles in the pellets must expand, which results in an increased
 354 volume of the pellets. This phenomenon seems to happen when the RH is greater than 60%. In the
 355 experiments, appearance of the conditioned pellets seems not to change, except for at 95% RH.
 356 Comparing the pellets conditioned between 60% RH and 80% RH, the average bulk density dropped
 357 about 10%, but pine wood pellets dropped more significantly than the recycled wood pellets.

358 Similar results can be found for the pellet flexural stress, the pine wood pellets have the highest
 359 strength at 40% RH but the recycled wood pellets have the highest strength at 60% RH. For higher RH,
 360 both pellet samples show the same trends for the bulk density and pellet strength.



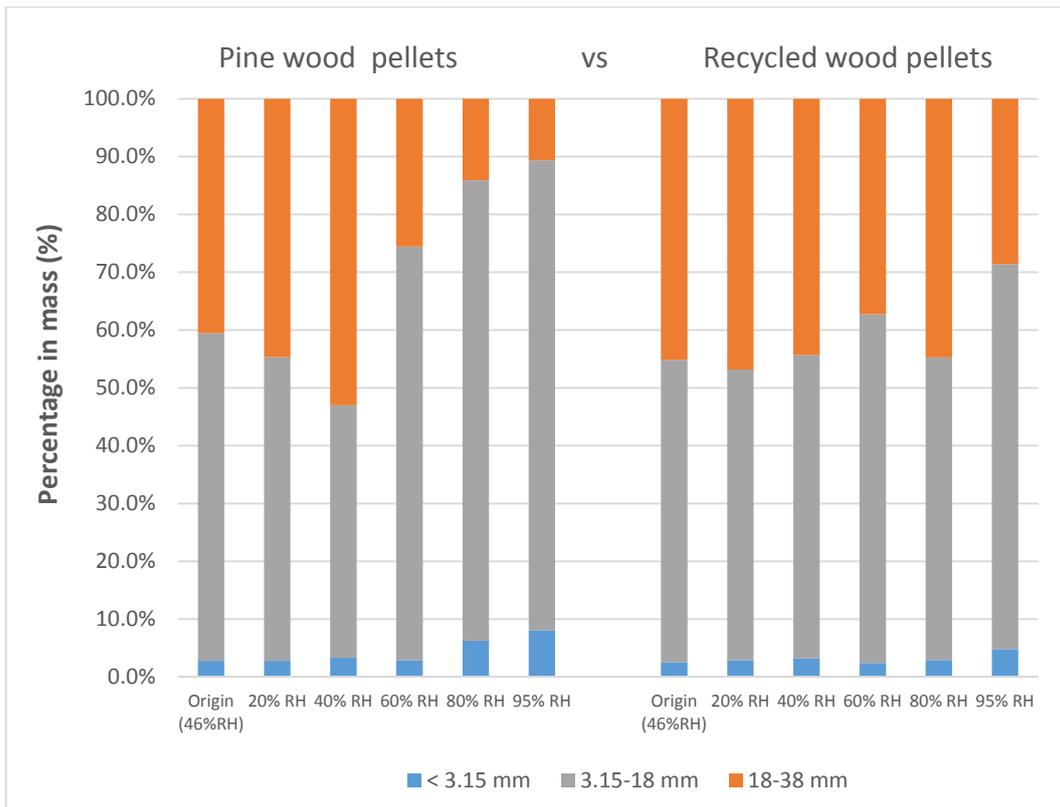
361
 362 Figure 9: Flexural stresses of the wood pellets conditioned at different humidity RH based on 6 tests

363 5.2 Influence of humidity on pellet attrition

364 Because humidity influences the pellets mechanical properties such as moisture contents and pellet
 365 strength, humidity would be expected to influence attrition behaviour of the wood pellets. These have
 366 been studied on two types of attrition testers, impact attrition and dustiness tests for pellet durability.

367 5.2.1 Impact attrition

368 The impact attrition of the pellets have been tested at one impact velocity of 20 m/s and one impact
 369 angle of 45° degrees for a conditioned pellets sample of 500 grams. This has been done for one single
 370 test and the degradation results are shown in Figure 10, for unconditioned sample (46% RH) and
 371 conditioned samples at 20%, 40%, 60%, 80% and 95% RH. The following size categories were used for
 372 analysis: <3.15mm; 3.15-18mm and 18-38mm. The <3.15mm fraction was determined using a round-
 373 hole sieve 200mm diameter and a shaker. Larger sizes were measured using a vernier calliper. The
 374 impact velocity of 20 m/s was selected because it is close to a popular conveying velocity of wood
 375 pellets in pneumatic conveying systems. For the same reason, the impact angle of pellets in a short
 376 radius bend of pneumatic conveying systems is typically around 45°.



377

378

Figure 10: Size distributions of the pellets after 20 m/s impact at 45° impact angle

379

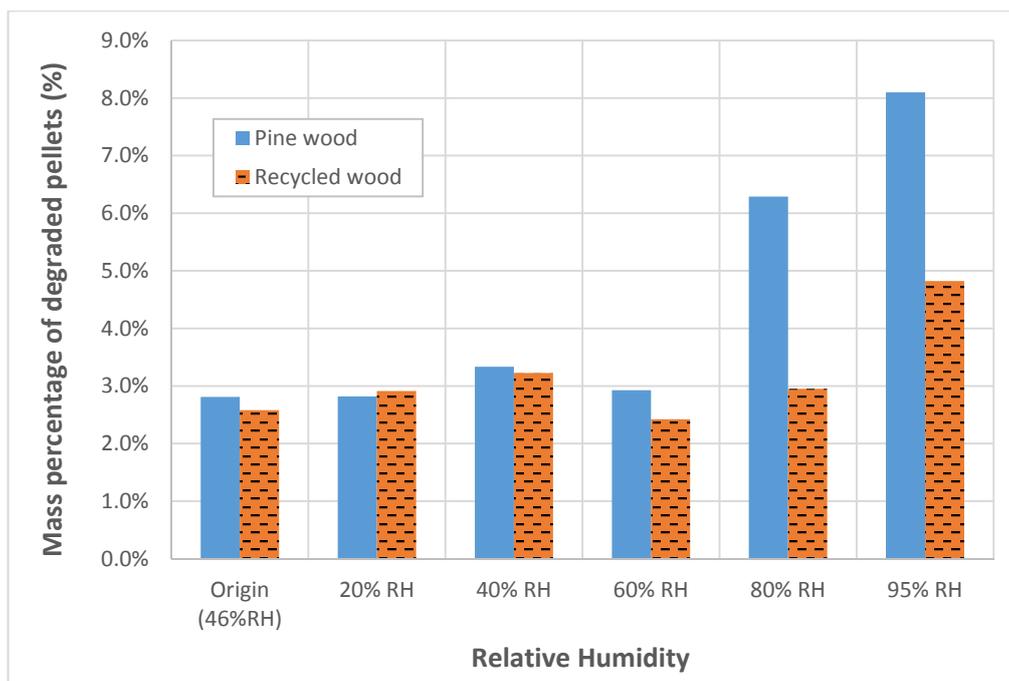
For virgin pellet samples, all the pellets were bigger than 3.15 mm in length before the impact tests and had a size distribution shown in Table 1. Therefore the results in Figure 10 are showing a size change after the impact tests at controlled impact conditions for the conditioned samples. In pellet utilisation, it is the fines content that causes combustion problems in some boilers, so the sub-3.15mm particle contents of the samples are shown on an enlarged abscissa in Figure 11.

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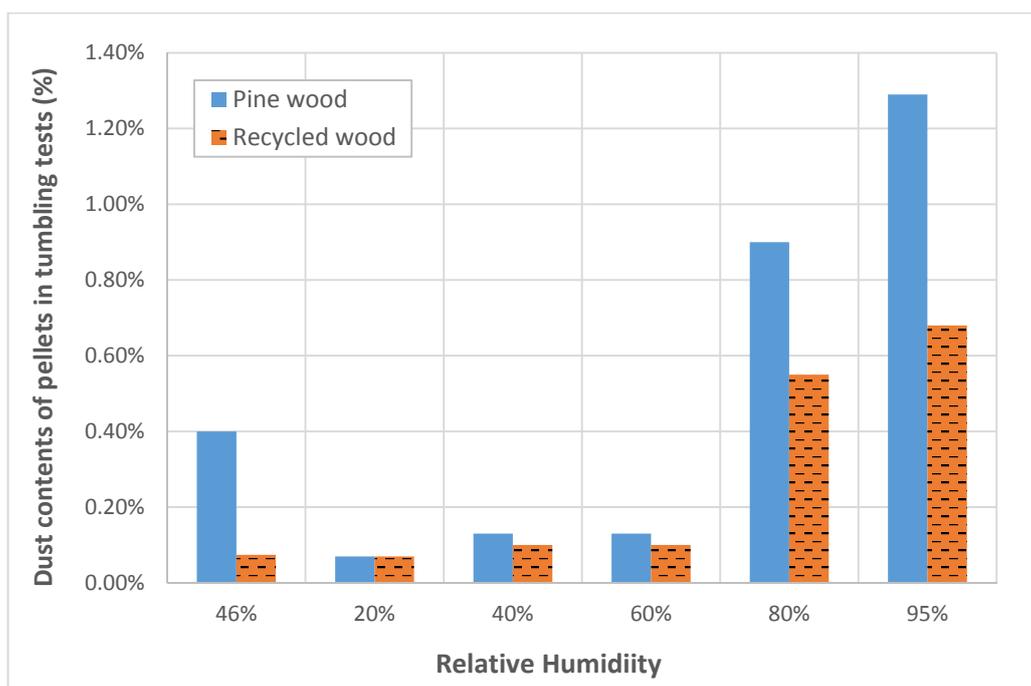
Figure 11: Degraded materials (< 3.15 mm) after impacts at velocity of 20 m/s and 45° impact angle

386 For the results shown, it can be seen that the pellets may break down more easily if exposed to a high
 387 humidity, *i.e.*, 95% RH. For a normal ambient condition between 20% RH and 60% RH, the pellets seem
 388 stable and levels of degradation are similar. The two different types of pellets had slightly different
 389 sensitivities to the humidity. The pine wood pellets showed a much higher degradation level at 80%
 390 RH in the tests, but the recycled wood pellets only showed substantial increase in attrition at 95% RH.
 391 For the both samples at 95% RH, the degradation was significantly increased and the number of long
 392 pellets dropped clearly.

393 For the pine wood pellets, a possible reason why they were more sensitive to the humidity may be
 394 because they had been stored in an ambient environment for almost three years, whereas the recycled
 395 wood pellets were recently purchased. Long term storage might possibly cause the pine wood pellets
 396 to be more susceptible to the effect of humidity due to aging effects of the wood pellets which have
 397 been shown to have some influence on strength and durability [24].

398 5.2.2 Mechanical durability in tumbling test

399 The dust generated during a simulated mechanical handling process with the conditioned wood pellets
 400 was measured by using the rotary drum tester described in section 4.3. The “durability” for the wood
 401 pellets is defined in Eq. 1. The results of dust generated (which is essentially equal to ‘100%-durability’)
 402 in tumbling tests are shown in Figure 12 for the samples conditioned at different humidity levels at
 403 20%, 40%, 60%, 80% and 95% RH.



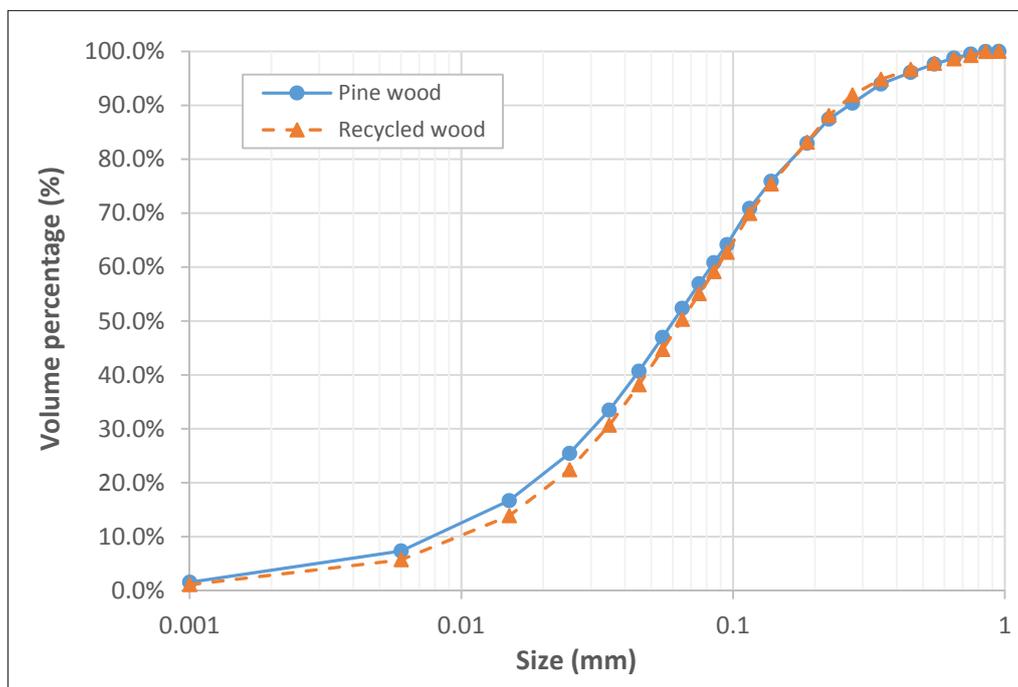
404
 405 Figure 12: Dust contents of the conditioned (varied RH) wood pellets in tumbling dustiness tests
 406 (dust content is equal to ‘100% - pellet durability’)

407 The results clearly show an increase of dust contents when humidity is higher than a certain level.
 408 Compared to the results in Figure 11, a broadly similar result can be found but in this test, both types
 409 of pellets showed very great increase in damage when conditioned at 80% RH or above.

410 Comparing against the results in Figure 9 show that pellet flexural strength is also reduced with a high
 411 humidity level. This gives supporting evidence that the pellets can be weakened by high humidity,
 412 which results in the pellets being broken down more easily for the same impact energy so the pellets
 413 have less durability in handling. In the results, it is noticed that, for the RH between 20% and 60%, the

414 durability for both pellets has not changed much, so for an average or lower than average storage
415 humidity, the wood pellets seem quite stable and the humidity has little effect on pellet degradation
416 behaviour. But with higher humidity, the pellets may have permanent changes and become degraded
417 more easily.

418 The size of dust particles generated in durability tests that were carried by the air flow (50 l/min) and
419 collected by the filter was analysed (Figure 13) using a Malvern Mastersizer 2000. It shows that the
420 top size of the dust is about 850 μm . Although the dust collected is only about 0.01% or less of the
421 total sample weight, with an average particle size of 65 μm , the number of particles is huge and the
422 particles are harmful as inhalable, which could cause severe problems in storage and handling of
423 pellets especially in flat stores operated by mobile plant. This size distribution is also in the range that
424 would be expected to lead to high values of explosion properties (rate of pressure rise and peak
425 explosion pressure in a contained explosion) so the deposition of this dust in a working environment
426 would present a high dust explosion risk.



427

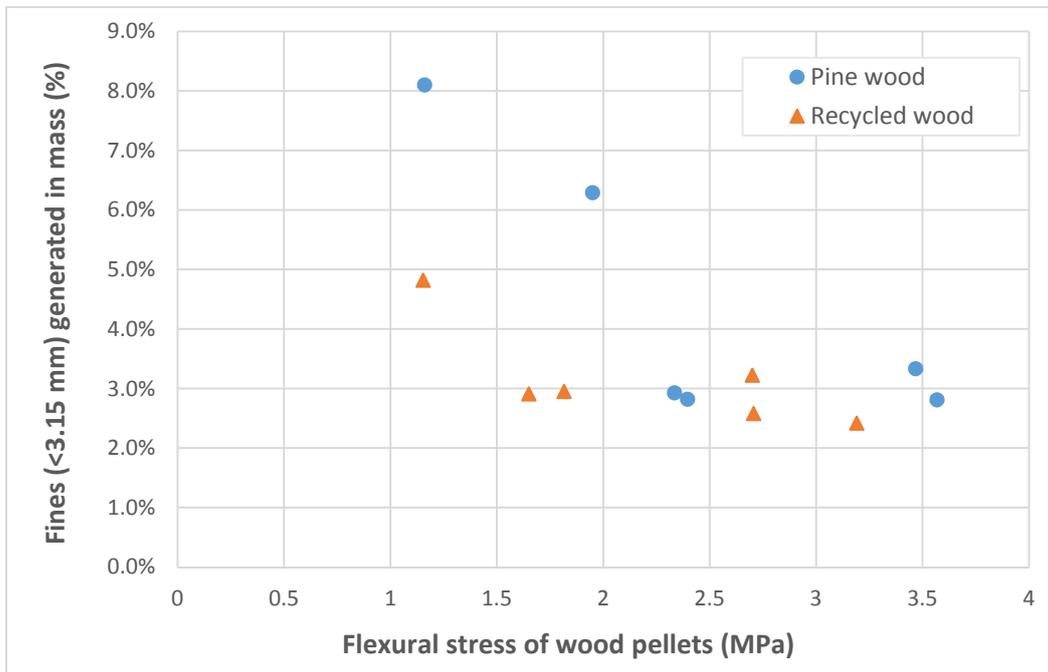
428 Figure 13: Size distributions of the dust collected by the filter in the rotary drum tester

429 5.3 Discussion on humidity influences and pellets attrition

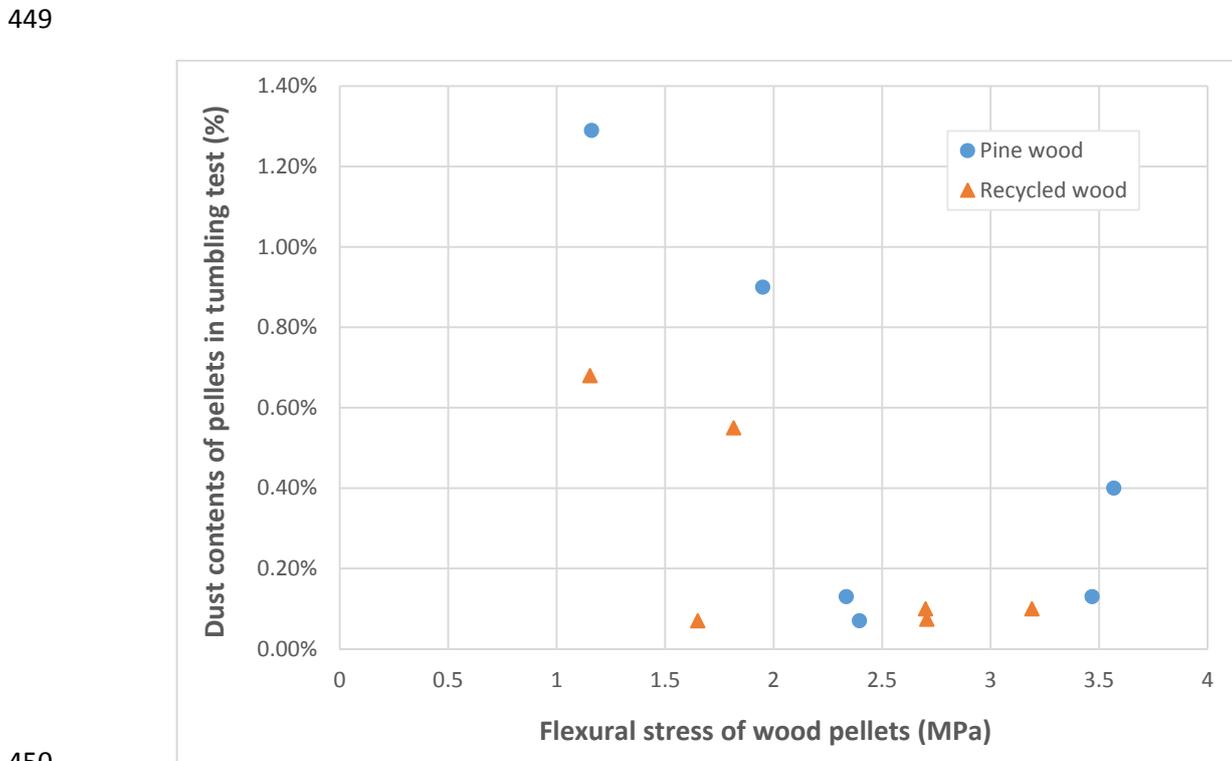
430 As discussed, attrition of wood pellets can be due to fragments of small cells and whole pellets
431 breaking down into smaller particles. Therefore the overall level of pellets degradation can be subject
432 to two major factors: the number of total pellet particles involved and pellet mechanical strength if
433 the same impact kinetic energy is applied.

434 The first factor is easy to understand, number of pellet particles. If degradation of single particles
435 breaking into smaller particles is the same, more particles will produce more fine particles for the same
436 impact energy applied. Therefore longer wood pellets broken down into more small particles would
437 reasonably be expected to increase the level of fine particles. The results in Figure 10 show that for
438 the pine wood pellets tested the percentage of longer pellets drops more than 50% at high humidity,
439 while the levels of fines have significantly increased. For the recycled wood pellets, the results also
440 show the same effect at 95% RH, with fines increase and coarse pellets decrease happening at the
441 same time.

442 For the second factor, pellet strength, this study shows some correlation between the pellet attrition
 443 and the pellet flexural stresses in Figure 14 and 15. In Figure 14, the results are for impact tests, which
 444 shows the level of fines (<3.15 mm) generated by 20 m/s impacts at 45° degrees. The results in Figure
 445 15 show the dust release from the pellets with different levels of flexural stresses.



446
 447 Figure 14: Level of fines (< 3.15 mm) generated by 20 m/s impact for the pellets with different
 448 strength

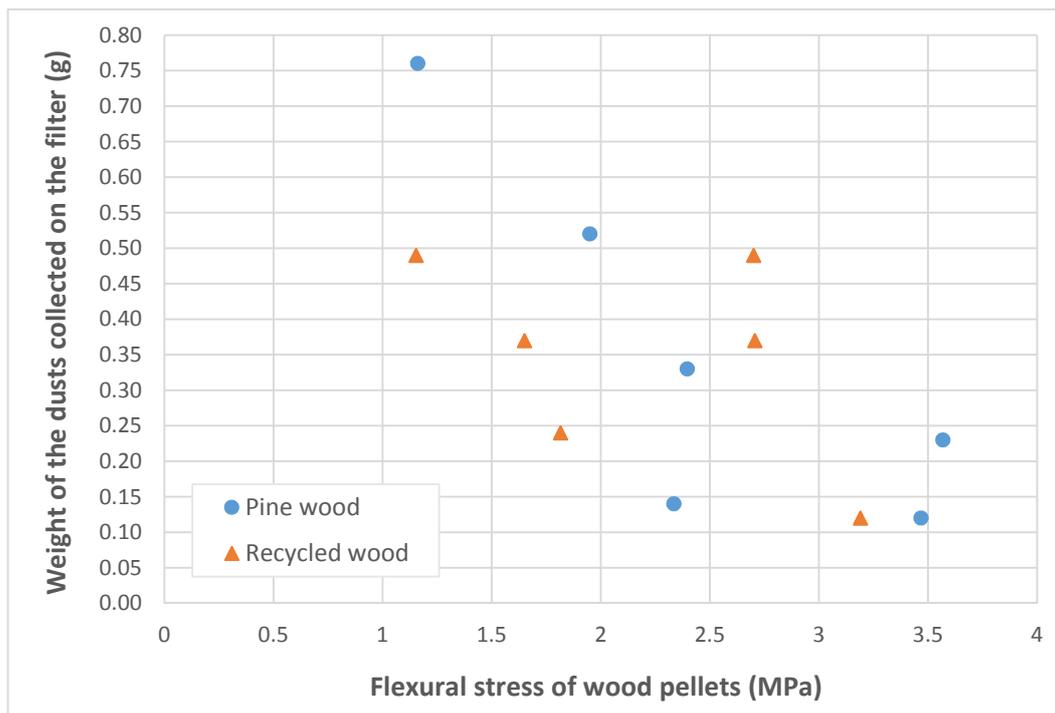


450
 451 Figure 15: Dust contents (equal to '100%-durability') of the conditioned (varied RH) wood pellets in
 452 tumbling dustiness tests with different levels of flexural stresses

453 For the results in Figure 14, it can be seen that there is a clear trend that the fines content generated
 454 by the impacts had a similar level of about 2.5% to 3.5% over most of the range of flexural strength,
 455 but started increase when the pellet flexural stress is smaller than 1.6 MPa for the recycled wood and
 456 2.4 MPa for the pine wood. The level of fines generated was doubled to between 5.0% and 8.0% for
 457 the weaker pellets. The results show that there could be a critical point or “threshold level” of pellet
 458 strength, below which weaker pellets may generate more fines. Also the results show that the level of
 459 fines generated seems to be at a fairly constant level once the pellet strength reaches or exceeds the
 460 critical level.

461 The results in Figure 15 show a similar trend for the pellet dust contents in the tumbling drum, in which
 462 the pellets again have a similar dust level (other than one result) for the pellet strength bigger than
 463 about 1.6 MPa for the recycled wood and 2.4 MPa for the pine wood. Pellet strength of 2.0 MPa could
 464 be the critical point for the both. Generally, the pine wood pellets are weaker than the recycled wood
 465 pellets, possibly due to long storage time.

466 Dust weights collected by the filter in durability tests are shown in Figure 16. The results show a broad
 467 correlation, such that the dust weight released by the weaker pellets tends to be significantly higher
 468 than the stronger pellets. The results show a clear decreasing trend of dust release from the pine wood
 469 pellets when the pellet strength increases as shown in the figure. However for the recycled wood
 470 pellets, there trend to show increased dust when the pellets are weaker, is much less clear.



471
 472 Figure 16: The weights of dusts collected by the filter for different levels of flexural stresses

473 The results in Figure 9 clearly show a tendency of the pellet flexural stress reduced with an increasing
 474 humidity level in storage. The photos in Figure 17 show the pellets that have been through humidity
 475 cycles of 20% - 95% RH (shown in Figure 17 (a)) show more cracks on the surface and less smooth
 476 compared to the origin fresh wood pellets of the recycled wood pellets (shown in Figure 17 (b)).

477 Since humidity can influence pellet physical properties such as pellet strength by absorbing water, high
 478 humidity in storage environment definitely has influence on pellet attrition behaviour in handling
 479 processes. With occasionally high humidity while pellets are in store [39], the pellets may continue to

480 lose strength in the period of a high humidity. Once in a transfer process, the pellets are more likely
481 to suffer increased attrition and dust release, for example, impact damage at belt transfer points
482 (around 3-10 m/s) or in pneumatic conveying systems (about 15–25 m/s) and abrasive damage in silos
483 during off-loading.



484 Figure 17: The samples of recycled wood pellets, (a) through humidity conditioned cycles, (b) fresh
485 For many cases, high humidity is difficult to avoid where the pellets are in storage or transportation,
486 which will result in physical property changes of the pellets and consequently generate more pellet
487 attrition in further handling processes. This study confirms that dust level can significantly increase
488 once humidity reaches a high level such as more than 80% RH. Therefore preventing any high humidity
489 levels in storage or controlling moisture contents in pellets can benefit further dust control and pellets
490 attrition in material handling processes.

491 6 Conclusions

492 For this study, it is concluded that high environmental humidity can affect the physical properties of
493 wood pellets significantly. Consequently with pellet property change such as pellet strength reduction,
494 higher pellets attrition and more dust generated are expected.

495 In this research, it is found that pellets can absorb water in a high humidity environment which causes
496 increases of moisture contents in pellets. However pellet strength does not proportionally decrease
497 with the moisture content increase. Whereas the pellets will take up and lose water right across the
498 humidity range, the results show that pellet flexural stress only starts to drop when humidity reaches
499 a certain threshold level, typically 80% RH or above.

500 Fragmentation and abrasion of pellets attrition behave similarly under the influences of environmental
501 humidity. For different types of wood pellets, the threshold level is slightly different but the tendency
502 of humidity influence once this threshold humidity has been exceeded, is broadly the same. Detailed
503 conclusions can be summarised as follows:

- 504 1. Wood pellets can absorb significant water and moisture contents may increase roughly
505 proportionally, when the environmental humidity increases. This process appears to be fully
506 reversible.
- 507 2. Bulk density and pellet flexural stress of wood pellets may reduce with a high relative humidity.
508 However with a low humidity, *i.e.* below 70% RH, the bulk density and pellet strength do not
509 have significant changes.
- 510 3. Wood pellets may break down easily once the pellets are exposed to a high humidity, *i.e.* 95%
511 RH. For a normal ambient condition between 20% RH and 60% RH, wood pellets seem stable
512 and levels of degradation are similar.
- 513 4. Two different types of pellets had slightly different sensitivities to humidity. The pine wood
514 pellets showed a higher degradation level at 80% RH in the tests, but the recycled wood pellets
515 showed at 95% RH.
- 516 5. For pellet durability, similar results have been obtained and show a decrease tendency when
517 humidity is higher than a certain level, for example 80% RH or above.
- 518 6. The top size of the dusts collected during the durability tests is about 850 μm with an average
519 particle size D50 of 65 μm .
- 520 7. The level of fines generated was doubled for the weaker pellets, from 3%-4% to 5.0%-8.0%.
521 There appears to be a critical point on pellet strength, above which, the level of fines
522 generated seems to be at a fairly constant level.
- 523 8. In regards to the above critical point concept, the pellets were found to have a similar
524 durability level for strength bigger than about 1.6 MPa for the recycled wood and 2.4 MPa for
525 the pine wood.
- 526 9. Dust weights collected show an increase when the pellet strength is reduced beyond a certain
527 point for pine wood pellets, but not for the recycled wood pellets which have a similar level.

528 Overall, significantly increased damage and dust emission arising from high humidity exposure of
529 wood pellets has been shown. The study indicates that preventing exposure to very high humidity will
530 reduce pellet degradation and dust in the pellet handling process. It is clear, however, that the
531 threshold level of humidity above which damage and dust emission will increase, is likely to be a
532 function of the individual pellet type. This is probably the most important finding in terms of improving
533 industrial practice; the authors recommend that the determination of this threshold humidity level for
534 increased damage is an essential characterisation that should be undertaken for pellets from individual
535 production streams, to allow the manufacturer and user to obtain an understanding of the importance
536 and indeed the possibility of reducing pellet damage and dust emission in their facilities.

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