

DURABILITY OF WOOD PELLETS

by

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Abstract

Durability is used for quantifying the quality of pellets by measuring the percentage of broken pellets. This work conducted durability measurement using different approaches, including Dural, Tumbler and drop test, and established relationship between them. In particular, 1) we developed a robust method that measures durability based on Dural. A series of experiments were conducted using eight different machine settings and four types of pellets. It was found that both pellet types and machine settings are statistically significant. The setting represented by 200 g sample, testing duration 15 s and rotational speed 1516 rpm was found to be the most appropriate for Dural. 2) We also conducted drop test for unveiling the effect of different factors on breakage of pellets, such as height, sample size, number of repeated drops, type of bedding and type of pellet. The relation between breakage and height was found to be linear. Harder surface had more impact on pellets. The percentage of dust increased significantly after each drop as the pellets tended to break more readily and the accumulation of fines was approximately 10% after five drops. An asymptote was observed for sample size greater than 1000 g. 3) Finally, we investigated correlations of durability measurement among Tumbler, Dural and drop test. When wood pellets were used, a strong correlation ($R^2 = 0.76$) was observed between the Tumbler-measured durability and the Dural-measured durability with a logarithmic curve. The correlation between the durability derived from the drop test versus the Dural tester was significantly stronger ($R^2 = 0.81$) than when it was compared to the Tumbler tester ($R^2 = 0.63$).

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List of Symbols

Symbols	Meanings
A	Projected area of the object (m^2)
a	Acceleration (m/s^2)
C_d	Drag coefficient
D_{ma}	Maximum deformation of a solid
dt	Interval of time over which the momentum (s)
dp	Changes in momentum ($\text{kg} \cdot \text{m/s}$)
E_1	Modulus of elasticity of body one
E_2	Modulus of elasticity of body two
F	Impact force (N)
g	Acceleration due to gravity (m/s^2)
k	Radius of the particle (pellet)
k_v	Volume breakage constant
KE	Kinetic energy
M_0	Initial mass of the size fraction (kg)
M_1	Mass of the unbroken material after the first drop (Kg)
m	Mass of the falling object (kg)
N	Number of drops
PE	Potential energy
s	Distance travelled (m)
TE	Total energy
V	Velocity (m/s)
V_t	Terminal velocity (m/s)
ρ	Density of the fluid through which the object is falling (kg/m^3)
μ_1	Poisson's ratio of body one
μ_2	Poisson's ratio of body two

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Chapter 1 Introduction

1.1 Background

In 2008, the total worldwide energy consumption derived from the combustion of fossil fuels was 4.74×10^{11} GJ or 80 to 90 percent of total fuels (Wikipedia, 2010). There are some limitations to the use and availability of fossil fuels. Sources of fossil fuels especially oil are becoming scarce and access to the limited available sources is becoming more expensive. Pollution caused by fossil fuels is high. The pollutants include greenhouse gases (CO_2 , N_2O , and CH_4), NO_x , SO_x , particulate matters and volatile organic compounds (VOCs) such as benzene.

To cope with the scarcity of conventional fuels and reduce pollution, bioenergy and biofuel are becoming more attractive to public. These types of fuels are derived from living and recently dead biological materials. Biomass can be used to produce different forms of energy. Bioethanol, biodiesel, pure plant oil, biokerosene, syngas, biogas and renewable natural gas, and solid biofuel are the most well known examples of bioenergy. Graham (2003) published a comprehensive review of agricultural waste conversion to energy. Different types of agricultural wastes, manure, mill wastes, black liquor and urban wood can be used to produce a variety of fuels. The paper illustrates that converting biomass wastes to fuels helps to control emission of greenhouse gases. Wood pellets are a type of solid biofuel made from compacted sawdust. Pellets are produced as a by-product of sawmill plants and other wood transformation activities. The current use of wood pellet is for combustion to generate heat and power (CHP, Combined Heat and Power). It can also be used as feedstock for ethanol production or

bio-oil production (Graham, 2003). Wood pellets are considered theoretically renewable energy sources because trees absorb the CO₂ generated during combustion to make new material .

Wood pellet production and consumption increased from 2003 to 2007 by 30% and 28% respectively in Canada (Table 1.1). In this table, Peng et al. (2010) show that the major buyers of Canadian pellet are in Europe and USA. For instance, the sales in Europe and USA are 450 and 765 thousand tonnes (kt) respectively in 2007. In addition, data in Table 1.2 indicates that the international demand for wood pellets is predicted to be 17 Mega tonnes (Mt) in 2010. The demand would be further increased to 55 Mt in 2015 (Peng et al., 2010).

Table 1.1 Wood Pellet Production and Consumption in Canada (kt) (Peng et al., 2010)

	2007	2006	2005	2004	2003	Rate of increase (%/yr, 2003-07)
Capacity	1600	1300	950	730	540	33.9
Production	1485	1145	935	727	533	30.0
Consumption	1415	1135	936	727	533	28.0
Domestic sales	200	135	88	87	88	27.8
USA sales	450	400	265	265	210	22.6
Overseas sales	765	600	583	375	235	31.8

Table 1.2 World wood pellet demand forecast (Mt) (Peng et al., 2010)

	2010	2015
Forecast based on 80% case A and 20% case B	17	55
Case A with linear growth based on 2001-2007 data	14	20
Case B with exponential growth based on 2001-2007 data	30	190

Wood pellet has high thermal efficiency, produces less air pollution and is cost effective. Olsson et al. (2002) sampled and assessed chimney smoke from pellet burners and specific compounds from sampled gases were assessed by gas chromatography and mass spectrometry (GC/MS). Benzene was the predominant aromatic compound found in emissions from pellet burners. The smoke also contained methoxyphenols with antioxidant properties and lower proportions of aromatic hydrocarbons. Obernberger and Thek (2004) reported the pellet production cost in Sweden and Austria to be \$78/t and \$113/t, respectively. The main reason for the cost difference was the larger plant capacity and the lower electricity price in Sweden. Availability of raw material is a major contributor to the cost of pellets produced (Mani et al., 2006). The raw material is made of i) mixture of ground sawdust and wood shavings, and ii) mixture of ground bark and stem wood. Figure 1.1 shows typical examples of raw material used for pelletization.



Figure 1.1 Typical examples of raw material used for pelletization.

1.1.1 Pellet characterization and quality

Pellets are produced with reference to certain standards. Wood pellet producers need to know the quantitative and qualitative characteristics of wood pellets in order to produce pellets with a desirable quality. Many parameters can be measured to characterize pellets. The most important ones are as follows: durability, moisture content, dimensions of pellets, bulk and particle densities, equilibrium moisture content. Also, ash content, gross and net calorific values, abrasion are measured to characterize pellets. Obernberger and Thek (2004) recommended the measurement of elements like C, H, N, Cl, K, and heavy metals such as Cd, Pb, Zn, Vr, Cu, Hg and As for elemental composition analysis.

A mix of tree parts from a variety of species, size, and moisture content is used to produce pellets. Prediction of pellets characteristics becomes challenging as biomass

properties vary depending on the source of feedstock. The variations can be in moisture content, heating value, bulk and particle density and durability of pellets. Optimization and modification of conventional methods for pellet characterization is the major task for producing pellets with desired quality.

For residential applications there are no after-use-facilities to collect particulate matters and other emissions. Pellets should have the highest grade quality. The lower quality pellets can be used in industrial applications. In industry the air quality can be controlled using appropriate equipment. Tumuluru et al. (2010) listed the quality of pellets that are exported from British Columbia to overseas and USA. The quality of pellets was compared against European and U.S. standards. According to Table 1.3, the U.S. standard classifies the quality of pellets into four grades, i.e., super premium, premium, standard and utility. The moisture content of pellets should be under 10% regardless of the grades. The durability has to be above 95% for standard and utility grades and above 96.5% for premium and super premium grades.

Table 1.3 Published Pellet Fuel Institute (PFI) grades for wood pellets for the United States (Tumuluru et al., 2010)

Specification		U.S. Grades for Residential Pellets			
S. No.	Pellet Property	Super Premium	Premium	Standard	Utility
1	Moisture content (% w.b.)	<8	<8	<10	<10
2	Length (mm)	<38	<38	<38	<38
3	Diameter (mm)	6.35-7.25	6.35-7.25	6.35-7.25	6.35-7.25
4	Bulk density (kg/m ³)	640-736	640-736	640-736	576-736
5	Durability (%)	>96.5	>96.5	>95	>95
6	Fines at mill gate (%)	<0.5	<0.5	<1.0	<1.0
7	Calorific value (MJ/kg) ⁺	<+2%	<+2%	<+2%	<+2%
8	Ash content (%)	<0.5	<1.0	<2.0	<6.0

+ The high heat value of wood is around 18.5 MJ/kg

1.1.2 Breakage in pellets

The breakage of pellets causes dust formation during handling. Figure 1.2 shows that the percentage of broken pellets (< 5.60 mm) increases from an initial value of 17.5% to 50.2% after repeated handling (eight transfers) of 22.6 tonnes of feed pellets. The average mass of dust removed in each transfer is 0.069% of the mass of pellets (Mina-Boac et al., 2006). Figure 1.3 shows the results of sieving airborne dust collected in two pellet plants (Melin, 2008). The dusts are collected from beams and ledges a few meters away from the source of the dust. Particles smaller than 420 microns (US screen 40) are considered explosive and the concentration of these particles are shown in Figure 1.3. Dark wood that may contain bark has a higher concentration of small particles of less than 63 μm than the white wood.

Fasina and Sokhansanj (1996) described a dust level of 10 percent at the time of export in alfalfa pellets. They discussed the effects that fines have on moisture adsorption rate, airflow resistance, angle of repose, and their relation to fines concentration. They further illustrated that fines exhibited a tendency to agglomerate in the presence of moisture. The agglomerate causes cake formation which may become a major problem in unloading pellets.

The released dust can also cause serious air pollution. Haddrell et al. (2005) show that inhalation exposure to particles, smaller than 10 microns, which are suspended in the troposphere is a factor in respiratory and cardiovascular diseases.

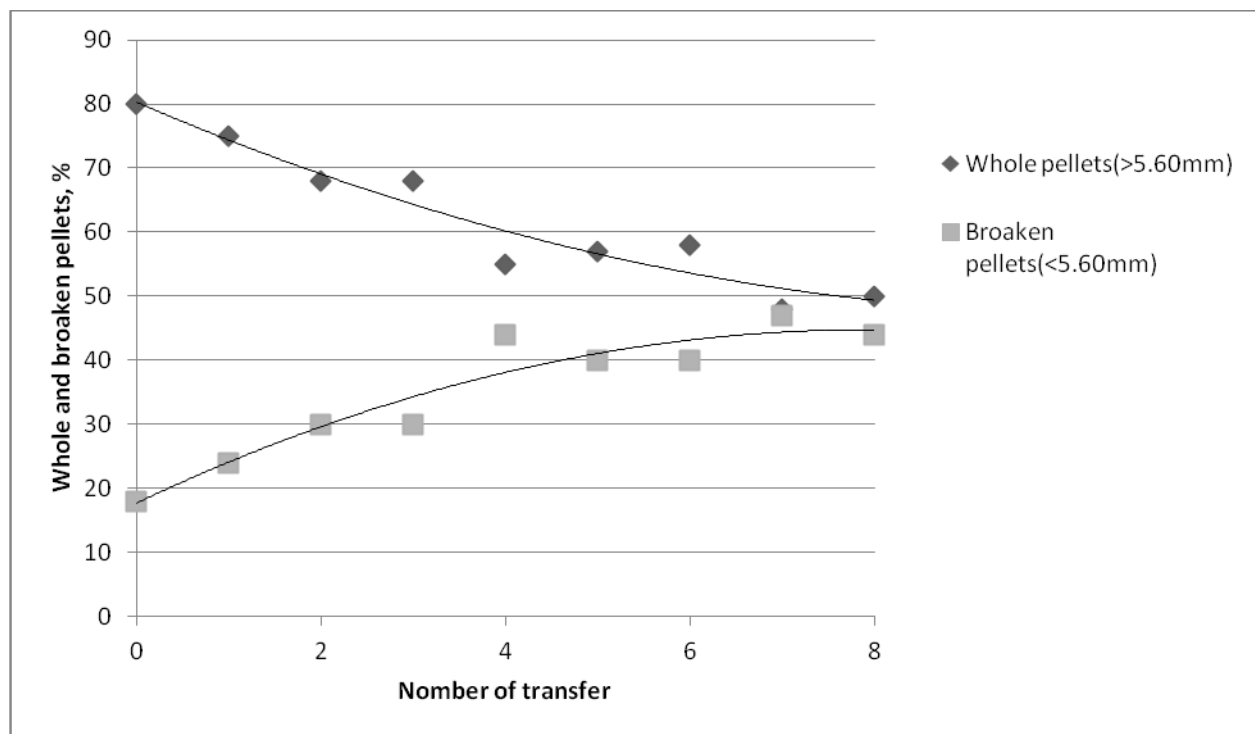


Figure 1.2 Percentage of whole and broken feed pellets from each of the eight transfers of 22.6 tonnes of feed pellets. (Mina-Boac, 2006)

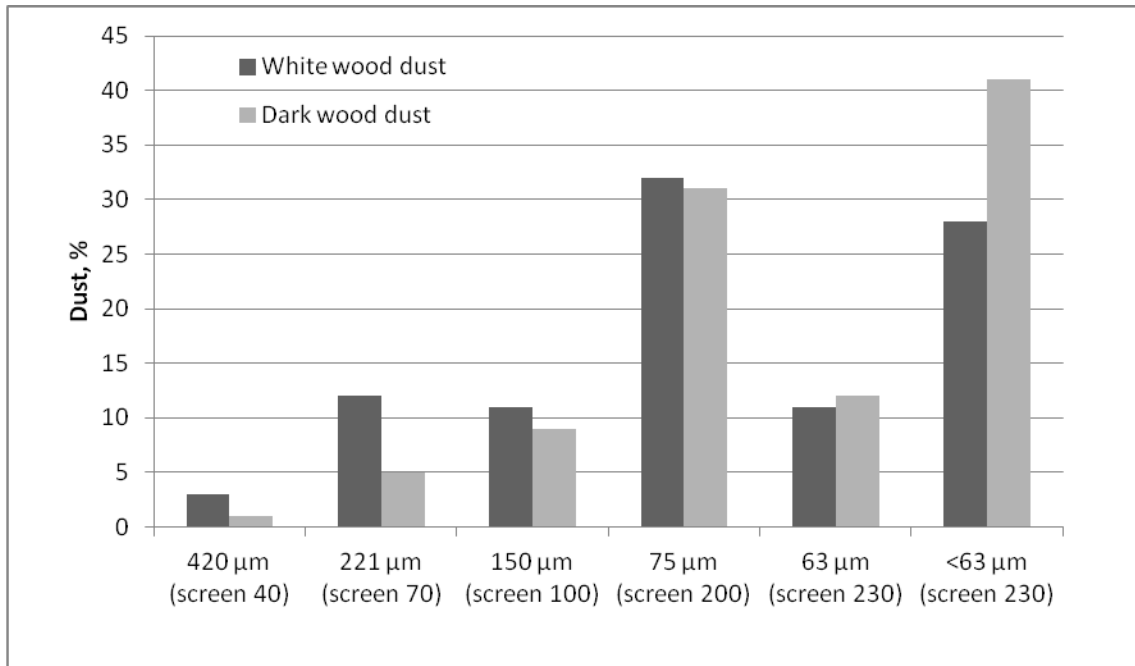


Figure 1.3 Airborne dust size distribution collected from pellet plants. (Melin, 2008)

1.1.3 Pellet durability

Several definitions for durability are available on the web. Each definition has a specific context. Durability can mean the ability to withstand wear and tear, decay, and loss of material through continual use; resistance to change from original appearance; the ability to resist weathering action or chemical attack. The closest definition of durability for wood pellet is “the resistance to change from its original appearance”. Another definition is “how well a product can resist external forces after a sustained period of use”.

Durability of pellets is an important property in the wood pellet industry and trade. A pellet with low durability may indicate the possibility of having storage and shipping difficulties as well as health and environmental issues because it tends to disintegrate easily either due to moisture adsorption or due to fall or friction. Measurement of

durability is also an indication of the likelihood that it would break. When durability is low there is higher chance of breakage in pellets.

By measuring the durability of pellets the market value of pellets can be assigned. Pellets with durability higher than 97.5% measured by a Tumbler defined by ASABE Standard S269.4 (ASABE 2006) is considered a high quality biofuel (Temmerman et al., 2006). Scientists and engineers have been conducting research covering several areas such as precisely defining durability, how to measure durability, what factors affect durability and how to improve durability. The details of definitions of durability and the factors that affect durability are given in Chapter 2.

Durability is a physical property of pellets which won't be changed regardless of measurement methods while "measured durability" of pellets varies depending on the methods used for measurement. In the rest of the paper, when we report and discuss the results from our experiments, we use "measured durability" as well as the word "durability" which means durability obtained from measurement.

A high percent breakage of pellet implies that investigation should be conducted on determining the cause of breakage, to design and operate systems that result in reduced breakage, and to make pellets more durable. Because the numerical value of durability has so much influence on the quality of pellets at various stages of its handling, it is crucial to have a robust durability measurement technique. A standard method should be established to measure durability. This measurement will help to recommend required actions to produce stronger pellets with less chance of breakage. For instance, modifications in shipping and handling can result in less pressure being

applied to the pellets. The raw material or procedure in which pellets are manufactured can also be changed.

1.1.4 Modes of pellet durability

Mechanical durability is a quality parameter that is defined as the ability of densified biofuels to remain intact when handled (Temmerman et al., 2006). Mechanical durability is measured by applying shock and/or friction to the pellet. It is an important quality parameter with regard to the loading and unloading of pellets, in which shock due to impact and friction are the dominating forces.

According to Kaliyan and Morey (2009), strength and durability are two different concepts. The strength of the densified products depends on the physical forces that bond the particles together. The effectiveness of the inter-particle bonds created during densification has been measured in terms of strength.

There are five forces that make the bonding possible: (i) solid bridges, (ii) attraction forces between solid particles, (iii) mechanical interlocking bonds, (iv) adhesion and cohesion forces, and (v) interfacial forces and capillary pressure. Feed materials such as fibre, fat, water, starch, protein, lignin and extractives can contribute to the strength of pellets. Particle size, preheating, pressure and residence time under a given force, are other important factors that can influence the strength. The strength of the bond can be determined by testing compressive resistance, impact resistance, and water resistance. These tests indicate the maximum force/stress that the densified products can withstand. On the other hand, Kaliyan and Morey (2009) indicate that

durability can be obtained by abrasion resistance measurement of the densified products. Durability was computed as the percentage of pellet mass remaining on 16-mm screen after tumbling. In their study, only two replicates were conducted for the durability measurement due to lack of samples. For each replication, five types of pellets were used. The test shows the amount of fines produced during handling, transportation, and storage.

1.1.5 Durability measurement equipment and methods

a) Tumbler

According to American Society of Agricultural Engineers Standard S269.4 (ASABE 2006) this durability test unit is made of a rectangular stainless steel container with inner dimension of 300 mm x 300 mm x 125 mm. Figure 1.4 shows the unit. One baffle is placed inside the container to enforce the tumbling effect. The rotation speed is adjusted to 50 rpm and the rotation time is 10 minutes. 500 g of sample is used. The percent of pellets remained unbroken to total sample weight is reported as durability index. The treated sample is sieved using round screen holes of 3.15 mm. This unit is used in North America and Europe. The European standard is CEN/TS 15210-1 (2005). There are some disadvantages associated with the Tumbler device which makes the machine less valuable. The disadvantages may be attributed to three factors:

- 1) Low resolution - The measured durability for low quality pellets would not be reliable or realistic. For instance, Temmerman et al. (2006) used 11 types of

pellets for durability measurement by Tumbler. The pellets had different sizes and were collected from different countries. The results showed that all the measurements fell within a very narrow range of 91-99%.

- 2) Amount of sample – The 500 g of sample materials needed for each test is a large amount. When the measurements cannot be done in the plant, this could become a constraint for the repeated Tumbler tests in laboratory.
- 3) Testing time - The 10 minutes of time required for each Tumbler test is too long. This may not be practical for industry when they need to measure durability over and over during the process. A faster method is preferred.

These characteristics provide the main motivation for investigating another type of equipment which yields more reliable and realistic test results in terms of the range of durability measurements for wood pellets.



Figure 1.4 Tumbler tester for durability measurement

b) Dural tester

Figure 1.5 is a picture of the Dural. Initially, the prototype was designed in the Agricultural Process Engineering Laboratory, University of Saskatchewan (Larsen et al., 1996). The Dural was later developed to simulate these forces (Sokhansanj and Crerar, 1999). The equipment consists of a grinder which produces and applies a consistent impact and shear to the pellets. This unit is relatively small, light and can be used on site. The amount of sample required for performing a typical test is 100 g and the testing time is reduced to 30 seconds. Hence, the running time and sample size for Dural are less than the Tumbler unit. Calculation for durability is similar to the calculation of durability with tumbler.



Figure 1.5 The picture on the left shows a Dural tester for durability measurement. The picture on the right shows the test housing and the rotating blades.

c) Ligno tester

The principle of this equipment is indicated in the Austrian Standard O' NORM M 7135 (1998) (Figure 1.6). Pellets are exposed to shocks caused by air stream that induces the particles to collide against each other and the walls of equipment. The test box has a four-sided pyramid form and air stream comes from below the box. Before the experiment, the fines have to be removed from the sample by sieving. 100 g of sample is placed in the box and air stream of 70 mbar is blown for 60 s into the Lingo tester. The produced dust is removed and the remaining pellets are weighed and durability is calculated.

Temmerman et al. (2006) showed that the Ligno tester tends to suffer a higher variability between experiments and this affects the repeatability of durability measurement. The unit is more complicated in terms of operation and structure. Air

facility needs to be available and this may cause problem in some cases particularly when it is used as in-plant equipment.

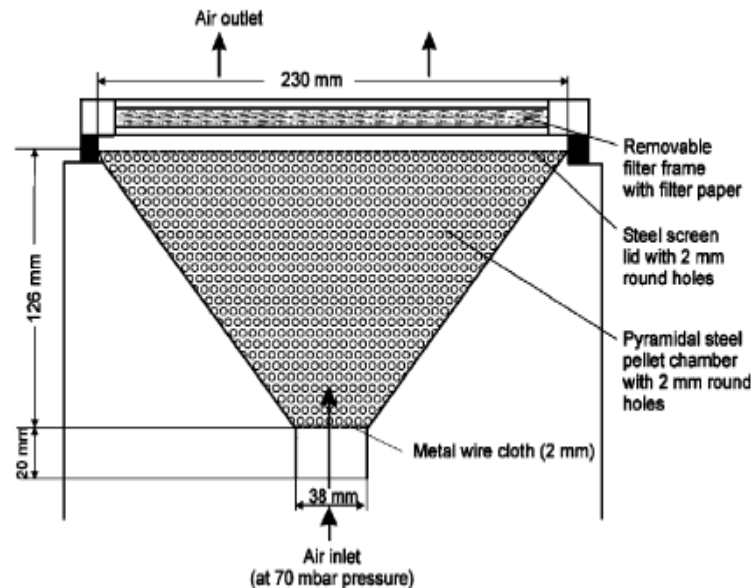


Figure 1.6 Lingo tester for measuring durability (Temmerman et al., 2006)

d) Holmen tester

The Holmen pellet tester (Figure 1.7) is a pneumatic system which simulates a more rigorous treatment of pellets. A 100-g sieved sample of pellets is introduced in a stream of air. Feed pellets are conveyed around in a closed circuit at an air velocity of about 20 m/s for a standard time (0.5 to 2 min) based on the pellet diameter. The air and pellets are circulated through right-angled bends, impinging repeatedly on hard surfaces. Pellet attrition will then happen. After treatment, the samples are sieved again with a sieve having an opening of about 80% of the pellet diameter. The Holmen tester was used for measuring pellet durability and described by Payne et al. (1994) as well as Thomas and van der Poel (1996). Thomas and van der Poel (1986) made a comparison between the Holmen tester and the Tumbler tester for animal feed pellets, and concluded that the

Holmen tester gave results in a wider range and in a shorter time span (for instance, 60-95% durability with a testing time up to 5 min) than the Tumbler tester (for instance, 91-98% durability with testing time up to 20 min). Similar to the Ligno tester, the Holmen tester also suffers from very strict requirement for air supply, which is not practical for in-plant applications.

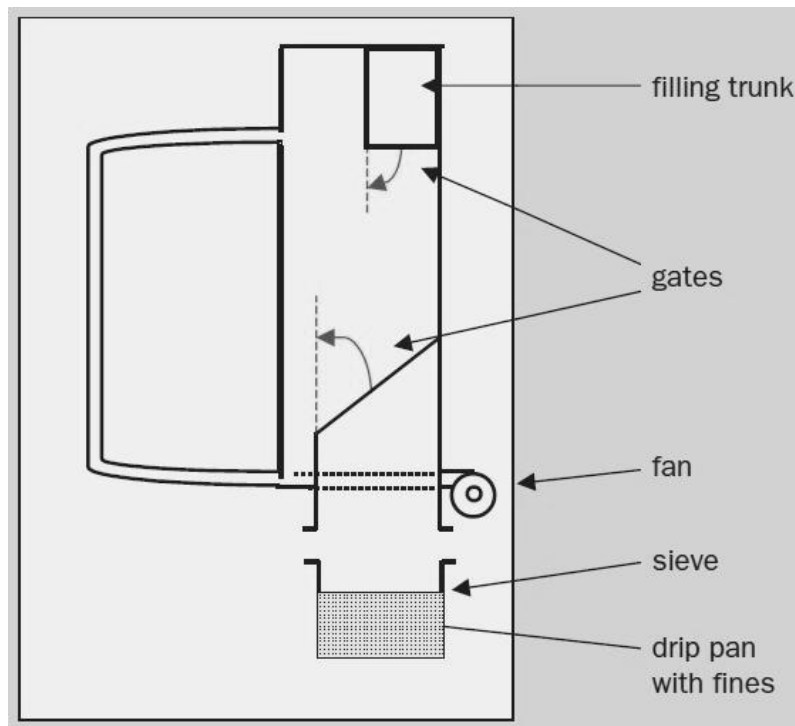


Figure 1.7 Holmen pellet tester (Borregaard Lignotech, Hull, UK)

e) Drop test

Drop test is used to test the durability of bulk materials, including coal, ore, and pellets. Sahoo and Roach (2005a) showed that the strength of coal can be determined by shatter tests. A five-meter drop tower was used to facilitate dropping the coal onto different surfaces (Figure 1.8). The different impact surfaces are steel plate, conveyor

belt and coal stockpile. The coal was contained in a hopper with a release at the bottom that allowed the coal to be dropped from various heights. The size of the coal used in the test was 20-30 mm. They used the term “strength index” to describe the empirical measurement. Sahoo and Roach (2005b) performed a new drop test procedure to measure the strength of the coal. The procedure was based on repeated drops. They found that: 1) fines generated from the coal in handlings were due to larger vertical drops; 2) disintegration of coal increased proportional to increased drop velocity; 3) replacing larger sample size with smaller sample size can reduce the fines produced; and 4) replacing larger drop heights with smaller drop heights can also reduce the fines generated.

The drop test is meant to measure the amount of dust in a situation close to reality. Pellets are dropped freely from a certain height. The dust produced from the drop is removed and remaining unbroken pellets is weighed to determine the percentage of breakage. The sample can be dropped as a single pellet or a number of pellets all together. Another possibility of dropping pellets is to put them in a physical package.

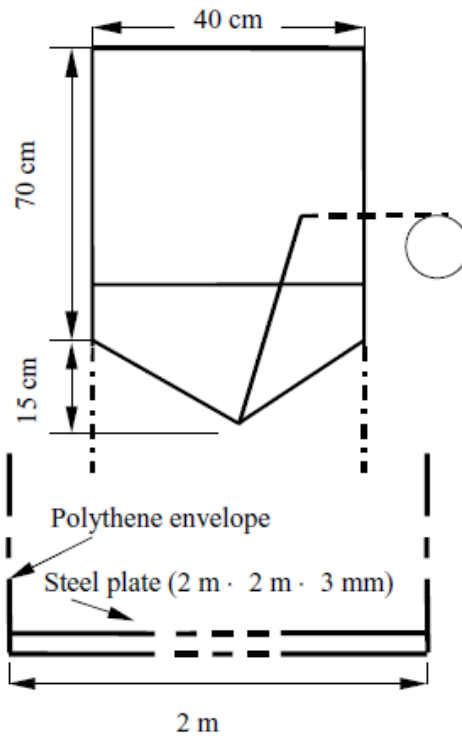


Figure 1.8 Line diagram of drop tower for measuring durability of coal.

1.2 Thesis objectives

Review of literature indicates that durability measurement for wood pellets is not yet well developed. There is no single equipment or method that can measure the durability of pellets in a repeatable manner.

The specific objectives of this thesis research are as follows:

- 1) To assess the applicability of the Dural tester for durability measurements and recommend a procedure for wood pellets;
- 2) To design and perform the drop test and determine the effect of height, sample size, number of repeated drops, and type of pellet on the breakage of pellets; and

3) To develop correlations between durability measurements as derived from Tumbler tester, Dural tester and the drop test.

1.3 Organization of the thesis

This thesis is divided into six chapters. Chapter 1 discusses the importance of wood pellets as bio fuel, durability of pellets, and a review of equipment and procedures to measure the durability. Chapter 1 also outlines the objectives of the thesis. Chapter 2 describes the durability measurement using Dural tester in detail. The theories behind the drop test are discussed in Chapter 3. The methodology and results relevant to the drop test are explained and discussed in Chapter 4. Analysis of the correlations between the measurements derived from Dural tester, Tumbler tester and the Drop Test is presented in Chapter 5. Chapter 6 lists the conclusions, and provides recommendations for future work.

Chapter 2 Durability Measurement

2.1 Introduction

Wood pellets are made by pressing finely ground biomass into dense cylindrical pieces. The bulk density of pellets at 0.75 g/cm^3 is almost ten times higher than the raw loose bulk ground biomass (Swaan and Melin, 2008). Handling of pellets is easier, cheaper, and safer than handling of loose biomass. Wood pellets are more uniform in moisture content and chemical composition than unprocessed biomass. Wood pellets tend to disintegrate during handlings and storage. Wood pellet production is a well established and rapidly expanding industry worldwide. In the United States and Canada the annual production is nearing 4 million metric tonnes (Tumuluru et al., 2010). Wood pellets are used for residential heating, district heating, electrical power production and animal bedding (Melin, 2005).

The breakage of pellets occurs immediately after the pellets come out of the presses during the cooling, screening, and storage. Such pellet breakage will generate dust by abrasion. Dust is a potential health and environmental hazard (Billate et al., 2002). Loading of pellets into rail cars or trucks, transport and transfer to large silos and ocean vessels exacerbate the problem. Harsh handling occurs particularly during loading at high rate ($\sim 500 \text{ t/h}$) into the holds of ocean vessels. The drop height is more than 21 m, as observed during loading and unloading pellets at Fiberco Inc., North Vancouver, BC. Pellets also lose their integrity when exposed to humid and warm temperatures during handling and storage (Fasina and Sokhansanj 1996).

Durability is one of the most important physical characteristic of pellets. Zaini et al. (2009) suggests that the physical damage during transshipment is highly correlated with the durability of pellets. Durability of wood pellets is affected by several factors. The main factors are wood species, particle size, moisture content, lignin content, preconditioning of raw materials, densification equipments used in pelletizing (Smith, 2004). Breakage of brittle particles is a complicated process (Tavares and King, 1998). Pellets made from fine particles are more durable than pellets made from larger particles because fine particles provide a larger surface area for bonding (Dutta 2007).

The maximum durability of 96.7% can be reached when moisture content is at the level of 8.62% (Colley et al., 2006). Lignin is one of the components contributing to the flexibility of wood (Gindl et al., 2002). Dos Santos Abreu et al. (1999) studied how lignin affects fiber elasticity. They found that decreasing fiber elasticity is associated with decreasing lignin content and reduction in elasticity might cause weakness in pellets. The degree of densification of biomass affects durability by a number of ways, including external load, wedging forces and bonding agent (Mani et al., 2003). Post-production conditions such as cooling and storage are factors to consider.

Accurate measurement of durability is important. This measurement is an indicator of the susceptibility of pellets to subsequent handlings and storage. Durability measurement is essential for quality control of pellets in the manufacturing process. Predicting pellet durability has become a challenge as biomass properties vary depending on the source of feedstock.

Three different methods are used to test particle breakage (Krogh, 1980): (i) slow compression, (ii) impact crushing and (iii) abrasion. Several devices are available for

durability measurement. Each type of device applies at least one of the above mechanisms for achieving the breakage. The tumbling device is commonly used in North America and Europe for durability measurement of feed pellets. It follows the ASAE Standard S269.4 (ASABE 2006). The Ligno tester, a pneumatic device, is another device that follows the Austrian Standard ÖNORM M 7135. By using a Tumbler or Ligno tester to measure durability of wood pellets with different mechanical strengths, results could fall within a narrow range.

Temmerman et al. (2006) showed that the durability measurements using tumbler for two series of tests that involved 11 samples each are within the range of 94% to 99%. This narrow span between the lowest and highest values of durability constitutes the main disadvantage of the Tumbler. In particular, it will affect the accuracy of durability for lower quality pellets. Another disadvantage of the tumbling device is the requirement of 500 g sample and a rotation time of 10 minutes.

With the Ligno tester and the Holmen tester, air supply has to be provided by an external source. This may not be feasible for tests to be performed at the production plants. It is therefore desirable to investigate the feasibility of using an alternate device for measuring durability.

Dural tester (Figure 2.1) was originally developed at the University of Saskatchewan (Larsen et al. 1996). The design of the unit is similar to a household grinder but much sturdier to handle feed pellets. The unit consists of a rotating impeller in a canister. The impeller in the canister has four blades. The dimensions of the canister are as follows: tip-to-tip diameter 16.5 cm, inside diameter 15.3 cm, outer height 20.7 cm, and depth 14.5 cm. The impeller is driven directly by a variable speed

motor mounted under the removable canister. The recommended operation of the tester is 100 g sample subject to grinding for 30 s at 1615 rpm. The treated sample is sieved using round screen holes of 3.15 mm or wire mesh screen 3.2 mm diagonal. The sieved material is weighed and durability is determined by dividing the mass of material left on the screen divided by the mass of original material.

Adapa et al. (2007) used Dural with rotational speed 900 rpm and testing duration 30 s for alfalfa cubes. Mani et al. (2006) used the machine for compacted corn stover cubes. Their results showed that changing any of machine operating parameters will affect the numerical value for durability. Durability increased with increasing amount of sample, and decreased with increasing rotation speed and duration of test.

Sokhansanj and Crerar (1999) recommended the operational settings for durability measurement of feed pellet - mass of 100 g, rotational speed 1615 rpm and testing duration 30 s. This setting will result in a 70% durability measurement for alfalfa pellets, which indicates 30% breakage of alfalfa pellets during shipment and handling. As the Dural tester is adapted to measure durability of wood pellets in this thesis research, initially the aforementioned settings will be used as the reference setting in the experimental protocol.



Figure 2.1 The picture on the left shows a Dural tester for durability measurement. The picture on the right shows the test housing and the rotating blades.

2.1.1 Objective

The objective of this research is to evaluate the effect of operating settings of the Dural tester on the durability measurements of wood pellets.

2.2 Materials and methods

Two series of experiments were carried out to test the performance of the Dural device in measuring the durability of wood pellets. For series one, tests were conducted to examine four factors: sample mass, run time, size of pellets and blade speed. For a

test, one factor is varied while other three were fixed. For second series, a factorial design of experiments were used for which mass, time and speed along with four types of pellets were tested. The outcome of the first experiment was used to select the parameters for the factorial design in the second experiment.

For all of the tests fines and particles were removed from the sample batch using a 3.15 mm wire mesh screen (Figure 2.2). The sieved clean lot was divided into 4 batches using a Hoffman R89P Riffle divider (Hoffman MFG, Jefferson, OR) (Figure 2.3). After each test, the contents of the container were dumped over the 3.15 mm sieve and shaken for 2 min by hand. The mass remaining on the sieve was weighed on a balance to 0.01 g precision. The following equation was used to calculate the durability of pellets (CEN/TS 15210-1, 2005):

$$D = 100 \cdot \frac{M_f}{M_i} \quad (1)$$

where D is durability (%), M_f is the mass (g) remaining on the sieve and M_i is the initial mass (g).



Figure 2.2 A 3.15 mm wire mesh screen used for removing fines and particles from pellets.



Figure 2.3 Hoffman R89P Riffle divider (Hoffman MFG, Jefferson, OR) used for randomly dividing a batch of pellets into two sub samples.

2.3 Test series I

2.3.1 Sample mass

Two types of pellets were collected from Princeton Co-generation Corp. One of the lots was white pellets (Figure 2.4) produced from pure sawdust (mostly pine). The other lot was brown pellets that contained up to 20% bark. Both samples had a moisture content of about 6% at the time of test. The moisture content of pellets was determined using a forced convection oven set at 103°C for 24 h (ASAE Standard S269.4, ASABE 2006). The dimensions of 160 pellets randomly selected from the clean lot were measured for both brown and white pellets. Table 2.1 lists the diameter, length, mass and density of the pellets.

Table 2.1 Physical specifications of white and brown pellets (replicates, n=160)

Pellet type	Statistics	Diameter (mm)	Length (mm)	Mass (g)	Density (g/cm ³)
White Pellets	Mean	7.24	15.1	0.69	1.11
	Standard deviation,	0.2	3.9	0.2	0.14
	CV, %	2.5	25.8	29.1	12.7
Brown pellets	Mean	6.9	14.9	0.77	1.15
	Standard deviation	0.19	3.90	0.21	0.16
	CV, %	2.7	26.2	26.1	12.9



Figure 2.4 White pellets used in the exploratory experiment.

2.3.2 Procedure

Pellets were divided into 50, 100, 150, and 200 g lots. The controller for the Dural was set at a speed of 1650 rpm and testing time of 30 s. The durability tests on brown and white pellets were repeated 20 times. The test with white pellets showed lower coefficient of variation, which indicates small experimental errors (Table 2.4 in the result section). It was decided to conduct the four tests in the first experiment using white pellets.

For examining the effect of mass, the number of batches charged to the Dural device was 18, starting from 30 g and increasing to 200 g in increments of 10 g. Each batch was replicated 3 times for a total of 54 tests. The purpose was to find the trend of the measured durability versus sample mass. The Dural machine was set at a speed of 1650 rpm and the duration of 30 s.

In order to determine how the size of pellets affects the Dural performance, three categories of sizes were used: larger than 15mm, between 5 mm and 15 mm and the

original batch that consisted of all sizes. The original sample batch was composed of about 15% of pellets larger than 15 mm, 10% smaller than 5 mm and the rest was in between. A side-by-side test was conducted to measure the durability using pellets larger than 6.7 mm. These pellets were separated with a 6.7 mm mesh sieve. For each run, the sample mass, the speed and the testing time were set at 100 g, 1650 rpm and 30 s, respectively.

Two baled speeds were tested: 1650 rpm and 1740 rpm. These two settings were the only options provided by the Dural machine. The sample mass and the time were fixed at 100 g and 30 s, respectively.

Tests were conducted for run times ranging from 5 s to 60 s, in increments of 5 s. The speed and the sample mass were kept at 1650 rpm and 100 g, respectively. The original sample batch was also employed in this test. All the above settings are summarized in Table 2.2.

Table 2.2 Summary of procedures for the first experiment

Factors	Range of values	No. of replicates	Dural setting		
			Testing time (s)	Speed (rpm)	Mass (g)
Sample mass (g)	30 – 200 increment: 10	3	30	1650	-
Testing time (s)	5 – 60 Increment: 5	10	-	1650	100
Speed (rpm)	1650 and 1740	20	30	-	100
Size of pellets (mm)	> 15, 5 – 15, mixture of all sizes, > 6.7	20	30	1650	100

2.4 Test series II

2.4.1 Sample mass

Six types of pellets were examined for durability measurement. The purpose of this experiment was to obtain samples from low to high durability. Four different types of pellets out of the six candidates were selected. These four pellets were wood (pine) pellets for animal bedding (PAB); alfalfa pellets for animal feed (AAF); recycled paper for animal bedding (RPAB); and wood pellets of unknown wood species for animal bedding (Eagle Valley Animal Bedding ABEV). These pellets were procured from a farm supplies store in Surrey BC.

2.4.2 Method

A full factorial design of experiment consisting of 3 factors was planned. Two factors were the rotational speed of the impeller (1615 and 1673 rpm) and the testing time (15 and 45 s). The third factor was the mass of pellets charged into the Dural container (50 g and 200 g). Table 2.3 lists the test setup combinations. The tests were performed for each type of pellets. Each set of tests was replicated 10 times.

Table 2.3 Factorial design for the four selected types of pellets (n=10)

Test No. (machine setting)	Mass (g)	Rotational speed (rpm)	Test duration (s)
1	50	1615	15
2	50	1615	45
3	50	1743	15
4	50	1743	45
5	200	1615	15
6	200	1615	45
7	200	1743	15
8	200	1743	45

2.5 Results

2.5.1 Test series I

Table 2.4 lists the results of the exploratory test on brown and white pellets, with sample mass of 50, 100, 150 and 200 g. The measured durability depended on the mass of pellets charged into the container. For brown pellets, durability was $58.3 \pm 1.9\%$ for the mass of 50 g. Durability increased to $66.1 \pm 1.6\%$ for the mass of 200 g. The range of

durability values decreased as the mass of a sample increased. Table 2.4 also shows that brown pellets exhibited a lower durability (average 58.3-66.1%) when compared to the durability for white pellets (average 62.8% to 69%). Coefficients of variations (CV) were higher at lower mass. CVs associated with white pellets were lower than those for the brown pellets, except for the sample mass of 50 g.

Figure 2.5 shows the durability of white pellets versus the mass of pellets charged into the container. The sample mass increased from 30 g to 200 g in increments of 10 g. Durability value increased from about 57% when sample mass was 30 g reaching an asymptote value of about 70%. It is also observed that the variance becomes smaller as the mass increased. For mass above 150 g, the variance was consistently small.

Table 2.5 shows the result of durability measurement with different ranges of pellets sizes with 20 replicates. The group with longest pellets, greater than 15 mm, shows the highest average durability of 67.3%. The lowest average durability 63.1% can be seen from the group of shortest pellets, from 5 to 15 mm.

Table 2.6 shows the effect of the rotational speed on durability measurement with 20 replicates. For 1650 rpm and 1740 rpm, the average durabilities were 65.8% and 66.0% and the standard deviations were 1.01 and 0.81 respectively, suggesting that the effect of rotational speed on durability value was negligible.

The plot of durability vs. testing time exhibits a linear relationship for the duration tested. The coefficient of variations at each time level was small, ranging from 0.2% to 2.3%, but it increased with testing time.

Table 2.4 Summary of durability measured using Dural tester – exploratory tests (n=20)

Pellet type	Statistics	Mass 50 g	Mass 100 g	Mass 150 g	Mass 200 g
Brown pellets	Mean, %	58.3	60.2	63.7	66.1
	Standard deviation, %	1.9	1.0	1.2	1.6
	Minimum, %	54.6	57.6	62.0	62.9
	Maximum, %	62.9	61.8	65.7	68.9
	CV, %	3.3	1.7	1.9	2.4
White pellets	Mean, %	62.8	65.6	66.8	69.0
	Standard deviation, %	2.4	1.0	0.8	0.9
	Minimum, %	59.7	63.5	65.5	67.1
	Maximum, %	68.3	68.0	68.5	70.3
	CV, %	3.8	1.6	1.3	1.3

Table 2.5 Effect of size (length) of pellets on durability measurement (n=20)

Statistics	Size > 15 mm	5 < Size < 15 mm	Size > 6.7 mm	original size (mix of sizes)
Mean, %	67.3	63.1	66.9	65.9
Standard deviation, %	1.43	1.66	1.57	1.01
CV, %	2.13	2.63	2.34	1.54
Minimum, %	64.2	60.9	63.5	63.8
Maximum, %	70.1	66.9	69.7	68.2

Table 2.6 Effect of rotational speed on durability measurement of pellets (n=20)

Statistics	Speed 1650 rpm	Speed 1740 rpm
Mean, %	65.8	66.0
Standard deviation, %	1.01	0.81
CV, %	0.02	0.01
Minimum, %	63.8	64.6
Maximum, %	68.2	67.2

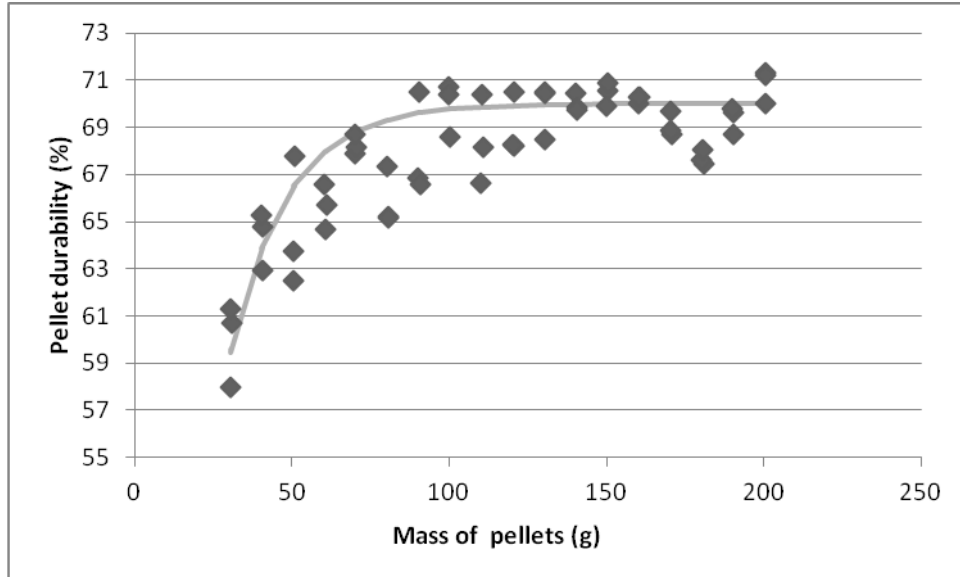


Figure 2.5 Durability measurements using sample mass of 30 to 200 g with 10 g increments (n = 3).

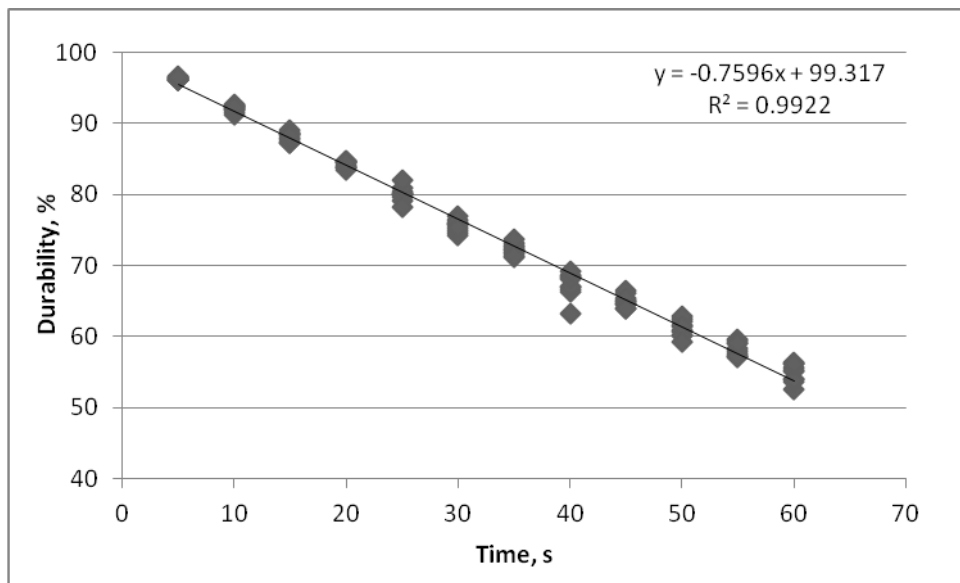


Figure 2.6 Durability measurement at different time settings in Dural (n = 10).

2.5.2 Test series II

Table 2.7 lists the performance of durability measurement for the six types of pellets. Ten replicated tests were conducted. The purpose of this screening test was to observe the sensitivity of the Dural to pellet type in terms of durability. Type AAF had the highest mean durability of 89.2% while type ABEV returned the lowest durability of 30.3%. The durability of types PAB and RPAB were found to lie between the minimum and the maximum durability measured. Type DF had a large coefficient of variation of 7.24%, while having an average durability similar to type ABEV. The durability of type WF was close to that of type RPAB.

Table 2.8 displays the data obtained from the subsequent factorial experiment on the four selected types of pellets PAB, RPAB, AAF, and ABEV. Alfalfa pellets AAF had the highest measured values of durability (77.1% to 94.9%). Type ABEV (unknown species of wood) had the lowest durability (11.3% to 58.2%). As expected, the machine setting and sample mass had marked effect on the durability value. The standard deviations for all measurements were small, at 2% durability or less. This implies that for a specific machine setting and sample mass, the measured durability value would tend to be consistent, which is a desirable characteristic for a durability measurement device.

The standard deviation of measured durability for sample mass of 200 g was consistently less than that for a sample mass of 50 g. Variability due to rotational speed of machine was not significant. For all four types of pellets, setting #5 (lower testing duration, higher mass and lower rotational speed) gave the highest and most consistent values of durability. The lowest durability was observed for setting #4. Machine setting

#3 was found to produce relatively unstable values of durability. In setting #3, the ABEV and RPAB pellets had high standard deviations of 3.3% and 4.0%, respectively.

Table 2.7 Durability measurement for the initial six candidate types of pellets in the screening test (n=10)

Durability (%)	DF	WF	PAB	RPAB	AAF	ABEV
Mean	30.3	57.1	73.0	52.2	89.2	28.8
STD	2.20	1.95	1.38	2.40	0.68	1.11
CV	7.24	3.42	1.89	4.59	0.76	3.86
Min	27.6	53.9	71.2	46.0	88.2	27.3
Max	33.4	59.9	75.2	54.4	90.5	30.7

DF = Dark - Fiberco Inc.

WF = White - Fiberco Inc.

PAB = Pine pellets for animal bedding

RPAB = Papers made from recycled paper for animal bedding

AAF = Alfalfa pellets for animal feed

ABEV = Wood pellets (unknown species of wood) for animal bedding

Table 2.8 Durability of four types of pellets selected for the factorial design(n=10)

Test No.	Mass (g)	Speed (rpm)	Time (s)	PAB	RPAB	AAF	ABEV
1	50	1615	15	86.0	76.3	93.5	49.3
				1.0	2.3	0.8	2.3
2	50	1615	45	59.3	29.7	83.7	16.5
				2.2	2.0	1.4	1.6
3	50	1743	15	82.4	69.1	92.7	44.2
				1.1	4.0	0.5	3.3
4	50	1743	45	49.6	19.5	78.6	11.3
				2.0	1.3	1.9	1.4
5	200	1615	15	89.7	80.6	94.9	58.2
				0.4	0.9	0.4	0.9
6	200	1615	45	67.3	46.5	83.4	35.3
				1.4	1.0	1.8	0.7
7	200	1743	15	85.7	74.5	92.6	53.2
				0.5	1.0	0.4	0.8
8	200	1743	45	57.5	36.5	77.1	28.6
				0.6	0.9	0.8	1.3
PAB = Pine pellets for animal bedding							
RPAB = Papers made from recycled paper for animal bedding							
AAF = Alfalfa pellets for animal feed							
ABEV = Wood pellets (unknown species of wood) for animal bedding							
The second row in each set of test shows the standard deviations							

2.6 Discussion

2.6.1 First experiment

Brown pellets are derived from raw materials with more bark in them, and they are supposed to show lower durability relative to white pellets. Data shown in Table 2.4 confirms this expectation. The durability of white pellets is higher than that of brown pellets by 4.2% on average for sample mass 50 to 200 g. In addition, white pellets provide lower CV than brown pellets. For example, for a mass of 200 g, the difference in

CV between white and brown pellets is 1.1%. These are the reasons for choosing white pellets for the rest of the experiment.

For the effect of sample mass on durability, the following equation was fitted to the data in Figure 2.5,

$$D = 70[1 - 0.8 \exp(-0.055M)] \quad (R^2 = 0.68) \quad (2)$$

where D is durability (%) and M is sample mass (g); the constant value 70 is the asymptote value; the constants 0.8 and 0.055 were estimated by an curve fit while minimizing the sum of the squared differences between predicted and experimental values. Equation (2) indicates that at a mass of 50 g sample size, the measured durability value is 95% of the asymptote value of 70. When the sample mass is increased to 75 g and 100 g, durability would increase to about 98% and 99% of the final value, respectively. This trend of results suggests that 100 g sample mass would be adequate for measuring the durability of wood pellets using the Dural tester.

From Table 2.5, higher durability can be observed from pellets of large sizes, but the mix of pellets with all the sizes (original sample batch) shows the smallest coefficient of variations. The CV for the pellets above 15 mm is 2.13% as opposed to 1.54% for the original sample batch. For the purpose of durability measurement, lower CV is preferred since it provides more consistent results. Therefore, we concluded that the recommended sample batch of 100 g is more suitable to be used in Dural tester, and we used that for our experiment.

Table 2.6 lists the average durabilities as 65.8% and 66.0% for 1650 rpm and 1740 rpm respectively. This indicates that changing from 1650 to 1740 rpm does not affect the durability measurement much. The same conclusion can also be drawn from

the standard deviations (1.01% vs. 0.81%). A wider range of rotational speed is necessary to provide a thorough examination of the effect that rotational speed has on measured durability.

In Figure 2.6, the linear relationship between the testing time (duration) and the durability measurement may be represented by:

$$D = -0.7596t + 99.317 \quad (R^2 = 0.99) \quad (3)$$

where t is the testing duration (s) and D is the durability of pellets (%). It is not practical to conduct the test with a testing duration that is either too short or too long. If the time is too short, the high durability pellets are not likely to be broken. As for a long period of time, the low durability pellets will disintegrate readily and no measurements can be obtained from the test.

2.6.2 Test series II

Table 2.9 lists the results of analysis of variance (ANOVA). Both main factors involved in the experimental design – the type of pellets and machine setting were significant. Durability differs significantly among eight machine settings four types of pellets ($p < 0.0001$). The effect due to interaction between pellet type and machine setting is also significant ($p < 0.0001$), meaning that the eight machine settings affect the durability differently among the four types of pellets.

Table 2.10 shows the effects that speed, duration, and sample mass and their interactions have on durability. Test duration has the greatest effect on the measured durability, decreasing from 76.4% to 48.8% as the testing duration increased from 15 s to 45 s. The smallest change in the measured durability is due to speed, with a difference of about 6% of durability. Since mass and testing time have the most

significant influence on durability, their joint effect is analyzed. The combination of 200 g and 15 s indicates the best performance with the highest durability and the lowest standard deviation, being 78.7% and 14.8%, respectively.

Figures 2.7 to 2.10 demonstrate the mean durability over four types of pellets with 95% confidence interval for the three factors. The area of overlapping of the error bars would indicate the relative significance of the factors – mass, testing time and rotational speed. From the plots, such overlapping area is about 1% for the sample mass and it is smaller than the 3% for the speed. Hence, sample mass affects measured durability more significantly than rotational speed. The lack of overlapping between the error bars at 15 s and 45 s further confirms that testing time has the greatest influence on measured durability. The joint effect of mass and time on durability is visualized in Figure 2.10. Again, it confirms that highest durability and lowest standard deviation can be achieved with greater mass and shorter testing duration.

Table 2.9 ANOVA results for durability measurements of four types of pellets with eight machine settings

Source	Degree of Freedom	Sum of Squares	Mean Square	F- value	P-value
Setting	7	69566	9938	17.917	1.547e-07
Type	3	113052	37684	15341.58	2.2e-16
SettingxType	21	11648	555	225.81	2.2e-16
Error	288	707	2		
Total	319	194973			

Table 2.10 The effect of the three factors and their interactions on the durability

Parameters	Mass (g)		Speed (rpm)		Time (s)		Mass and testing time (g, s)			
	50	200	1615	1740	15	45	50, 15	50, 45	200, 15	200, 45
Number of samples	160	160	160	160	160	160	80	80	80	80
Mean durability, %	58.9	66.3	65.6	59.6	76.4	48.8	74.2	43.5	78.7	54.0
Standard deviation, %	27.4	21.1	23.8	25.3	16.5	23.9	17.8	26.8	14.8	19.3

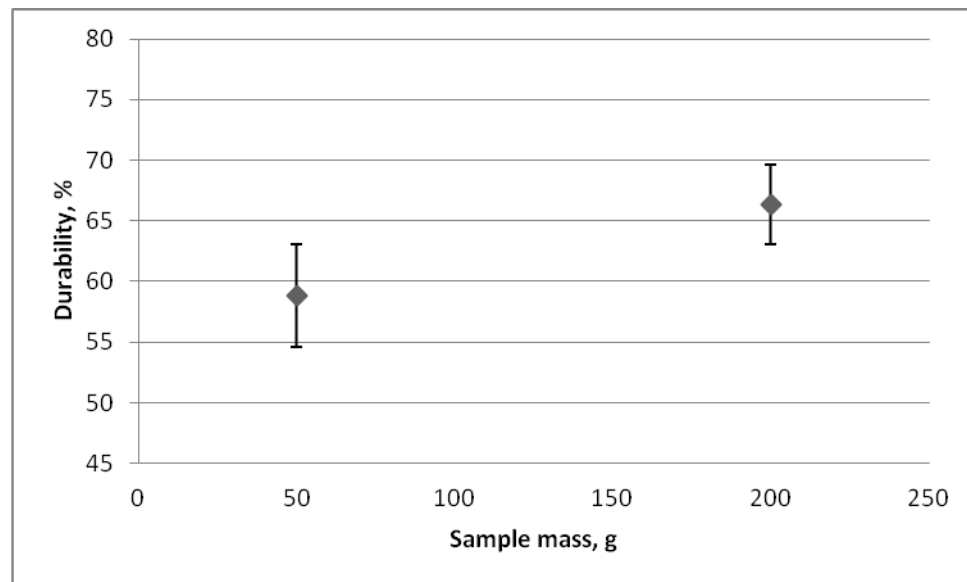


Figure 2.7 Relationship between measured durability and sample mass of pellets

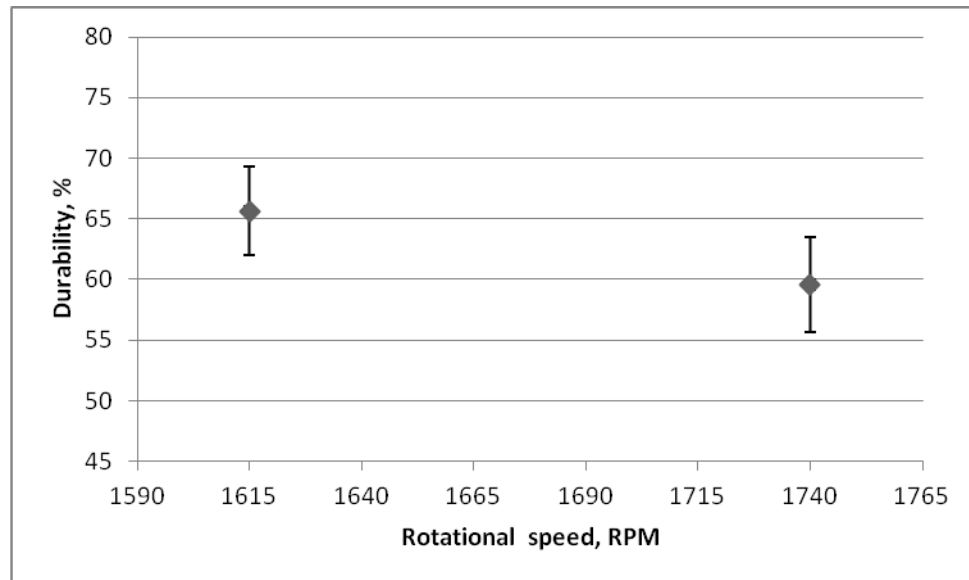


Figure 2.8 Relationship between measured durability of pellets and rotational speed

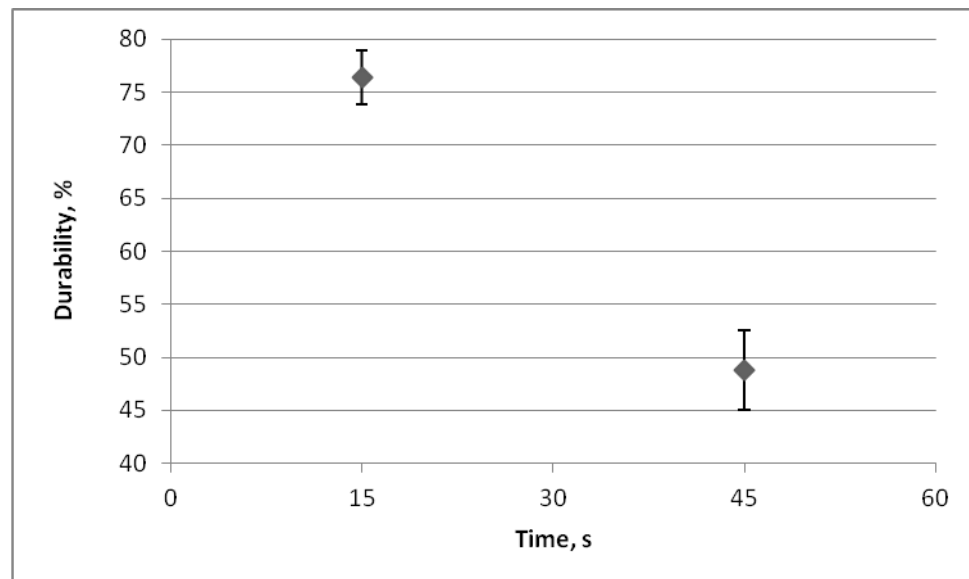


Figure 2.9 Relationship between measured durability of pellets and testing duration.

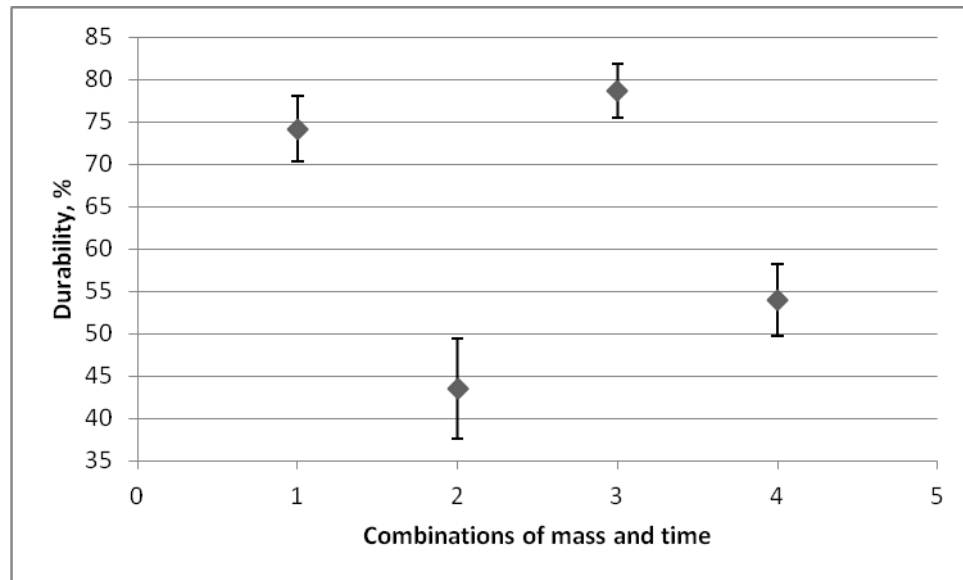


Figure 2.10 Relationship between measured durability of pellets and the combination of mass and time. #1: 15s and 50g; # 2: 45s and 50g; # 3: 15s, 200g; #4: 45s and 200g.

2.7 Conclusion

Durability measurement experiments were conducted using Dural tester in this chapter. The intention was to obtain the most appropriate setting for reliable durability measurements for the Dural tester. The machine setting with sample mass 200 g, testing time 15 s and rotational speed 1615 rpm gave the highest durability with the least standard deviations and consistently among all four types of pellets tested. The results from this setting also covered a wide range of durability values for different types of pellets.

Chapter 3 Drop Test – Theoretical Development

3.1 Modes of pellet breakage

Teo et al. (1990) indicate that two major types of breakage are considered in pellets, volume breakage and surface breakage. Figure 3.1 depicts these two modes of breakage. In volume breakage the pellets are broken into smaller pieces including a fine dust. This happens along the cracks, line of weakness when pellets experience impact force. After breakage the new fragments have smaller mean length than the pellet. Dural is an example of a device that imparts severe impact and shear on pellets to cause volume breakage.

For the case where the impact force is not large enough surface breakage happens as shown in Figure 3.2. In this case only abrasive forces cause chipping and removal of dust and fines from the surface of the pellets (Teo et al., 1990). For instance, vibration may cause surface breakage. The degree of dust generation in volume breakage is less than in surface breakage. Tumbler is a good example of surface breakage. Pellets tested in tumbler remain in their original shape. Only small amount of dust is produced in Tumbler due to surface breakage. From our observation these dusts and fines are mainly from the surface or corners of pellets. Figure 3.3 illustrates the difference between the dust produced by volume breakage (with Dural) and surface breakage (with Tumbler).

In a drop test both kinds of breakages, volume and surface breakages happen depending on the impact force, which is affected by the mass of pellets and height in

which pellets are dropped from. This is reconfirmed by our observation and results from Chapter 4.



Figure 3.1 Volume breakage in pellets when impact forces are severe: original pellets (left), pellets after volume breakage (middle), and dust from volume breakage (right).



Figure 3.2 Surface breakage in pellets when impact forces are mild: original pellets (left), pellets after surface breakage (middle), and dust from surface breakage (right).



Figure 3.3 Side by side comparison of dust from surface breakage (left) and volume breakage (right).

3.2 Crack propagation

Woody materials are *anisotropic*; the mechanical properties are direction dependent. When water is adsorbed by a piece of wood, the amount of water absorbed along the three axes will be different. Similarly, the percent of weight loss will be different along these axes when wood is dried or cooled. Local mass loss or gain causes expansion or shrinkages within the volume of a pellet leading to internal stresses. A stressed pellet eventually cracks and breaks into pieces.

A piece of wood is also heterogeneous in terms of its ingredients and structure both in microscopic and macroscopic scales (Kaliyan and Morey, 2009). Pellets develop cracks with different length and depth within their structures. Certain amount of

force has to be applied in order to initiate the growth of a crack. Variations in strength, direction, discontinuities between grains affects overall crack propagation.

There are planes of separations in pellets. The applied force, such as impaction, compression and shear, to pellets overcomes the interatomic forces across these planes. Kaliyan and Morey (2009) showed that short-range forces such as hydrogen bridges, van der Waals' forces and magnetic forces are examples of interatomic forces. Short range forces are forces between two particles which is negligible beyond certain distance. Hydrogen bonds are due to the attractive interaction of a hydrogen atom with an electronegative atom. Van der Waals forces are the sum of the attractive or repulsive forces between molecules. Magnetic forces are attraction or repulsion that arises between electrically charged particles because of their motion. These interatomic forces hold the particles together in pellets. According to Tavares (2009) after an external force is applied that overcome the internal binding forces, pellets break down into smaller pieces around their cracks. New pieces have new patterns of cracks with different length and depth. Waters et al. (1987) and Teo and Waters (1998) imply that particles with larger size are more likely to have larger cracks and hence be more prone to breakage. In the case of wood pellets, long pieces break easier and produce more dust and particles compared to short pellets.

Wang (1996) describes the three major modes of crack propagations that can occur in pellets due to variation in forces and direction of forces (Figure 3.4).

- Opening mode - When *tensile stress* is normal to the plane of crack, then the crack opens up.

- Sliding mode - *Shear stress* acts parallel to the plane of the crack and perpendicular to the crack front; this causes the sliding of two parts over each other.
- Tearing mode - *Shear stress* acts parallel to the plane of the crack and parallel to the crack front.

In a typical drop test the last two modes appear more likely to occur. There is no evidence of tensile stress as the impact force is perpendicular to the surface of pellets. Shear stress is the dominant force and it causes sliding or tearing propagations. Similarly, shear stress is again the major stress associated with the Dural tester and Tumbler tester as there is also no tensile stress. Litster et al. (1987) confirmed that in Tumbler the fines are produced due to friction.

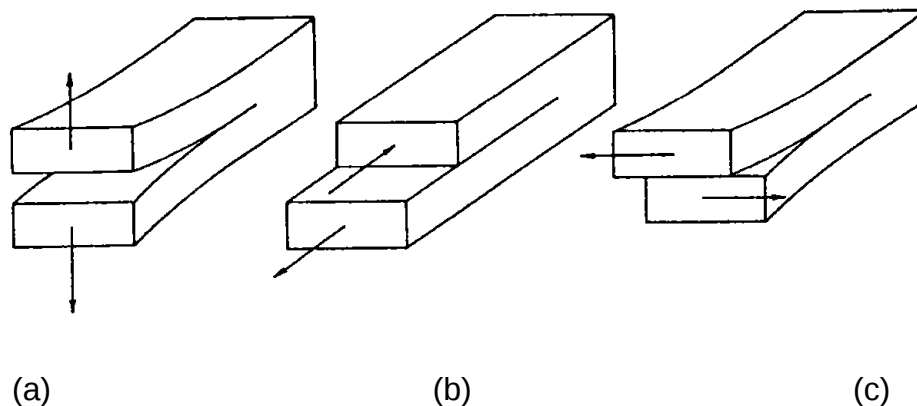


Figure 3.4 Three ways of applying a force to start a crack propagation. (a) opening mode, (b) sliding mode, (c) tearing mode.

3.3 Hardness test

It is known that hardness reflects the resistance of material to its permanent deformation. Hardness of agricultural processed materials is measured based on crushing test. Kaliyan and Morey (2006) investigated major factors that contribute to strength and durability of densified product, and they unveiled four major parameters: compression time, particle size distribution, moisture content, and compaction conditions.

A machine that is generally used for measuring the mechanical strength of materials (such as compressive strength and tensile strength) can also be used for determining the hardness of pellets. During the hardness test on pellets, the maximum load to break a pellet will be recorded. The Meyer hardness (MPa) is defined as the applied force (N, when the pellet is crushed) divided by the projected indentation area, knowing the indentation depth and the initial diameter of a pellet's cross section (Tabil et al., 2002). The maximum breaking force and the Meyer hardness of the pellets can be obtained from a typical force-displacement graph displayed during the test.

3.4 Terminal velocity

When downward force of gravity (F_g) equals the upward force of drag (F_d) a free-falling object reaches its terminal velocity (Mohsenin, 1986). Figure 3.5 shows a free-fall object with forces acting upon it. The magnitudes of forces change at three stages of the fall: before the drop, while it is falling, and the forces at terminal velocity (Figure 3.6). When

the body is at rest, only gravity force exists. When the body is falling, drag force makes an opposite effect on the body due to friction of fluid. If the density of body is low or it has a certain type of shape then buoyancy force will take effects too. Buoyancy is caused by fluid pressure and it is an upward force. If density of the object is high the buoyancy is small relative to the gravity and can be neglected.

Mohsenin (1986) proves that the terminal velocity of a particle in a free fall can be estimated by the following equation

$$V_t = \sqrt{\frac{2mg}{\rho A C_d}} \quad (1)$$

where V_t = terminal velocity (m/s), m = mass of the falling object (kg), g = acceleration due to gravity (m/s^2), C_d = drag coefficient, ρ = density of the fluid through which the object falls (kg/m^3), and A = projected area of the object (m^2).

According to equation (1), as mass of object increases the terminal velocity increases. The mass used for measurement of traveling time using the drop test method varied from 100 g to 5000 g. This range of mass allows a large variation of the terminal velocity. The fluid involved in the drop test is air and dry air has a density of 1.2 kg/m^3 at 20°C and 101.3 kPa. A single pellet with a diameter of 6.3 mm and length of 24 mm weighs 0.8 g (density of 1200 kg/m^3).

If we assume the axis of the pellet is normal to the falling direction, and the projection area is a rectangle (6.3 mm x 24 mm), then the drag coefficient C_d may be considered to be 1.2 (Table 9.1 in Mohsenin 1986). Using these values, Equation (1) will yield a terminal velocity of 9.0 m/s. This terminal velocity is not sensitive to length of pellet if the density of the pellet remains constant. The terminal velocity increases to 9.4

m/s for pellet density of 1300 kg/m^3 and reduces to 8.6 m/s for pellet density of 1100 kg/m^3 . We therefore expect the terminal velocity of a single pellet falling down with its longitudinal axis perpendicular to the axis of fall would range from 8.6 to 9.4 m/s.

However, if we assume the pellet falls with its longitudinal axis parallel to the axis of fall, the area is then the cross-section of the pellet ($\pi (6.3/2)^2 = 31.2 \text{ mm}^2$). The drag coefficient of a circular projection area is 0.47 (Table 9.1 in Mohsenin 1986). In this case the terminal velocity will increase to 19.8 m/s.

We assume that half of the pellets tend to drop on the side and the other half tend to drop on the head so that the resulting terminal velocity of a stream of pellets would be in between the two extremes, at about $(9.4 + 19.8)/2 = 14.6 \text{ m/s}$.

In drop tests, pellets were contained in bags and sample mass of pellets in bags varies. For example, when 300 g of sample mass was used in the test the bag was 200 mm x 260 mm and about 10 mm thick. This bag thus yields a bulk density of 850 kg/m^3 . Using these values and a drag coefficient of $C_d = 0.80$ from Mohesenin (1986) yields a terminal velocity of 34.28 m/s when the bag falls on its flat side. For the bag falling on the narrow side parallel to the falling direction, the content of the bag may give a form of a spherical ball to the bag roughly 50 mm in diameter. This diameter yields a projected area of 0.0020 m^2 . The drag coefficient for spherical shapes is about 0.47, which will yield a terminal velocity of 72.1 m/s.

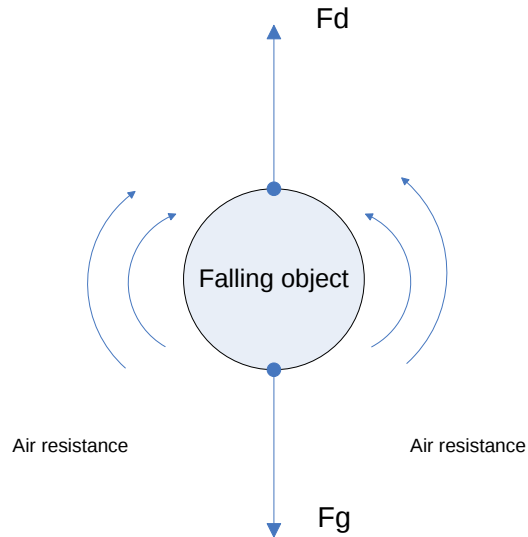


Figure 3.5 Forces acting on a falling object: air resistance and gravity.

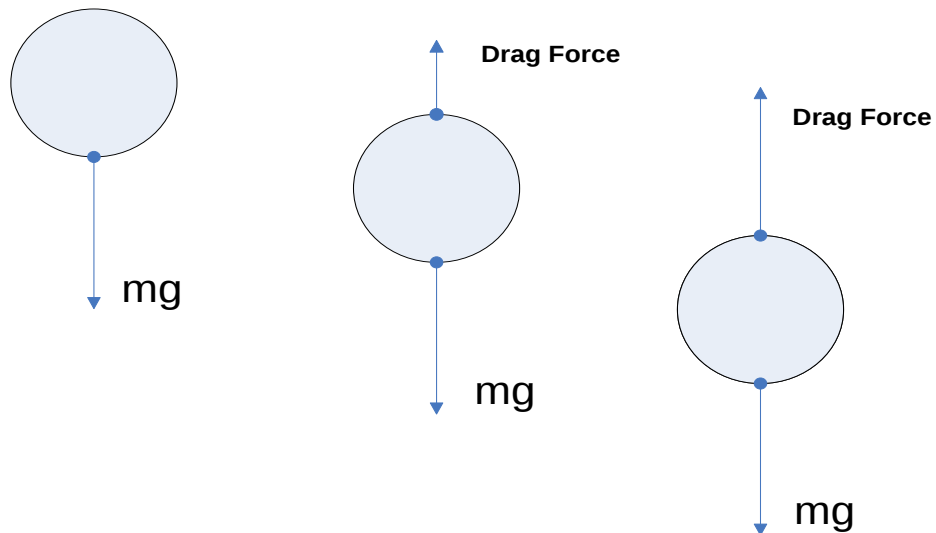


Figure 3.6 Falling body at three stages: i) Falling just starts ii) During acceleration iii) at terminal velocity.

3.5 Calculation of velocity using the total energy of bags

At the beginning before the bags are dropped the total energy of bags is:

$$TE = PE + KE = mgh + 0.5 mV^2 \quad (2)$$

Because the bags are at rest position, then the initial velocity is zero. Therefore the above equation is simplified to

$$TE = PE = mgh \quad (3)$$

Just before the bag hits the ground, there is no height ($h=0$):

$$TE = KE = 0.5 mV^2 \quad (4)$$

The bag will have velocity V just prior to hitting the concrete surface. The entire PE is converted to KE:

$$PE = KE = mgh = 0.5 mV^2 \quad (5)$$

$$V = \sqrt{2gh} \quad (6)$$

This equation can be used to estimate the velocity of pellets assuming there is no air resistance.

The highest elevation in drop test and gravitational acceleration are 21 m and 9.81 m/s², respectively. Using these values in equation (3) will yield a potential energy of 61.8 J for 300 g of pellets. Equation (6) yields a velocity of 20.3 m/s for the pellets. This number will be used to compare with the terminal velocity reported in chapter 4.

3.6 Momentum

To calculate the impact force we need to consider the momentum of our object.

Momentum is defined as:

$$dp = d(mV) \quad (7)$$

$$dp = Fdt \quad (8)$$

$$F = \frac{dp}{dt} = \frac{d(mV)}{dt} = ma \text{ (Newton's second law)} \quad (9)$$

where dt = interval of time over which the momentum is changed; dp = changes in momentum and F = the impact force.

The impact duration may be estimated knowing the time when the bag hits the ground and the time when it is totally stopped.

Equation (9) indicates that when dt is very short, F is large. That is the case when concrete is the surface of impact. In case pellet bedding is used then dt would be bigger and F is smaller, again according to equation (9); so the breakage is less. We expect the pellet breakage results from the drop test would follow these principles.

Equation (9) states that a larger mass develops a larger momentum and consequently the impact force F will be higher. The time for the bag to be stopped by the ground, dt , is very short and it is hard to be measured. By calculation of dp (momentum) the impact force can be estimated. Momentum is affected by mass and velocity. According to equation (6) the velocity is the same for all bags, the momentum and impact force is affected only by the mass of pellets in the bag. In the case that the height is equal to 21 m, the velocity at which pellets hit the ground is 20.3 m/s. Experiment shows that with small masses the velocity changes while the velocity remains the same for the masses above 300 g. Using equation (9) the momentum for a 400 g sample of pellet is $8400 \text{ g} \frac{\text{m}}{\text{s}}$. The momentum at the same height for 1000 g sample is $21000 \text{ g} \frac{\text{m}}{\text{s}}$. The momentum increased linearly and as the mass of pellets increased. Again, based on equation (9) in order to calculate impact forces we need to have data of dt .

3.7 Repeated drop test

In drop test pellets are broken into smaller pieces as impact forces are big enough relative to the resistance of the pellets.

The breakages in drop test are predominantly volume breakage. By drop test the strength of pellets may be measured. The actual forces applied to the pellets in a pellet manufacturing plant are simulated to study the degradation of pellets. Here, “degradation” is defined by Goodwin and Ramos (1987) and Sahoo et al. (2002a and 2002b) as defined as the conversion in which a smaller size fraction of a particle is produced. Such kind of drop test has been developed both theoretically and experimentally to measure the strength of wood pellets in handling. For all the approaches for the measurement, it is necessary to drop a single particle several times from a certain height. The mass or number of pieces remained intact from the original single particle can be used to estimate impact resistance. ASTM method D440-86 (ASTM, 1998) described how to conduct a drop-shatter test for coal to measure the impact resistance. This test method takes into account the processes including loading, handling, transporting and unloading. It assumes that pieces with small size have a cushioning effect which would reduce the breakage of the larger pieces. Li and Liu (2000) also used ASTM method D440-86 (ASTM, 1998) for evaluating the durability of biomass logs. Four types of biomass are tested in their study. They also compared their results from drop tests with results from Tumbler test. Tumbler test shows only volume breakage while drop tests yield both volume and surface breakages. Richards (1990) introduced an impact resistance index (IRI) that relates the number of drops and the number of broken pieces.

Lindley and Vossoughi (1989) measured the shatter resistance as the percentage loss of weight from shattering. Shatter index is measured to show the strength of pellets as follows:

$$Shatter\ index(\%) = \left(\frac{mass+3.15mm\ after\ drop}{Initial\ mass} \right) \times 100 \quad (10)$$

The concept of shatter index and durability index are similar and they both quantify the breakage of pellet. Having a mathematical expression for repeating drop test is essential as it can formulate the strength of pellets.

Sahoo and Roach (2005c) studied the theoretical aspect of repeated drop test. The breakage kinetics equation is assumed to be first order:

$$M_1 - Mo = -K_v Mo \quad (11)$$

where Mo = initial mass of the size fraction; M_1 = mass of the unbroken material after the first drop; K_v = volume breakage constant.

Therefore:

$$Mo(1 - K_v) * M_1 = -K_v Mo + Mo \quad (12)$$

Similarly, for the second drop:

$$M_2 - M_1 = -K_v M_1$$

$$Mo(1 - K_v)^2$$

For N drops:

$$M_n = Mo(1 - K_v)^N \quad (13)$$

where M_n is the mass of material still in the initial size fraction after N drops. K_v is determined numerically from the slope of the straight line on a plot of $\log \left(\frac{M_n}{Mo} \right)$

versus N , the number of drops. K_v is considered as an index of the strength of pellets. A large K_v means a greater extent of breakage. High breakage, in turn, indicates a lower resistance of pellets to shatter and it implies lower bulk strength. Figure 3.7 shows the experimental results derived from a bag of pellets after five repeated drop tests. The K_v value of 0.01 indicates a small extent of breakage of pellets and their bulk strength.

Figure 3.8 shows the ideal stacking of pellets and the forces being applied to them. When pellets hit the ground the impact F_1 is produced and applied to the first layer. As a result, there are some volume and surface breakages. Same thing happens between the other layers as impact force is generated due to impaction of two layers of pellets. If the impact force is big enough the weight loss will increase linearly by increasing the mass. There are two surface areas which should be considered and investigated as impulse forces are exerted to the pellets: a) the surface area which is in contact with the ground (e.g. concrete) and b) the surface area between the layers of pellets. At these points some portion of impact forces are exerted to the cracks as stress. The rest of impact is transferred to other layers releasing heat or causing mechanical movement in the pellets and layers. If the transferred stress to the cracks is big enough then crack propagation starts; otherwise it is again converted to heat or some mechanical movements. There is a cushioning effect between layers of pellets, which can reduce the breakage level. For example, Waters et al. (1989) conducted experiments and found that the cushioning effect can decrease the breakage by 10% in the case of iron drop test.

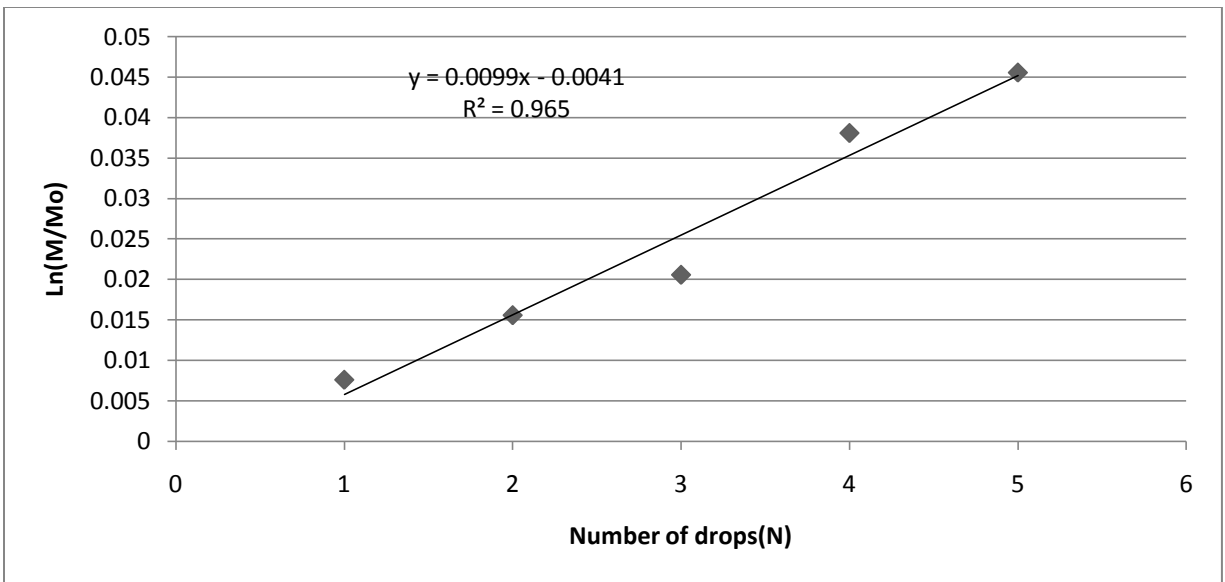


Figure 3.7 Effect of repeated drop tests on pellets' breakage.

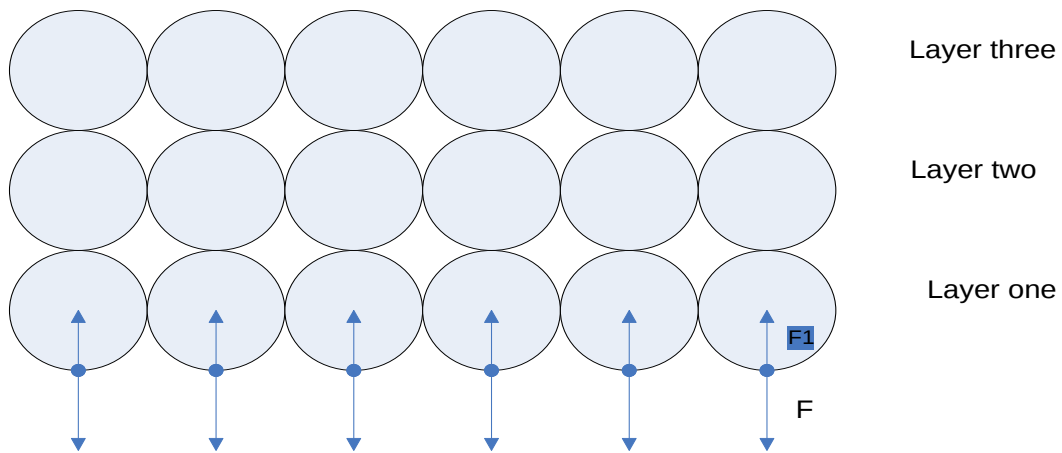


Figure 3.8 Demonstration of ideal schematic of layers in pellets.

Chapter 4 Wood Pellet Breakage due to Free Fall

4.1 Introduction

Wood pellets are increasingly being used as alternative to fossil fuels. As a manufactured product, wood pellets are more uniform in moisture content and chemical composition than unprocessed biomass. Pellets have less water content and their heating value is higher compare to non processed biomass. Emitted gasses, odour and dust produced during the manufacturing of pellets are among main concerns in pellet industry.

Particles should provide good resistance against both static and dynamic loads (Pitchumani et al., 2004). Pellets with a lower durability can break more readily and potentially generate a large amount of dust. Handling and loading of bulk material into rail cars or trucks, transporting and conveying and transferring to large silos and ocean vessels exacerbate the breakage (Sahoo, 2007). Harsh handling happens particularly when the pellets are loaded into the holds of ocean vessels at high rates. The drop height in silos is more than 21 m, as observed during loading and unloading pellets at Fiberco Inc., North Vancouver, BC. Pellets may also lose their integrity when exposed to humid and warm temperatures (Fasina and Sokhansanj, 1996). The presence of fines causes problems in shipping and handling. It is very important to minimize the amount of fines in the bulk materials. This motivates the understanding of breakage mechanisms, which could help predict the generation of fines (Oberholzer and van der Walt, 2009).

Studies have been done to investigate drop tests of bulk materials, such as lump ores and coal. Their findings can help us establish our drop test procedures on wood pellets.

Fagerberg and Sandberg (1973) investigated the breakage of lump ores. Their results showed that disintegration of the particles is mainly caused by impact force when the material was dropped. In comparison, compression and abrasion have less influence on the degradation of particles. They also suggested that the breakage of particles dropped from a large height level is equivalent to the breakage of the same particles dropped from several smaller drops that add up to the same total height.

Norgate et al. (1986) tested the cushioning effects and found that the effects can reduce the fines generation from lump iron ore. Waters and Mikka (1989) studied the cushioning effects of fines which are smaller than 6.0 mm. Their results indicated that the more percentage of initial fines, the less degradation the iron ore lumps have. They showed that after five drops breakage can be reduced by about 10% if there is cushioning effects. Sahoo et al. (2002c) had the same observation when they investigated on the cushioning effects of fines smaller than 16.0 mm on coal degradation.

Goodwin and Ramos (1985) conducted test on the degradation of coal at transfer points. The main purpose of their research was to develop, design and manufacture a facility that processes a large variety of products in handling. Vogel and Quass (1937) reported that coal lumps are reduced in size during mining and handling operations as a result of impact and attrition. Kelly et al. (1991) studied coal degradation during mining and handling. Their results indicated that the fines generated were caused by larger

vertical drops. Sahoo et al. (2004) tested breakage on single particles and established a breakage model for coal handling. Sahoo and Roach (2005b) emphasized that there are limitations of tumbler drum tests. They suggested drop tests are an alternative for tumbler tests since drop tests are more applicable to measure the volume breakage.

Sahoo and Roach (2005a) also did drop tests on coal and commented dropping pellets will also cause degradation. Ramos (1992) suggested that the factors contributing to the degradation at transferring were the change in direction from loading, height of the transfer points and impact of materials in facilities.

In the case of wood pellets, the weight losses of the pine wood pellets and alfalfa pellets were in line with values observed by Fasina and Sokhansanj (1996). Their results indicated that alfalfa pellets had weight losses of 0.8% and 1.2% when dropped from a height of 5.5 and 7.6 m, respectively onto concrete surface. When dropped onto pellet bedding, the weight losses were reduced to 0.4%. Mina-Boac et al (2006) examined the durability and breakage of feed pellets during repeated handling processes. They reported that the average mass of dust removed per transfer is 0.069% of the mass of pellets.

It can be noted from above that the breakage of pellets, an typical example of bulk materials, is affected by the following factors: the height, geometric angle when pellets start to be loaded, initial speed of pellets, the type of pellets, the mass of pellets dumped into the vessel or silo, the surface onto which pellets are loaded, and the number of handlings.

4.1.1 Objectives

The objectives of this Chapter are: (1) to conduct drop tests from heights similar to what takes place when filling silos or other containers and vessels, (2) to measure the durability of pellets, and quantify the weight losses due to drop heights.

4.2 Materials and method

White pellets were used in all our tests. They were available from RONA warehouse in 15 kg bags (North Vancouver, BC). They were produced in British Columbia mostly from a combination of coastal wood (Douglas fir, spruce and pine). The durability values of this type of pellets were 68.8% and 97.0% measured by Dural and Tumbler respectively. The bags were stored in plastic containers and placed in a lab until the tests were performed.

The drop test was conducted at the Chemical & Biological Engineering (CHBE) Building (Figure 4.1), University of British Columbia, Vancouver, Canada. Choosing this building is due to its sufficient height. The building has five floors. The height of each floor from the ground was estimated using a laser distance meter (Rayobi TEK4, Henderson, SC) – Figure 4.2. The floors 1, 2, 3, 4, and 5 provided a drop height of 4.2 m, 8.4 m, 12.6 m, 16.8 m and 21.0 m, respectively.

Drop tests were conducted with a sample mass of wood pellets enclosed in 20 cm x 26 cm mesh size bags (Figure 4.3). The bags were made of durable synthetic material with a zip lock (Imported by Daiso Ltd., manufactured in China/Vietnam). The

woven mesh was about 1 mm openings. The bags of pellets were dropped from an open window on each floor of CHBE to the concrete side walk below. Several preliminary tests from various heights showed that the bags did not break open during a drop test.

In all experiments a Hoffman R89P Riffle divider (Hoffman MFG, Jefferson, OR) was used to randomly divide pellets into lots and sub-lots. Prior to each test a batch of pellets were sieved manually using a wire mesh sieve with 3.15 mm openings. This size sieve is recommended by CEN/TS 15210-1 (2005a) for quantifying the percent broken pellets for commercially traded pellets.

In all our drop tests, the percent breakage was calculated from:

$$W_L = 100 \times \frac{W_i - W_f}{W_i} \quad (1)$$

where W_L is percent weight loss, W_i is initial weight of pellets and W_f is weight of pellets left on 3.15 mm sieves after sieving.

Moisture contents of pellets were measured by drying whole pellets in a convection oven at 105°C for 24 hours (ASABE, 2007). Its moisture content is 5.6%. The length and diameter of a minimum of 20 pellets were measured using a calliper. The durability of each batch of pellets was measured using a tumbler box according to the ASAE Standard S269.4 (ASABE, 2006).



Figure 4.1 CHBE building and the sidewalk used for drop tests.



Figure 4.2 Laser distance meter (Rayobi TEK4, Henderson, SC).

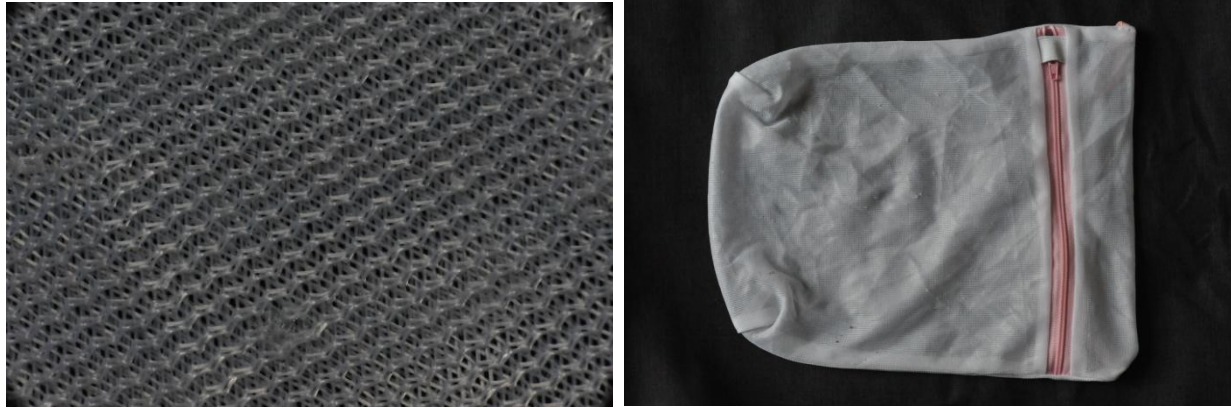


Figure 4.3 Left: magnified appearance of the bag which shows the holes; Right: mesh bag used for the drop tests.

4.2.1 Drop tests with varying drop height for two different beddings

Bags with 300 g of sieved pellets were prepared to be dropped from a certain height. The sample mass of 300 g was chosen because it lies between the standard mass of 500 g used in the Tumbler tester and mass of 100 g used in the Dural tester. The concrete surface on the sidewalk was swept dry and clean. The filled bags were individually dropped from each floor directly onto the concrete sidewalk. The bag was collected from the ground immediately after each drop, and it was taken to the lab for sieve analysis.

For pellet-on-pellet test, a 1.5 m x 1.5 m x 0.15 m wooden frame was constructed and placed on the concrete sidewalk directly beneath the drop window. The frame was filled with pellets to 0.15 m, and bagged pellets were dropped onto this layer of pellets. Ten bags that serve as replicates were dropped from each of the five floors, which provided a drop height of 4.2 m, 8.4 m, 12.6 m, 16.8 m and 21.0 m, respectively.

4.2.2 Drop tests with repeated droppings

Repeated drop tests are useful because they are highly reproducible (Pitchumani et al., 2003). Particles become increasingly weaker after repeated impacts (Tavares and King, 2002). Results from the tests with varying drop heights indicated that the greatest pellet breakage occurred at a drop height of 21 m. Therefore, for tests with repeated droppings, bags with 300 g of sample mass were dropped from the 5th floor (21.0 m). Two series of tests were performed for repeated drop tests.

In the first series of tests, the bag was collected from the side walk after each drop. The material in the bag was sieved on 3.15 mm mesh size sieve. The fines were discarded and the pellets remaining on the sieve were returned to the bag. The bag was then dropped again from the same height. This cycle of dropping and sieving was repeated five times.

In the second series of tests, five identical bags each with 300 g sample mass were prepared. The replicates for this experiment were two. Bag #1 was dropped once; bag #2 was dropped twice, bag #3 was dropped 3 times, and so on. The pellets were not sieved after each drop. During each drop, the bag contained the resulting fines and broken pellets from the previous drop. The purpose was to observe whether the fines and broken pellets might provide some cushioning effect thereby reducing the breakage of pellets upon repeated droppings.

4.2.3 Drop tests with varying sample mass

Ten batches of pellets with sample mass ranging from 100-1000 g and in increments of 100 g were prepared. The size of mesh bags was 20 cm x 26 cm. Batches with sample

mass of 2000 g, 3000 g, 4000 g and 5000 g were also prepared in larger bags of 28 cm x 33 cm. Again, all drops were from the 5th floor (21.00 m height). There were ten replicates in this part of the experiment.

4.2.4 Traveling time measurement

Initially, the travelling time by the bagged pellets during the drop tests was measured using a chronometer. Since the travelling time was typically about 2 s, applying the chronometer at the exact time proved to be difficult and the results were not accurate. To resolve this problem, a camcorder with capability of recording in 0.01 s intervals was used to capture the movement and the duration of falling. By playing back the recorded clips, the exact moment at which a bag was released from the window and the exact moment at which it hit the ground were determined. The differences between these two times provided the total traveling time. To ensure a high degree of accuracy, the clips were watched as many times as required.

4.2.5 Size distribution analysis

Thirty identical bags each having sample mass of 600 g white pellets were prepared. The bags were dropped from the 5th floor (21.0 m height) with a procedure as outlined below.

All of the 30 bags were dropped once. Six of them were labelled as bags #1. The labelled bags were separated from the other bags. The remaining 24 bags were dropped again and again, six of them were labelled as bags #2. The same procedure was adopted for the rest of the samples, that is, each time six bags were separated after dropping and labelled and the remaining bags were dropped again.

Subsequently, for particle size distribution analysis, the pellets from two bags with the same label were combined. We considered two sessions of analysis: i) analysis for particles using apertures 6.7 mm, 4.0 mm, and 3.15 mm, and ii) analysis for particles smaller than 3.15 mm, with apertures: 2 mm, 1mm, 0.5mm, 0.25mm, and 0.09mm. For the first part, the sieved materials were categorized into particles that are larger than 6.7 mm, particles in between 4.0 mm and 6.7 mm, particles in between 3.15 mm and 4.0 mm, and particles smaller than 3.15 mm. For the second part of analysis, particles with size less than 3.15 mm were sub-divided into six categories: i) $3.15 \text{ mm} > \text{size} > 2 \text{ mm}$, ii) $2 \text{ mm} > \text{size} > 1 \text{ mm}$, iii) $1 \text{ mm} > \text{size} > 0.5 \text{ mm}$, iv) $0.5 \text{ mm} > \text{size} > 0.25 \text{ mm}$, v) $0.25 \text{ mm} > \text{size} > 0.09 \text{ mm}$, and vi) $\text{size} < 0.09 \text{ mm}$. These numbers reflect the size of sieves used in our experiment.

The experiments and the setting parameters are summarized in Table 4.1.

Table 4.1 Summary of procedures for the drop tests

Factors	Range of values	No. of replicates	Description
Height (m)	4.2 – 21 increment: 4.2	10	Two beddings were used: concrete and pellets
Repeating	1 – 5 increment: 1	5	Drop height 21 m
Mass (g)	i) 100 - 1000 increment: 100 ii) 1000 – 5000 increment: 1000	10	Drop height 21 m
Time (s)	-	2	Time was measured after dropping the following masses of particles: i) 100 – 1000, increment: 100 ii) 1000 – 5000, increment: 1000
Size distribution A (mm)	i) size > 6.7 ii) 6.7 > size > 4, iii) 4 > size > 3.15	6	-
Size distribution B (mm)	i) 3.15 > size > 2, ii) 2 > size > 1, iii) 1 > size > 0.5 iv) 0.5 > size > 0.25 v) 0.25 > size > 0.09 vi) size < 0.09	6	Particles size < 3.15 mm were subdivided into six categories

4.3 Results

4.3.1 Drop tests with varying drop height

Figures 4.4 and 4.5 depict the extent of pellet breakage when bagged pellets were dropped onto concrete surface and pellet bedding, respectively, from the various heights. For the concrete surface, the percent broken pellet ranged from 0.3 to 0.9% (average 0.6%) when drop height was 4.2 m; and it ranged from 0.6 to 2.2% (average 1.4%) when the drop height was increased to 21 m. By comparison, for the pellet bedding, the percent broken pellets ranged from 0 to 1% (average 0.2%) with 4.2 m

drop height; and it ranged from 0.2 to 2% (average about 1%) with 21 m drop height. Hence, more breakage occurred with increasing drop height for both types of surfaces.

The data in Figures 4.4 and 4.5 were fitted with a linear equation of the form:

$$B = aX + b$$

where X is the height of drop (m) and B is the percent breakage of pellets. Table 4.2 lists the estimated values of the coefficients a and b , along with the uncertainties in the estimated values. We note that the goodness of fit to the data is quite low ($R^2 = 0.45$ for pellet on concrete and $R^2 = 0.37$ for pellet on pellet) due to the spread/variability in the data. The uncertainties (standard deviations) in the estimated values of a and b for pellet on pellet are slightly higher than those for pellet on concrete. It is interesting to note that the slopes of the two fitted lines are almost the same.

Table 4.2 Estimates of coefficients for linear equations fitted to the data for drop tests

Equation	a	SD for a	b	SD for b	SD for B	R^2
Pellet on concrete $B = aX + b$	0.0477	0.0076	0.3982	0.1059	0.32	0.45
Pellet on pellet $B = aX + b$	0.0462	0.0088	-0.0515	0.1235	0.37	0.36
Repeated drops without sieving after each drop $B = aY + b$	2.3283	0.00332	-1.8297	2.8161	3.703	0.988
Repeated drops with sieving after each drop $B = aY + b$	2.1337	0.2455	-0.7517	0.6210	3.4308	0.967

B: percent breakage; X: drop height; Y: number of drops; SD: standard deviation

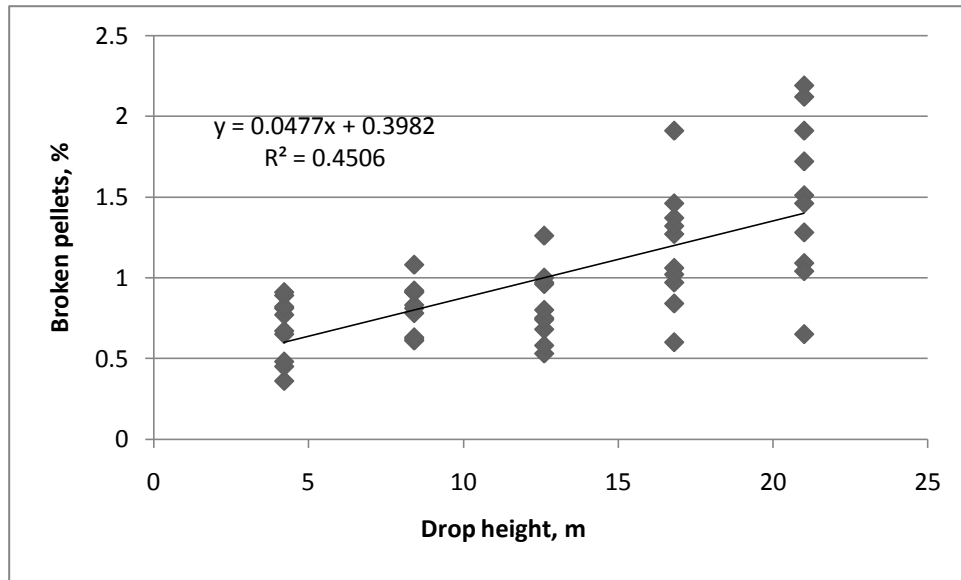


Figure 4.4 Percent broken pellets when a bag of 300 g pellets was dropped onto concrete bedding from various heights.

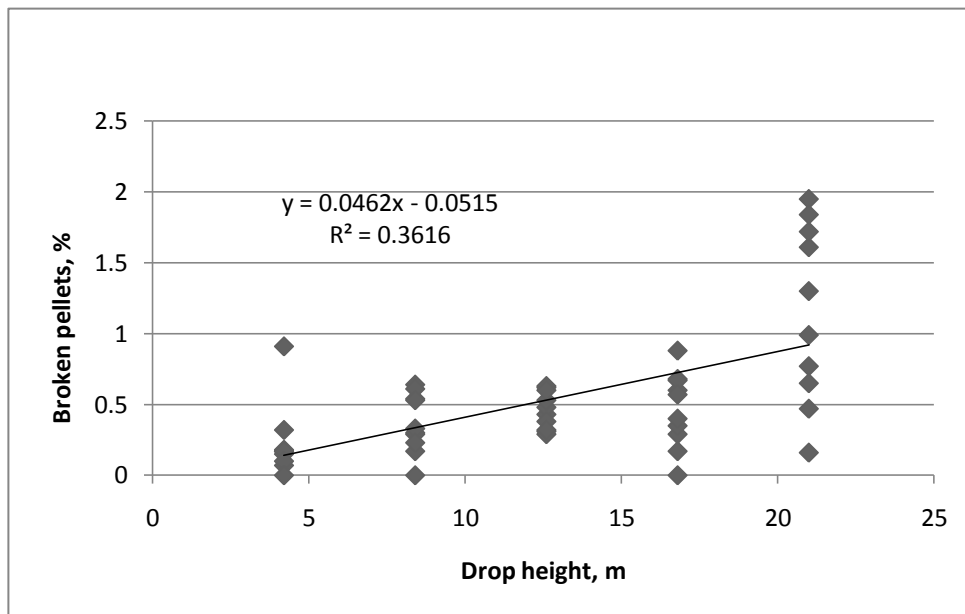


Figure 4.5 Percent broken pellets when a bag of 300 g pellets was dropped onto pellet bedding from various heights.

4.3.2 Drop tests with repeated droppings

Figure 4.6 shows the percent broken pellets after each successive drop. The breakage increased almost linearly with the number of drops and reached 10% after five drops.

The data may be fitted with a linear equation of the form:

$$B = aY + b$$

where Y is the number of drops and B is the percent breakage of pellets. The estimated values of the coefficients a and b are also listed in Table 4.2 along with the uncertainties in the estimated values. The upper fitted line is for data pertinent to drop tests with dust and small broken pieces removed after each drop. The lower fitted line/data is for pellets not sieved, and hence without dust removal after each drop. The sieved pellets tended to have a slightly higher degree of breakage.

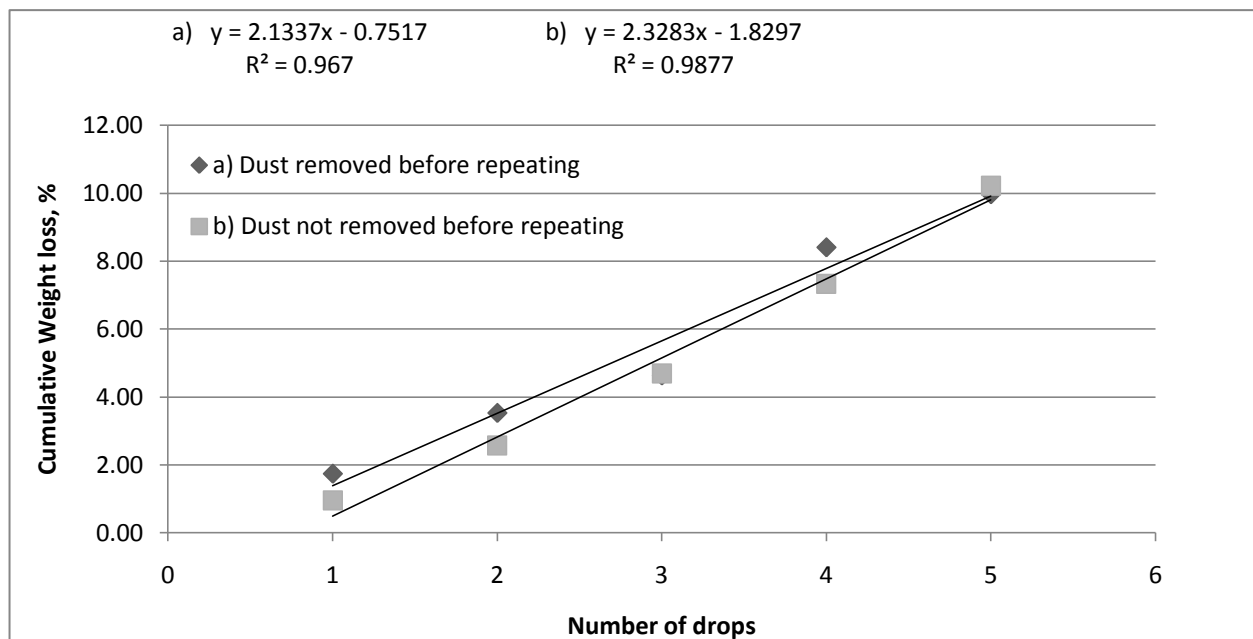


Figure 4.6 Cumulative weight losses on five repeated drops from a height of 21 m, with and without dust removed from the bag of pellets before each repeated drop.

4.3.3 Drop tests with varying sample mass

Figure 4.7 shows the percent broken pellets vs. mass of pellets when dropped from 21 m height. The mass ranged from 100 g to 1000 g, at 100 g intervals. The average percent broken pellets increased from an average of 0.84 % for a mass of 100 g to an average of 1.96% for a mass of 1000 g. Similar to the two previous tests, the variations in percent breakage of the pellets were large for the range of sample mass tested. Such variations exceeded 1% in most cases, thus leading to high coefficients of variation (CV). The rate of increase in percent breakage was progressively smaller as the mass of pellets in the bag was increased.

A logarithmic curve was fitted to the data:

$$B = 0.43 \ln(M) - 1.08 \quad R^2 = 0.34 \quad (3)$$

where M is the mass (g) of pellets in the bag and B is percent broken pellets. The degree of fit to the data is low ($R^2 = 0.34$) due to the spread in the data.

Figure 4.8 shows the percent broken pellets vs. mass of pellets when dropped from 21 m height, but with larger sample mass of pellets which increased from 1000 g to 5000 g in increments of 1000 g. The percent broken pellets for 5000 g mass was the greatest, ranging from 1.8% to 2.7%. Again, the rate of increase in percent breakage was progressively smaller as the mass of pellets in the bag was increased. This trend on graph is because of cushioning effect. The trend is an extension of the previous test with sample mass varying from 100 g to 1000 g. An attempt was made to fit a logarithmic curve to the data. The result showed a low R^2 value of 0.17 which means the equation is not useful for predictive purposes.

Equation (3) was again applied to analyze the data, and the predicted percent breakage of pellets would be 2.5% at 4000 g and 2.6% at 5000g. The calculated values are about 0.5% above the observed data.

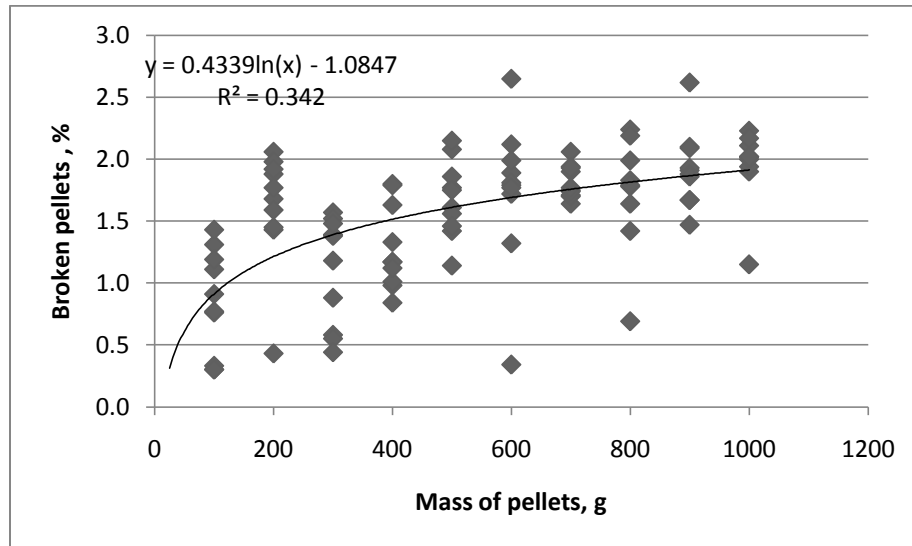


Figure 4.7 Percent broken pellets when pellets were dropped from a height of 21 m, with mass ranging from 100 g to 1000 g.

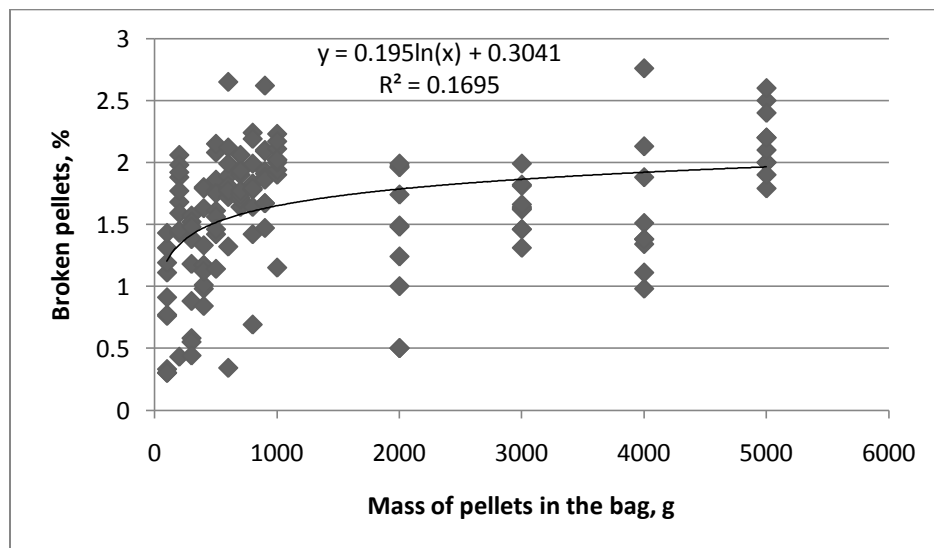


Figure 4.8 Percent broken pellets when pellets were dropped from a height of 21 m, with mass ranging from 100 g to 5000 g.

4.3.4 Traveling time measurements

Figure 4.9 is the plot of elapsed times recorded using the camcorder. The mass of pellets ranged from 100 g to 5000 g. The drop height was 21 m. The 100-g bags required 3.20 s (s.d. = 0.29 s, n=5) to reach the ground, whereas the 200-g bags took about 2.81 s. The traveling time further decreased to 2.09 s (s.d. = 0.03 s, n=5) for the 300-g bags. It is significant to note that the time remained constant at 2.09 s (with small standard deviations) for larger masses up to 5000-g bag as tested.

Breakage of particles is highly related to velocity. Higher velocity of the dropping bag will cause more breakage in a linear way (Salman et al., 2002). Using the following formula (the final velocity for a falling object), the velocity at which the bag reach the ground is calculated:

$$V = gt + V_o \quad (4)$$

where V is the drop velocity (m/s), t is drop time (s), g is the acceleration due to gravity (9.81 m/s^2) and V_o is the initial velocity at the time of bag release. Substituting 2.09 s for t and assuming $V_o = 0$ in equation (4) yields a value of 20.5 m/s for the drop velocity. This value can also be calculated using the free fall formula. The returned value is 20.3 m/s for a drop height of 21 m.

$$V = \sqrt{2gh} \quad (5)$$

20.5 m/s and 20.3 m/s are theretical velocities for the bagged pellets (with mass ≥ 300 g) upon hitting the ground.

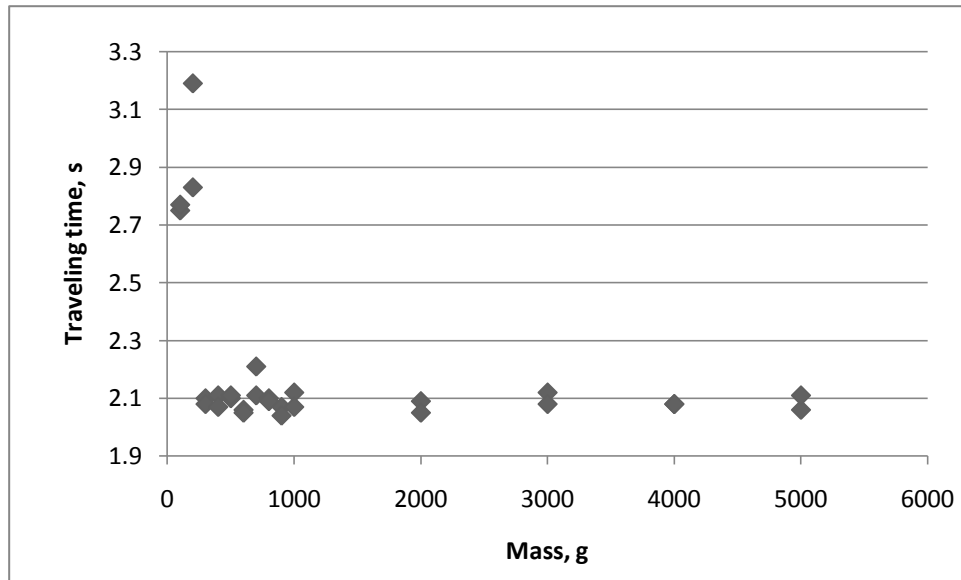


Figure 4.9 Travelling time measured for bagged pellets being dropped from a height of 21.0m.

4.3.5 Size distribution analysis

As mentioned before, two parts of analysis were conducted: i) size distribution of particles with apertures: 6.7 mm, 4.0 mm, and 3.15 mm and ii) particles smaller than 3.15 mm. Figure 4.10 and Figure 4.11 are referred to the first part of the analysis while Figure 4.12 and Figure 4.13 illustrate the results for the second part. As demonstrated in Figure 4.10, the major portion in all treatments were from pellets with particle size greater than 6.7 mm. The mass after one drop was 1175.4 g and after five drops it became 1075.4 g. It can be seen from Figure 4.11 that particles with size between 3.15 mm and 4.0 mm constitute the least portion in all treatments. Three sub-categories are contained in this figure, namely i) 6.7mm > size > 4mm, ii) 4 mm > size > 3.15 mm, and iii) size < 3.15 mm. The mass of these three sub-categories after one drop were 13.2 g, 4.0 g, and 12.1 g, and after five drops they became 41.9g, 17.3 g, and 68.9 g,

respectively. The size distributions for i) particles between 3.15 mm and 0.25mm and ii) particles less than 0.25 mm are shown in Figure 4.12 and Figure 4.13 respectively. Figures 4.11, 4.12 and 4.13 (for particles smaller than 6.7 mm) indicate that by increasing the number of drops the percentage of each particle size fraction was found to increase. The opposite trend is observed from Figure 4.10 for size greater than 6.7 mm.

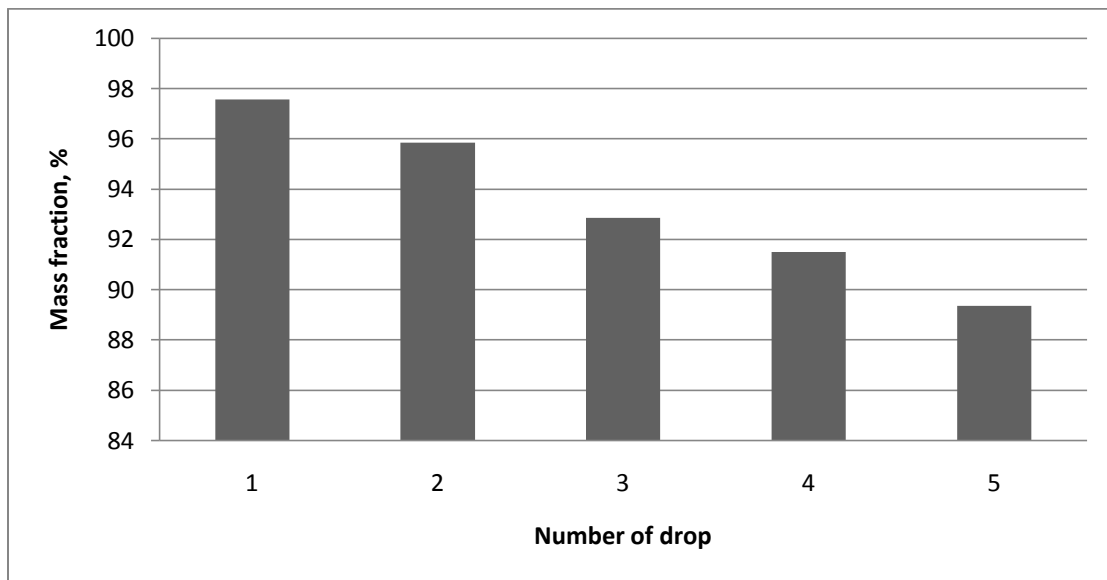


Figure 4.10 Mass fraction of particles with size greater than 6.7 mm.

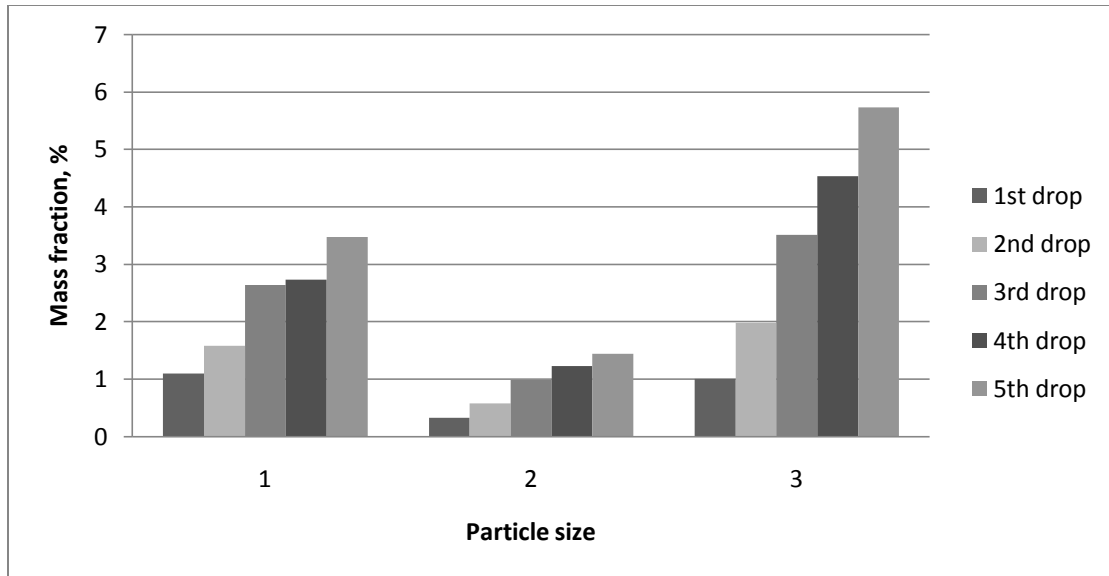


Figure 4.11 Mass fraction of particles with size smaller than 6.7 mm: 1) 6.7mm > size > 4 mm; 2) 4 mm > size > 3.15 mm; 3) size < 3.15mm.

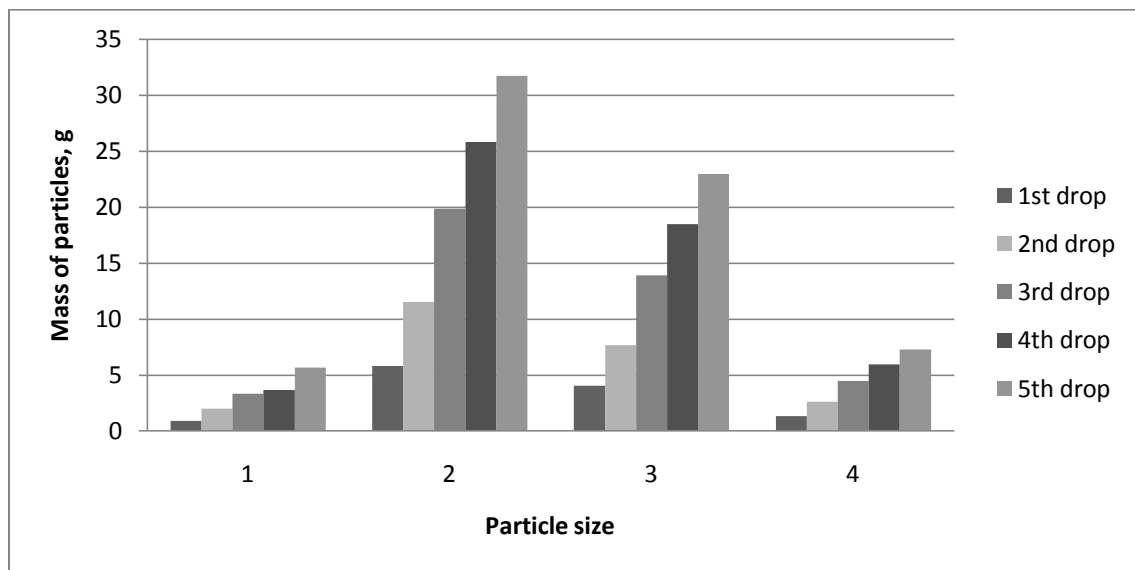


Figure 4.12 Mass of particles with size smaller than 3.15 mm: 1) 3.15 mm > size > 2 mm; 2) 2 mm > size > 1 mm; 3) 1 mm > size > 0.5mm; 4) 0.5 mm > size > 0.25mm.

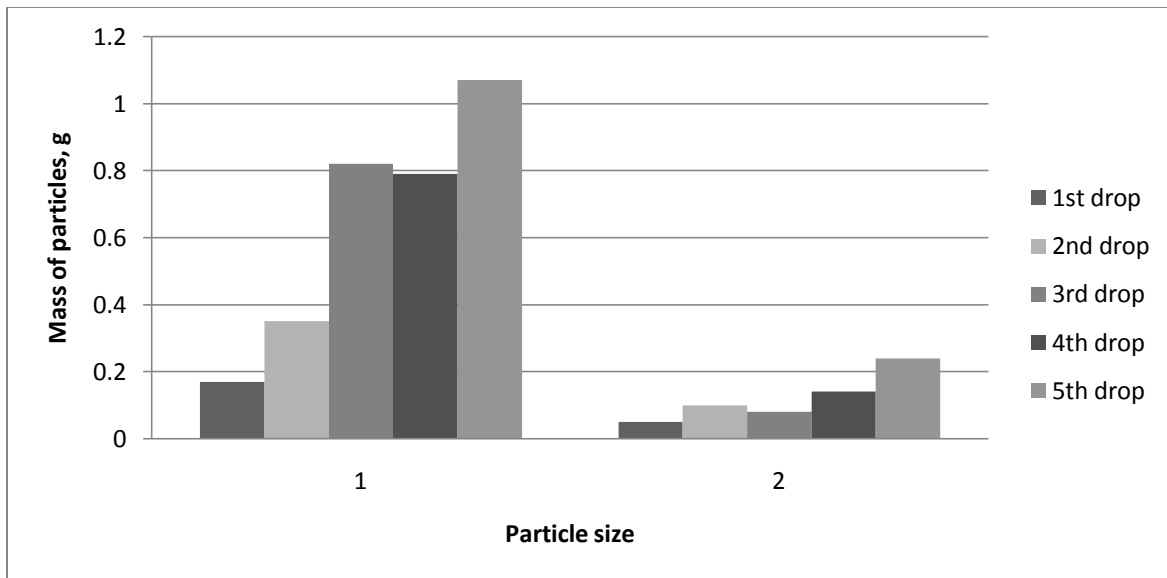


Figure 4.13 Mass of particles with size smaller than 0.25 mm: 1) 0.25 mm > size > 0.09 mm; 2) size < 0.09 mm.

4.4 Discussion

Observations for loading and unloading activities at the Fiberco Inc. yard show that the drop of pellets happens from different heights. The pellets may fall down from conveyers, truck loading, silo filling, vessel loading and so on. The height for the storage silos in Fiberco is 21 m. This height is close to the highest elevation in the Chemical and Biological Engineering building (CHBE). The drop height essentially decreases with time as a silo is being filled with wood pellets.

Two possible ways of arranging the pellets for the drop test were considered at the outset of the experiments. The first method is to drop single pellets one at a time. Obviously, this method does not simulate the real situation of filling a storage silo or movement of pellets from conveyor to conveyor during their handling. A single pellet will reach its terminal velocity soon after dropping and this would render the results obtained from high elevations less realistic. As the following equation shows:

$$V_t = \sqrt{\frac{2mg}{\rho AC_d}} \quad (6)$$

For example, if the mass of pellet is 0.8 g, dimensions of pellet are 6.3 mm X 24 mm and C_d is 1.05, then the terminal velocity will be 9 m/s.

The second method is to work with a large number of pellets which would exhibit average characteristics. Putting the pellets in a bag with small openings would enable air to go through the bag thus minimizing the air resistance; it would also be easier to collect the pellets after dropping onto the designated surface. This method was adopted to proceed with the experiment.

Drop height can affect the breakage of pellets linearly (Figure 4.14). If the material reaches a constant terminal velocity upon falling, then theoretically the percent breakage should not increase beyond the height at which the terminal velocity is attained. This suggests that percent breakage needs not be linear with the drop height and it may follow an exponential or logarithmic curve.

Concrete surface had more effect on breakage as it induced a higher momentum, dp or lower dt on the pellets, according to the theoretical development section in Chapter 3. For pellet bedding dt is longer and that makes the impact force smaller. This is evident from the smaller breakage experienced when pellets were dropped on pellet bedding (Figure 4.5 pellet bedding versus Figure 4.4 concrete surface).

Multiple drops were done in two manners. First the bags were cleaned each time before the next drop. Second, the bags were not cleaned and the dust and small broken pieces were kept inside the bags. In both cases the cumulative weight losses was about

10 percent (Figure 4.6). Cleaned bags exhibited slightly higher breakage which seems natural, as there was no cushioning from broken pellets or dust in the bag when they are removed. When pellets were dropped repeatedly, the cumulative weight losses increased linearly with the number of drops. Whether fines (broken particles) were sieved out or not had small effect on the results, likely due to the minor cushioning effect of the fines around the unbroken pellets.

Figure 4.15 shows the actual value of K_v (slope of the curve) in repeated drop tests for the bags of pellets after five drops. The K_v value of 0.01 reflects a relatively small breakage of pellets and it indicates the bulk strength of pellets.

Results plotted in Figure 4.9 reveal that the time for all samples with mass greater than 300 g had the same traveling time. They will reach the ground at the same time if they are released simultaneously. Having same traveling time suggests that the gravitational field is uniform and there is no air resistance. Table 4.3 and Table 4.4 also show the time durations that are required to reach the theoretical terminal velocities for different mass sizes using the formula below:

$$S = \left(\frac{v_t^2}{g} \right) \ln(\cosh(agt)) \quad (7)$$

The time durations are greater than the measured time (2.09 s). This also suggests that the terminal velocity cannot be reached at the height of 21 m.

Table 4.3 Parameters used for computing the theoretical terminal velocity

Bag Number	mass (kg)	Thickness (m)	Dimensions (m ²)	C_d (Flat)	C_d (Narrow)
1	0.1	0.01	0.2 x 0.26	0.8	0.47
2	0.2	0.02	0.2 x 0.26	0.8	0.47
3	0.3	0.03	0.2 x 0.26	0.8	0.47
4	0.4	0.04	0.2 x 0.26	0.8	0.47
5	0.5	0.05	0.2 x 0.26	0.8	0.47
6	0.6	0.03	0.28 x 0.33	0.8	0.47
7	0.7	0.04	0.28 x 0.33	0.8	0.47
8	0.8	0.05	0.28 x 0.33	0.8	0.47
9	0.9	0.05	0.28 x 0.33	0.8	0.47
10	1	0.03	0.33 x 0.5	0.8	0.47
11	2	0.06	0.33 x 0.5	0.8	0.47
12	3	0.09	0.33 x 0.5	0.8	0.47
13	4	0.13	0.33 x 0.5	0.8	0.47
14	5	0.16	0.33 x 0.5	0.8	0.47

Table 4.4 Terminal velocity of bags and the time required to reach it at 21 m

Bag Number	Projection area 1 (m ²)	Projection area 2 (m ²)	$V_{t,1}$ (m/s)	$V_{t,2}$ (m/s)	$V_{t,ave}$ (m/s)	T (s)
1	0.052	0.05	6.26	8.34	7.30	3.39
2	0.052	0.06	8.85	10.50	9.68	2.85
3	0.052	0.07	10.84	12.02	11.43	2.63
4	0.052	0.08	12.52	13.23	12.87	2.51
5	0.052	0.09	13.99	14.25	14.12	2.44
6	0.0924	0.09	11.50	15.15	13.32	2.48
7	0.0924	0.10	12.42	15.95	14.18	2.43
8	0.0924	0.10	13.28	16.67	14.98	2.40
9	0.0924	0.10	14.09	17.34	15.71	2.37
10	0.165	0.11	11.11	17.96	14.53	2.42
11	0.165	0.14	15.71	22.63	19.17	2.27
12	0.165	0.16	19.24	25.90	22.57	2.21
13	0.165	0.17	22.22	28.51	25.36	2.18
14	0.165	0.18	24.84	30.71	27.78	2.16

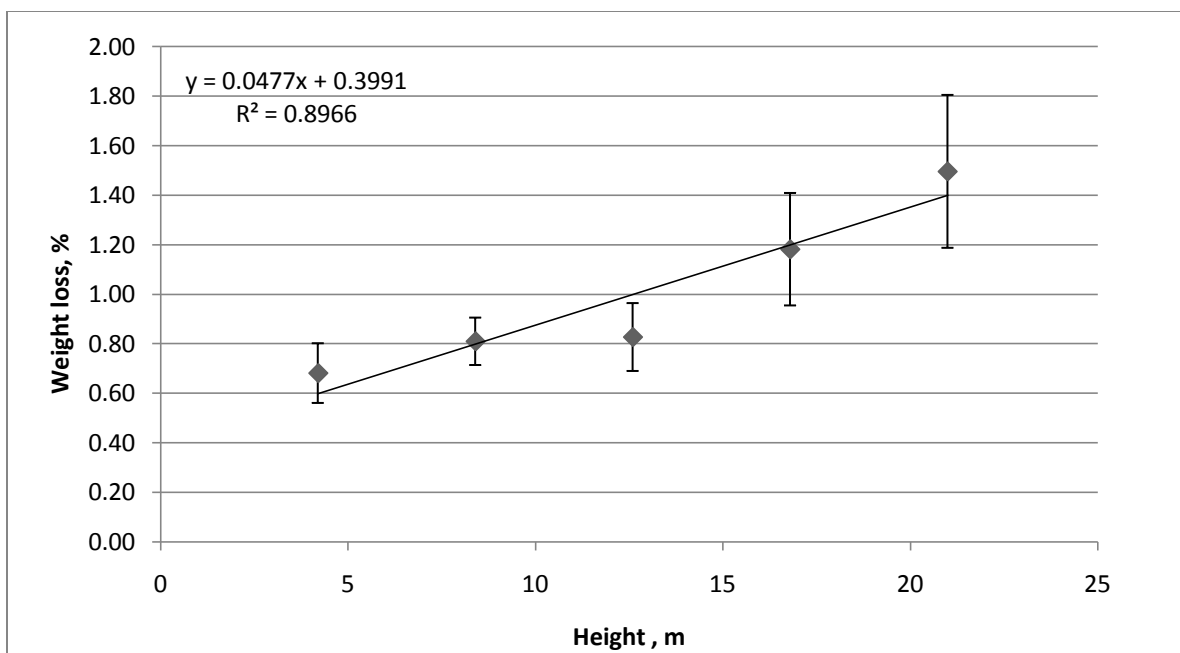


Figure 4.14 Weight loss vs. drop heights on concrete beddings.

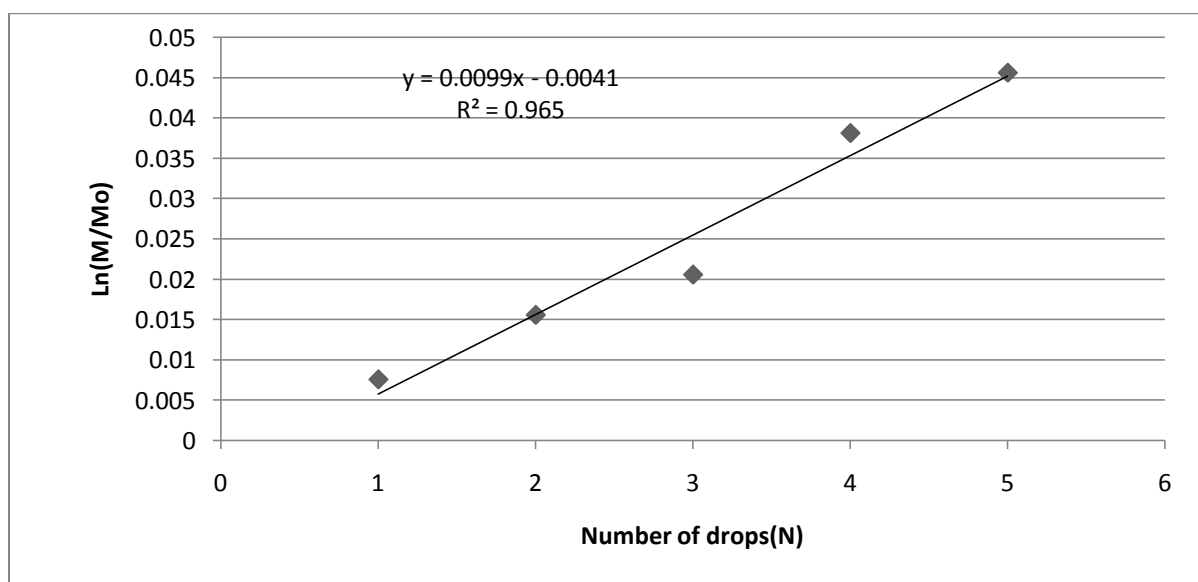


Figure 4.15 Determination of K_v (slope of the curve), indicating bulk strength of pellets.

4.5 Conclusions

Four series of experiments were performed to investigate the effects of drop height, bedding material, mass of pellets, and repeated handling (drops) on the breakage of pellets. The relation between pellet breakage and drop height was linear (the maximum height was 21m). A harder surface, i.e., concrete, had greater impact on pellets compared to softer bedding, a layer of pellets. Results of repeated drops showed that the accumulation of fines was approximately 10% after five drops. As for the effect of mass of pellets, results revealed a linear relation between drop height and mass of pellets for masses less than 1000 g. But for larger masses up to 5000 g an asymptote was observed.

Chapter 5 Relationships between the Dural, Tumbler and Drop Test Results

5.1 Introduction

Characterization of pellets helps to categorize the product in terms of its market value. The relevant physical properties are: dimensions, particle density, bulk density, moisture content, durability and calorific/heat value. Most physical properties of pellets change over time. The changes can be due to chemical reactions which are related to enzymatic activities, respiration or attack by microorganisms. Changes in physical properties arise from handling of the materials. Durability and moisture content are major properties, and these two parameters are related to each other. Moisture content of the raw material used for making high quality pellets is typically 9-12% (Tumuluru et al., 2010).

Durability is a qualifying index (Gil et al., 2010). It shows the amount of breakage of pellets during handling. The breakage causes dust which poses a health hazard (Vinterbäck, 2002). The dust may also contribute to fire or explosion (Lehtikangas, 2000).

Various devices are available to measure the durability of pellets (Lowe, 2005). Among the different techniques of durability measurements, the Tumbler tester, Ligno tester, Holmen tester, and Dural tester have been reviewed earlier in this thesis. Each device was evaluated based on criteria such as simplicity, availability and accuracy in measurements. For certain materials durability measurement is not a fixed number and it depends on the equipment setting.

5.2 Objective

The main goal of this chapter is to identify relationships between the durability measurements made on the Dural device and the tumbler tester, and the drop test.

5.3 Theory

Effectiveness of a densification process to produce strong and durable bonding in pellets can be determined through testing the strength and durability of the pellets. Usually, the strength tests refer to compressive resistance, impact resistance, and water resistance. Durability indicates the abrasion resistance of the densified products. In the standards relevant to durability measurements for pellets, durability is expressed as the percentage of unbroken pellets. The breakage could result from abrasion, compact, shear or friction. These tests can report the maximum force/stress that the densified product can withstand. The tests can also show the amount of fines produced during handling, transportation, and storage. In recent years, studies of the factors affecting the mechanical durability of biofuel pellets have been published (for instance, Bergstrom et al., 2008; Kaliyan and Morey, 2009; Samuelsson et al., 2009). Mechanical durability is a quality parameter, and it is defined as the ability of densified biofuels to remain intact when handled. Durability refers to the amount of fines that are recovered from pellets after they have been subject to mechanical or pneumatic agitation (Lehtikangas, 2001; Thomas and van der Poel, 1996).

5.3.1 Deformation and breakage of pellets

Pellets deform in response to applied force. If the force is high enough then cracking or splitting occurs, eventually leading to breakage. These breakages can be abrasion or chipping of pellets. The percent of breakage then shows how durable is the pellet. Most of the deformations in pellets are not reversible. Several factors affect the deformation and breakage in pellets. The factors include the rate at which force is applied, the history of previous loading, moisture content, and composition of pellet.

5.3.2 Compaction, impaction, friction and shear

Different types of forces can cause the breakage in pellets. While the pellets are stacked there is compaction force applying vertically on them. This force may be a reason for partial breakage in pellets. The pellets which are not crushed are more readily broken in the future when more force is applied to them. Compaction of pellets occurs in silos and warehouses. Pellets are dropped onto the surface when they are shipped or handled. There is impaction force that initiates the breakage. The impaction can be affected by the amount of pellets and the surface to which pellets are smashed against. Impaction decreases as the silo is filled. The maximum impact and minimum impact are related to an empty silo and a full silo respectively. In the handling of pellets, there are some frictions. While there is a flow of material the friction is generated. The friction could be between layers of pellets or between pellets and other surfaces. When

pellets hit the sharp edges, cut-off happens in pellets due to shear effect. The sharp edges can be found mostly in conveyers.

5.3.3 Durability testers

Equipments for durability measurements have different principles for the measurement. The structure, complexity, mass of sample, and the time required for performing the tests are varied in the testers. The force that causes the breakage is different in each machine. Each tester is applying one or more of the forces mentioned above (compaction, impaction, friction and shear) to simulate the breakage. The difference in force simulation is one of the factors that cause different results of durability for the same sample. The dominant forces in the durability testers are summarized in Table 5.1. The Dural tester is applying three major forces: impaction, friction and shear. Because of the complexity of the forces in the Dural, more pellets are broken and more fines are produced. In the other two methods, Tumbler tester and Drop test, less dust is produced as there are fewer forces simulated during the process.

Table 5.1 Durability testers and possible forces involved in each equipment

	Dural	Tumbler	Drop test
compaction	N/A	N/A	mild
impaction	major	minor	major
friction	major	major	minor
shear	major	N/A	N/A

5.4 Materials and method

At the beginning of the tests, samples were cleaned to remove all the dust and fines using 3.15 mm sieve according to ISO 3310-2 (1999). The pellets were shuffled using a Hoffman R89P Riffle divider (Hoffman MFG, Jefferson, OR). After each test the sample was cleaned again by the sieve with the same size, and unbroken pellets were measured and recorded. Durability was calculated using the formula:

$$Durability(\%) = 100 \frac{\text{mass left on screen after test (g)}}{\text{initial mass (g)}}$$

5.4.1 Test series I - wood and non-wood pellets

Test series I involved wood pellets and non-wood pellets derived from alfalfa, beet pulp, recycled paper. These tests were conducted side by side to compare the Dural and the Tumbler. In total eleven types of pellets were used. The pellets represent different qualities of densified pellets for use as biofuel. Each sample was tested three times. In Dural tester 100 g of sample was tested for a duration of 30s at 1615 rpm. In Tumbler tester, 500 g of pellets was treated for 10 minutes at 50 rpm.

5.4.2 Test series II - pine wood pellets

Test series II involved five types of pine wood pellets from different sources. The dimensions, moisture content and bulk density of the pellets are shown in Table 5.2. Durability tests were conducted using Dural, Tumbler and drop test. The number of replicates for each treatment was five. The setting for Tumbler tester was the same as

Test Series 1. Two different settings were used in Dural tester. In Dural setting #1, 100 g of sample was treated for 30s at 1615 rpm. In Dural setting #2, 200 g of sample was used, but the testing time was reduced to 15 s while the rotational speed was kept at 1615 rpm. The drop test took place on the 5th floor of Chemical and Biological Engineering Building (CHBE) at UBC with a drop height of 21 m. The samples were transferred to synthetic bags with woven mesh openings about 1 mm. The mass of each sample bag was 300 g. The bagged pellets were dropped onto concrete surface of the sidewalk. After each drop, the pellets were cleaned and the unbroken pellets were weighed to compute the durability.

Table 5.2 Test Series II – Bulk density, moisture content, diameter of pine wood pellets.

	Eagle Valley Dark	Eagle Valley White	Fire Master Premium	Horse Bedding	Stall Dry Bedding
Bulk density, kg/m ³	714 (4.37, n=5)	781 (5.56, n = 5)	750 (6.31, n = 5)	800 (5.89, n = 5)	740 (4.73, n = 5)
Moisture content, %	3.5 (0.21, n=3)	4.8 (0.17, n=3)	4.6 (0.25, n=3)	3.8 (0.31, n=3)	3.6 (0.28, n=3)
Diameter, mm	5.9 (0.19, n=20)	6.2 (0.23, n=20)	6.7 (0.29, n=20)	6.1 (0.21, n=20)	6.4 (0.26, n=20)

First number in brackets represents Standard Deviation and second number indicates replicate

5.5 Results

5.5.1 Test series I

Durability was calculated for the selected pellets and results are displayed in Table 5.3. The pellets were divided into two major groups: wood and non-wood pellets. When Tumbler was used the durability for wood pellets ranged from 95.6% to 99.2%. For non-wood pellets durability from Tumbler measurements varied from 97.5% to 99.3%. By comparison, when the Dural was used to determine durability, the wood pellets exhibited lower durability (49.8% to 83.1%), whereas the non-wood pellets also showed lower durability (74.0% to 87.9%).

Table 5.3 Test Series I – Durability measurements of wood and non-wood pellets (average is given in parenthesis; n = 3)

Alfalfa feed				Recycled Paper	Beet pulp	pine wood						
Sample No.	1	2	3	4	5	6	7	8	9	10	11	
Dural	75.4	79.2	84.0	87.5	72.3	83.0	69.1	75.4	59.7	66.3	49.4	
	77.0	81.1	86.2	88.1	74.9	84.4	69.5	73.0	60.8	64.6	49.3	
	75.9	79.0	85.4	88.2	75.0	81.9	69.3	72.3	60.7	63.1	50.6	
	(76.1)	(79.8)	(85.2)	(87.9)	(74.0)	(83.1)	(69.3)	(73.5)	(60.4)	(64.7)	(49.8)	
Tumbler	97.8	98.2	99.3	98.7	97.7	99.2	99.0	99.2	97.9	98.9	95.8	
	97.8	98.2	99.3	98.7	97.3	99.3	98.9	99.1	97.7	98.9	95.2	
	98.1	98.2	99.3	98.7	97.4	99.2	99.0	99.2	98.2	98.9	95.9	
	(97.9)	(98.2)	(99.3)	(98.7)	(97.5)	(99.2)	(98.9)	(99.2)	(97.9)	(98.9)	(95.6)	
Moisture content	4.7%	4.6%	3.8%	5.6%	4.8%	4.1%	9.3%	5.1%	3.5%	3.8%	3.5%	
1	Dehydrated alfalfa, Legal, Alberta				7	Eagle Valley Premium, pine						
2	Alfalfa feed for hamster				8	Horse bedding, pine						
3	Alfalfa feed, Pro-form				9	Dark sample, Fiberco						
4	Recycled paper				10	White sample, Fiberco						
5	Beet pulp feed, Pro-Form				11	Eagle Valley, Dark, broken						
6	Stall Dry, soft wood, pine											

Figure 5.1 shows the linear relationship (obtained using Excel function) between durability measurements of all samples (wood pellets and non-wood pellets) when Dural and Tumbler are used for the measurements. The insignificant correlation is not unexpected. In a similar manner, Timmerman et al (2006) observed the lack of correlation between Tumbler and another non-standard durability measurement device, the Ligno tester.

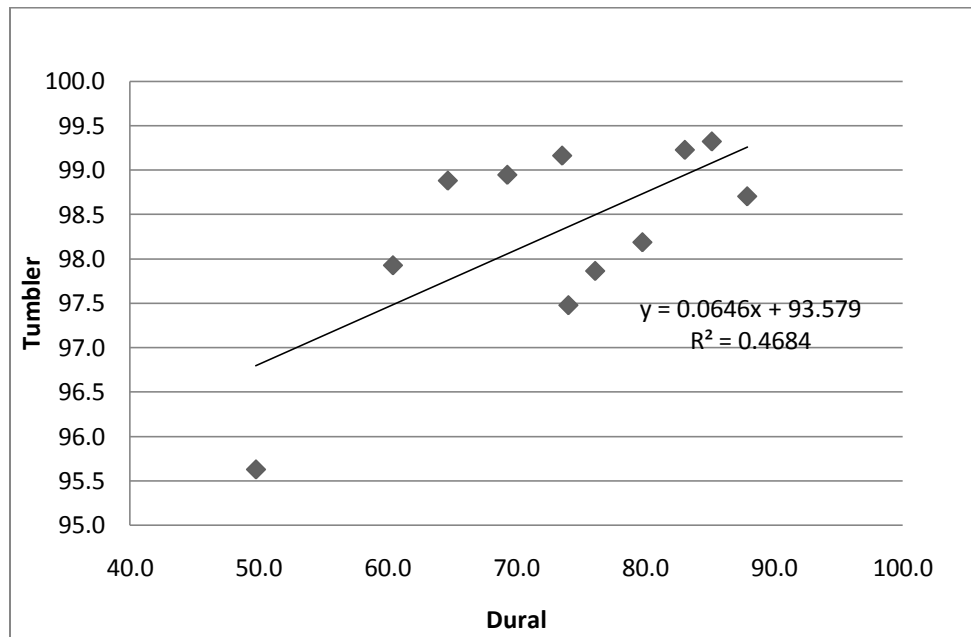


Figure 5.1 Durability measurements in Dural and Tumbler testers for woody and non-woody pellets.

With wood pellets only, a non-linear relationship was developed based on the Dural and the Tumbler durability measurements as demonstrated in Figure 5.2. Curve fitting with least squares optimization returns the expression:

$$y = 99.5299 - \exp(-0.0949x + 6.0817) \quad (1)$$

where x is the durability of Dural Setting #1 and y denotes durability measurement from Tumbler. As shown in Table 5.4, the accuracy of this fitted curve is high with maximum error as low as 0.32%.

Table 5.4 Comparison between actual and estimated durability for Tumbler

Pellet #	Dural, %	Tumbler (measured), %	Tumbler, (estimated), %	Error, %
6	83.1	99.2	99.4	0.17
7	69.3	98.9	98.9	0.02
8	73.5	99.2	99.1	0.08
9	60.4	97.9	98.1	0.22
10	64.7	98.9	98.6	0.32
11	49.8	95.6	95.7	0.05

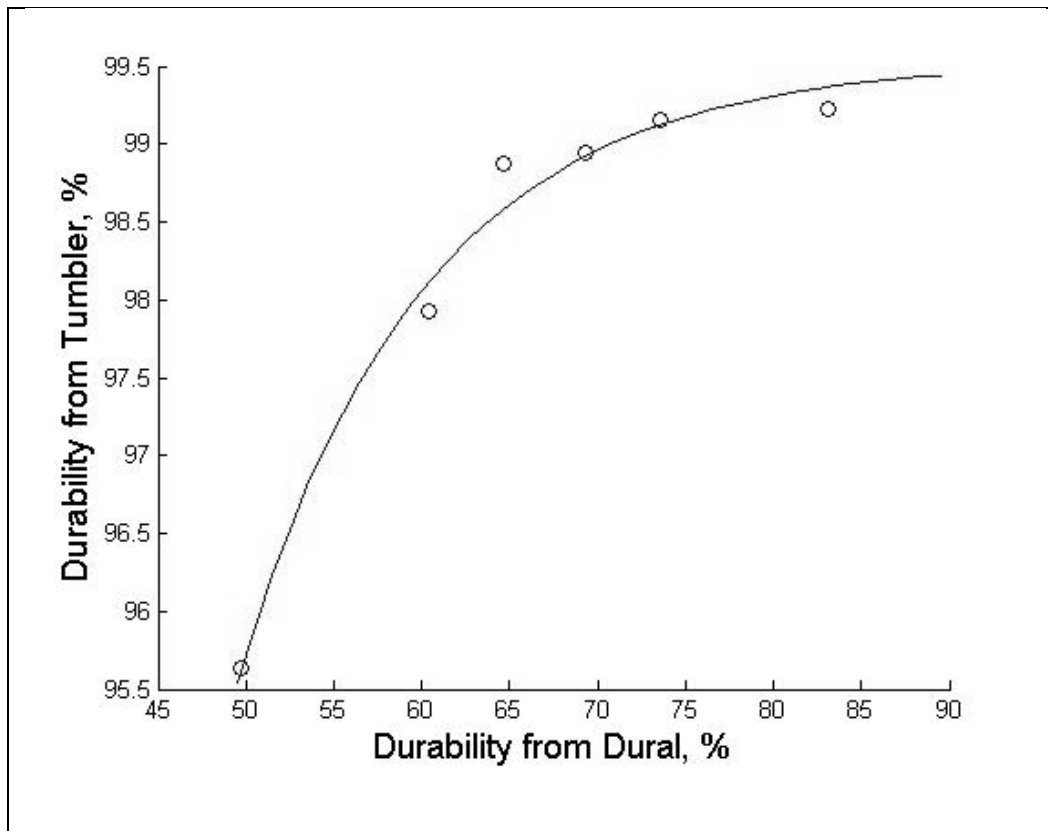


Figure 5.2 Durability measurements in Dural and Tumbler testers for woody pellets only

5.5.2 Test series II

For the pine wood pellets tested, durability ranged from 97.4% to 99.3% as estimated by the Tumbler (Table 5.5). For the Dural tester, operational setting #1 had durability of pellets varying between 65.4% and 81.1%, whereas setting #2 had durability of pellets varying from 81.2% to 92.3%. As in Test Series I, all five types of wood pellets have high durability values above 97.5% according to the Tumbler, and thus belong to the highest pellet quality class (CEN standard, 2005c).

Table 5.5 Test Series II - Durability of pine wood pellets using four methods. (numbers in the parenthesis are average and standard deviation; n = 5)

Wood pellets	Durability, %			
	Tumbler ^a	Dural Setting 1 ^b	Dural Setting 2 ^c	Drop Test ^d
Eagle Valley	98.6 - 98.9	67.1 - 68.3	84.2 - 85.5	97.3 - 98.3
Dark	(98.8, 0.1) ^e	(67.9, 0.7)	(85.1, 0.5)	(97.8, 0.4)
Eagle Valley	98.7 - 98.8	67.8 - 69.8	83.7 - 85.1	97.7 - 99.0
White	(98.7, 0.0)	(68.7, 0.8)	(84.4, 0.6)	(98.3, 0.5)
Fire Master	97.4- 97.6	65.4 - 69.3	81.2 - 83.5	96.7 - 98.1
Premium	(97.5, 0.1)	(67.3, 1.6)	(82.2, 0.9)	(97.5, 0.6)
Pine Horse	98.8 - 99.3	71.2- 73.7	87.6 - 88.0	97.7 - 99.1
Bedding	(99.0, 0.2)	(72.2, 0.9)	(87.9, 0.2)	(98.4, 0.5)
Stall Dry	99.0 - 99.1	79.0- 81.1	91.5 - 92.3	98.5 - 99.1
Bedding	(99.1, 0.0)	(80.0, 0.8)	(91.9, 0.3)	(98.9, 0.3)

^a mass 500 g, duration 10 min, rotational speed 50 rpm

^b mass 100 g, duration 30 s, rotational speed 1615 rpm

^c mass 200 g, duration 15 s, rotational speed 1615 rpm

^d mass 300 g, dropping height 21.0 m

^e (mean, standard deviation)

5.6 Discussion

5.6.1 Test series I

For the wood pellets, the differences in measurements due to Tumbler versus Dural vary from 16.1% to 45.8%. According to the European standard CEN/TS 14961 (2005c), high durability pellets are defined as those attaining a pellet durability index PDI of 97.5% or above. In this standard Tumbler is suggested for durability measurement. As such, all types of wood pellets used in the test would qualify as highly durable. Even though data is limited, Figure 5.2 indicates that with the Dural tester, the results are significantly different from the Tumbler tester. There is a threshold durability value for the Tumbler (around 98.5%), below which the Dural tester shows a better resolution (larger range of durability). A better resolution will allow us to distinguish between different types of pellets with more confidence. This represents the first attempt to demonstrate that the Dural tester could be more useful than the Tumbler for durability measurements, especially for wood pellets having a lower durability.

ANOVA is conducted for both Dural and Tumbler tests, and the p-values are 2.11×10^{-21} and 2.32×10^{-17} respectively. These two values are much lower than the typical thresholds of 0.005-0.05. This confirms that the individual pellet type highly influences the variability of the measurements. The standard deviations indicated that the measurements with higher durability have less variability, and conversely pellets with lower durability have more variability. A comparison of the coefficients of variation (CV) indicated that the Tumbler leads to lower variability compared to Dural. A linear regression analysis was conducted with results given by the Tumbler versus the Dural (Table 5.6). For the wood pellets only, the coefficient of determination (R^2) for the

regression line is 0.756, implying that the durability measurements due to Tumbler and Dural have a fairly good degree of correlation. Figure 5.1 proves that the durability changes within a narrow range in the Tumbler against a broad range in the Dural when all types (woody and non-woody) of pellets were involved in the regression analysis. The degree of correlation is substantially improved when the wood pellets are isolated out for analysis. As seen in Figure 5.2, a quadratic relation was obtained with a R^2 of 0.988. This relationship between the Tumbler and the Dural suggests that when the Dural-measured durability was above 65%, the Tumbler-measured durability would be 99% or greater. It seems to reaffirm a major disadvantage of using the Tumbler for durability measurements, in that it has low resolutions, hence it could only present the durability results within a very narrow range.

Equation (1) which expresses the relationship between the Dural-derived durability and the Tumbler-derived durability of wood pellets was then subject to validation. Samples supplied from Fiberco Inc. were used for the validation tests. Each month they provided white and brown pellets to keep track of the physical characteristics of wood pellets. Among other properties, durability of the sample pellets was measured by Dural and Tumbler. Figure 5.3 shows the percentage errors between the measured durability from the Tumbler and the corresponding estimated values using equation (1), given the measured durability from the Dural. It is seen that for all samples except one outlier, the percentage error is within 1%.

Table 5.6 Test Series I & II - coefficients of linear regression, R^2

	Test series I			Test series II				
	T/D1	T/D1	T/D1	T/D1	T/D2	Dp/D1	Dp/D2	Dp/T
A	0.08	0.11	0.07	0.07	0.13	0.09	0.13	0.67
b	91.68	91.16	93.53	93.50	87.28	91.79	87.03	31.89
R^2	0.96	0.76	0.47	0.36	0.60	0.77	0.81	0.63
	(Alfalfa)	(Wood)	(All)	(Wood)	(Wood)	(Wood)	(Wood)	(Wood)

T: Tumbler (mass 500 g, duration 10 min, speed 50 rpm)
D1: Dural, setting #1 (mass 100 g, duration 30 s, speed 1615 rpm)
D2: Dural, setting #2 (mass 200 g, duration 15 s, speed 1615 rpm)
Dp: Drop test (mass 300 g, dropping height 21 m)

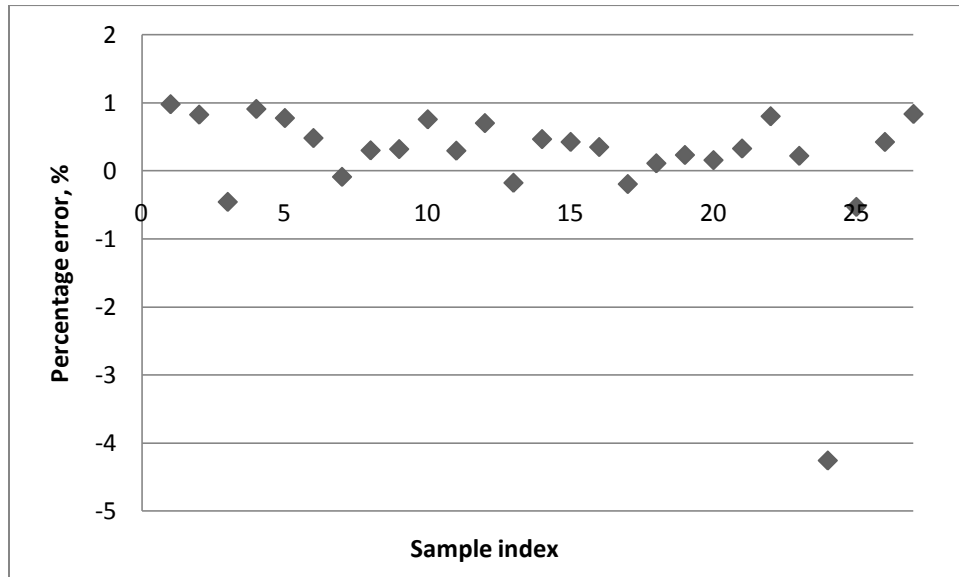


Figure 5.3 Percentage error between the actual and the estimated durability from the Tumbler, using 27 Fiberco pellet samples.

5.6.2 Test series II

As in Test Series I, all five types of wood pellets have high durability values above 97.5% as obtained from the Tumbler tester, and thus belong to the highest pellet quality class (CEN standard, 2005c). ANOVA test was conducted for the Dural settings versus Tumbler respectively. The p-values are 2.9×10^{-6} and 8.7×10^{-5} accordingly. The ANOVA analysis confirms that results due to Dural and Tumbler are significantly different. Comparison of the coefficients of variation indicates the higher variability of the Dural measurements.

Linear regression analysis was conducted with results given by the Tumbler and the Dural (Table 5.6). For these wood pellets, the coefficient of determination R^2 for the regression line is 0.357 for Dural setting #1 (100 g, 1615 rpm, and 30 s). The coefficient of determination improves to 0.598 for Dural setting #2 (200 g, 1615 rpm, and 15 s). Regression analysis was then extended to determine the relationship between the results obtained from Dural and Tumbler, respectively, and those from the drop test. The coefficients of determination R^2 for durability (drop test versus Dural setting #1), (drop test versus Dural setting #2) and (drop test versus Tumbler) are 0.773, 0.806 and 0.632 respectively. This means, again, Dural setting #2 durability correlates quite well with drop test durability, and the correlation is better than that with the Tumbler. It is further noted that measured results based on Dural setting #1 correlated quite well with those based on Dural setting #2 with $R^2 = 0.887$ (Figure 5.4). This implies the results are consistent for different types of wood pellets when the Dural machine was operated with different settings.

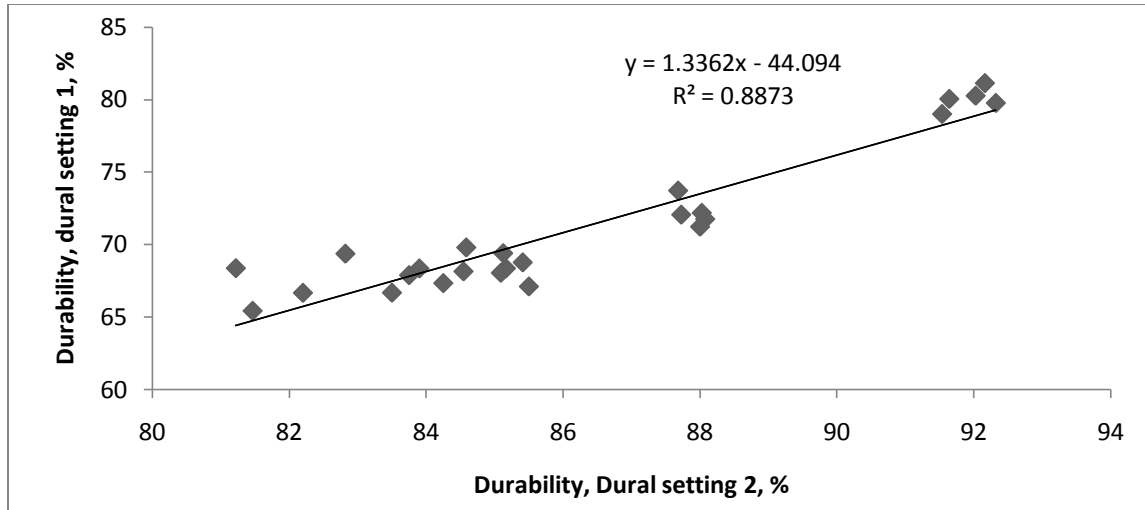


Figure 5.4 Correlation between durability measurements using Dural settings 1 and 2.

5.7 Conclusions

A low degree of correlation was found between Dural-derived and Tumbler-derived durability measurements when both wood and non-wood pellets were used and analyzed together using linear regression. However, when only the wood pellets were used, a higher degree of correlation was obtained using nonlinear regression between the Tumbler-measured durability and the Dural-measured durability. The correlation between the durability of pellets derived from Dural setting #2 was found to be significantly stronger against the drop test results, whereas Dural setting #1 and drop test had a slightly lower correlation. Therefore impact force could be the dominant mechanism causing breakage. By comparison, the correlation between Tumbler-derived durability and drop test results is relatively weak. Impact force might not be significant

with the Tumbler tester as it was operated at a much lower rotational speed of 50 rpm compared to the rotational speed of 1615 rpm with the Dural tester.

Chapter 6 Conclusions and Future Work

This chapter concludes the work on durability measurement using different methods including Dural, Tumbler and drop test. Possible future work is also recommended for continuing this research.

6.1 Conclusions

In this thesis, 1) a consistent method of durability measurement using Dural tester was developed, 2) drop test was performed for determining the effect of different factors on breakage of pellets including height, sample size, number of repeated drops, type of bedding and type of pellet, and 3) correlations of durability measurement among Tumbler, Dural and drop test were investigated.

6.1.1 Dural

In Chapter 2 the appropriate setting for reliable durability measurements using Dural was studied. A series of experiments were conducted using eight different machine settings and four types of pellets. It was found that both pellet types and machine settings are statistically significant. The machine setting with sample mass 200 g, testing time 15 s and rotational speed 1615 rpm gave the highest durability with the least standard deviation, consistently among the four types of pellets. Besides, its output covered a wide range of durability values. Thus, such a setting (200g, 15s, 1615 rpm) is considered to be most appropriate when the Dural tester is adopted to determine the durability of wood pellets. This setting can potentially overcome the major

shortcomings of using the Tumbler tester for wood pellets durability determination, which are long in experiment duration and low in resolution.

6.1.2 Drop test

Five series of experiments were performed to investigate the effect of pellet type, drop height, bedding material, mass of pellets, and repeated handling (drops) on the breakage of pellets in drop test. Results showed that i) the breakage of pellets varied for different types of pellets; ii) the pellets that were more durable generated less dust; iii) the relation between pellet breakage and drop height was linear; iv) higher elevation produced more dust; v) the amount of dust and fine particles generated depended on the bedding material - a harder surface such as concrete had greater impact on pellets compared to softer bedding such as a layer of pellets; vi) tests with repeated drops returned the highest values of dust and fine particles production among all factors - the percentage of dust increased significantly after each drop as the pellets tended to break more readily; and the accumulation of fines was approximately 10% after five drops; and vii) a linear relation was found between drop height and mass of the pellets for sample size lower than 1000 g while an asymptote was observed for sample sizes greater than 1000 g.

6.1.3 Correlation

The correlations of durability results among Dural, Tumbler and drop test were studied. Low linear correlation between Dural and Tumbler durability measurements was observed when a mixture of wood and non-wood pellets was used. However, using the wood pellets only led to a much higher correlation between the Tumbler-measured durability and the Dural-measured durability with a logarithmic curve. This fitted curve was verified using 27 samples whereby durability was measured using both Dural and Tumbler; the error between the estimated and the actual durability is less than 1%. The correlation of the durability of pellets was found to be significantly stronger ($R^2 = 0.81$) when Dural machine setting #2 (mass 200 g, rotational speed 1615 rpm and testing time 15 s) and drop test were used. By comparison, the correlation between Tumbler and drop test is lower with $R^2 = 0.63$. Since the drop test simulates several handling processes of wood pellets, these results are encouraging for the potential applicability of the Dural tester for wood pellets durability measurements.

6.2 Recommendations for future work

The following recommendations are made for future experimental work, with the primary aim to deduce a standard method for using the Dural tester for wood pellets durability determination. Recommendations also concern the investigation of other parameters that can affect durability of pellets during handling and storage.

- a) The current Dural has only two settings for rotational speed (1615 and 1740 rpm). Finding the best rotational speed for Dural requires a change in the current equipment. Starting the rotational speed from the initial high value 1615 rpm and progressively lowering it to 50 rpm may improve with respect to the testing of wood pellets.
- b) Conducting a greater number of Dural versus Tumbler tests in order to verify whether the Dural could potentially overcome the shortcomings of the Tumbler tester in terms of the resolution of durability measurements.
- c) A greater number of drops will lead to larger extent of breakage in the wood pellets. It is desirable to find the maximum number of allowable drops that can help to reduce dust generation in silos due to breakage of pellets.
- d) Performing the drop test at elevations greater than 21 m would be beneficial as silo height and depth of ocean vessel containers can be somewhat larger than this value.
- e) The pellets were dropped at essentially zero initial velocity in the drop tests. In silo filling operation, pellets usually leave the conveyor with a certain initial velocity. It is useful to repeat the drop test with a predetermined initial velocity, in order to observe the behaviour of the pellets upon hitting the ground.
- f) Overburden pressure over an extended time period during storage is another major factor that may cause breakage in pellets. The effect of overburden pressure was not investigated in this study, and it is recommended for future studies.

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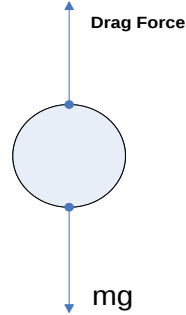
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Appendix I Terminal Velocity Determination

A. Time, distance and terminal velocity



$$m \frac{dv}{dt} = mg - Kv^2 \quad (1)$$

$$K = \frac{1}{2} Cd * A * \rho \quad (2)$$

Cd = drag coefficient(decimal)

A = projected area(m^2)

ρ = air density($\frac{Kg}{m^3}$)

Integrate equation (1) to yield:

$$\int \left(\frac{dv}{1-a^2V^2} \right) = g \int dt \quad (3)$$

$$\left(\frac{1}{2a} \right) \ln \left(\frac{1+aV}{1-aV} \right) = gt + C \quad (4)$$

$$\left(\frac{1}{2a} \right) \ln \left(\frac{1+aV}{1-aV} \right) = g \quad (\text{at } t=0, V=0) \quad (5)$$

$$\frac{1+aV}{1-aV} = e^{2agt} \quad (6)$$

$$V = \left(\frac{1}{a} \right) \frac{e^{2agt} - 1}{e^{2agt} + 1} \quad (7)$$

$$V = \frac{ds}{dt} \quad (S=\text{distance travelled}) \quad (8)$$

$$\frac{ds}{dt} = \left(\frac{1}{a}\right) \left(\frac{e^{agt} - e^{-agt}}{e^{agt} + e^{-agt}}\right) = \left(\frac{1}{a}\right) \tanh(agt) \quad (9)$$

$$ds = \left(\frac{1}{ga^2}\right) \tanh(agt) (agt) dt \quad (10)$$

$$S = \left(\frac{1}{ga^2}\right) \ln(\cosh(agt)) + C2 \quad (11)$$

$$S = \left(\frac{1}{ga^2}\right) \ln(\cosh(agt)) \quad (at \ t = 0, S = 0, C2 = 0) \quad (12)$$

We had

$$V_t = \left(\frac{2mg}{\rho A C_d}\right)^{0.5} \quad (13)$$

$$V_t = \left(\frac{mg}{0.5\rho A C_d}\right)^{0.5} \quad (14)$$

$$V_t = \left(\frac{mg}{K}\right)^{0.5} \quad (15)$$

$$k = \frac{mg}{V_t^2} \quad (16)$$

$$a^2 = \frac{k}{mg} \quad (17)$$

$$a^2 = \frac{1}{V_t^2} \quad (18)$$

$$a^2 = \left(\frac{1}{sg}\right) \ln(\cosh(agt)) \quad (19)$$

$$\frac{1}{V_t^2} = \left(\frac{1}{sg}\right) \ln(\cosh(agt)) \quad (20)$$

$$S = \left(\frac{V_t^2}{g}\right) \ln(\cosh(agt)) \quad (21)$$

We have S and t , V_t can be estimated from this equation.

For 3.2s and 21 m the calculated terminal velocity is about 7.96 m/s.

For 2.5s and 21 m the calculated terminal velocity is about 13.05 m/s.

For 2.15s and 21 m the calculated terminal velocity is about 48.08 m/s.

The equation is sensitive to time and 2.15 is critical value.

Mohsenin, N.N. (1986)

B. Impact

Maximum deformation of a solid mass dropped on a plane surface is expressed: $D_{\max}$

$$D_{\max} = \left(\frac{15V_1^2 Am}{16\sqrt{R}} \right)^{\frac{2}{5}} \quad (22)$$

Where V is the velocity of impact (10-20m/s)

And A is defined as:

$$A = \frac{1-\mu_1^2}{E_1} + \frac{1-\mu_2^2}{E_2} \quad (23)$$

E_1 is modulus of elasticity of body one

E_2 is modulus of elasticity of body two

μ_1 is poisson's ratio of body one

μ_2 is poisson's ratio of body two

m is mass of the particle (pellet)

k radius of the particle (pellet)

If we know critical $D_{\max}$ then we know if the particle breaks:

$$t = 4.53 \left(\frac{Am_1}{\pi\sqrt{R_1V_1}} \right)^{\frac{2}{5}} \quad (24)$$

$$S_{\max} = 0.2515 \left(\frac{\pi V_1^2 m_1}{A^4 r_1^2} \right)^{\frac{1}{5}} \quad (25)$$

Sample calculation of equations 22 to 25

The following values have been incorporated in the above formulas:

$\mu_1=0.1$, $\mu_2=0.2$, $E_1=1885520\text{psi}$, $E_2=4351200\text{psi}$,

$v=787.4016\text{in/s}$, $m_1=4.55487\text{E-}06(\text{lb-sec}^2/\text{in})$, $r_1=0.6\text{in}$.

We get

$A = 7.45683\text{E-}07$ /psi,

$D_{\max}=0.0058\text{in}$,

$t=2.16463\text{E-}05$ sec,

and $S_{\max}=38178.8$ psi.

C.Terminal Velocity sample calculation

$$V_t = \sqrt{\frac{2mg}{\rho A C_d}}$$

V_t = terminal velocity (m/s),

m = mass of the falling object (kg),

g = acceleration due to gravity (m/s^2),

C_d = drag coefficient,

ρ = density of the fluid through which the object is falling (kg/m^3)

A = projected area of the object (m^2).

1) Pellets

Data from Mohsenin (1986)

Mass of pellet = 0.8 gr

Dimensions of pellet = 6.3mm X 24mm

$C_d= 1.05$

Case 1: Longer side of pellets perpendicular to the axis of fall

$$V_t = \sqrt{\frac{2mg}{\rho A C_d}} = \sqrt{\frac{2 * 0.0008 * 9.81}{1.2041 * 6.3 * 24 * 0.001 * 0.001 * 1.05}} = 9 \text{ m/s}$$

Case 2: the pellet fall on with their longitudinal axis parallel to the axis of fall

$$V_t = \sqrt{\frac{2mg}{\rho A C_d}} = \sqrt{\frac{2 * 0.0008 * 9.81}{1.2041 * 3.14 * 3.15 * 3.15 * 0.001 * 0.001 * 1.05}} = 19.96 \text{ m/s}$$

Average= (9+19.96)/2=14.48 m/s

2) Pellets-Firemaster

Mass of pellet = 0.69 gr

Dimensions of pellet = 7.33mm X 15.13mm

Cd= 1.05

The mass and dimensions of pellets are the averages obtained from 165 samples of pellets.

Case 1: Longer side of pellets perpendicular to the axis of fall

$$V_t = \sqrt{\frac{2mg}{\rho A C_d}} = \sqrt{\frac{2 * 0.00069 * 9.81}{1.2041 * 7.33 * 15.13 * 0.001 * 0.001 * 1.05}} = 9.82 \text{ m/s}$$

Case 2: the pellet fall on with their longitudinal axis parallel to the axis of fall

$$V_t = \sqrt{\frac{2mg}{\rho A C_d}} = \sqrt{\frac{2 * 0.00069 * 9.81}{1.2041 * 3.14 * 3.67 * 3.67 * 0.001 * 0.001 * 1.05}} = 15.91 \text{ m/s}$$

Average= (9.82+15.91)/2=12.84 m/s

3) Bags

- Mass of pellets in the bag= 300 g
- Dimensions of bag are 180 mm x 200 mm and about 10 mm thick.
- Bulk density of 0.85 g/cm³.
- C_d=0.80 from Mohesenin (1984)

The bag falls on its flat side (V1)

$$Vt = \sqrt{\frac{2mg}{\rho A C_d}} = \sqrt{\frac{2 * 0.3 * 9.81}{1.2041 * 180 * 200 * 0.001 * 0.001 * .8}} = 13.02 \text{ m/s}$$

The bag falling on the narrow side (V2)

Diameter of spherical ball of bag is roughly 44 mm.

Projected area is 0.0015 m² and Cd is 3.

$$Vt = \sqrt{\frac{2mg}{\rho A C_d}} = \sqrt{\frac{2 * 0.3 * 9.81}{1.2041 * .0015 * 3}} = 33 \frac{m}{s}$$

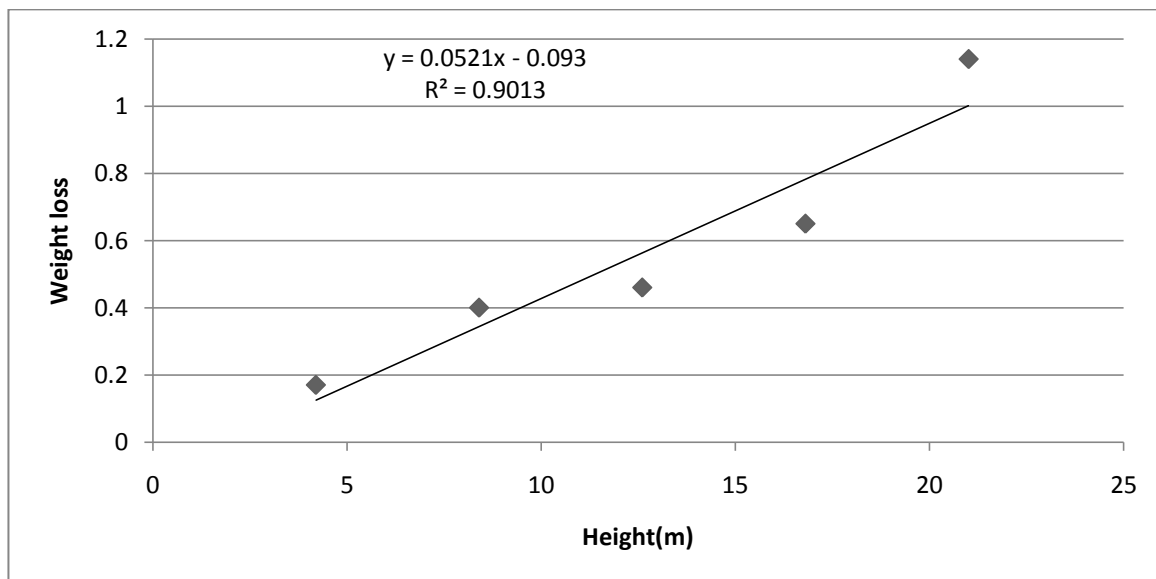
The average velocity= (33+13.02)/2= 23.01 m/s

Appendix II Breakage Calculation in Silos

A single pellet is considered with a diameter of 6.3 mm and length of 24 mm and the density of is 1200 kg/m³.

A) Total breakage calculation using integration method

The setting of our particular experiment in drop test shows the linear relationship as shown in below



Weight loss vs. height where pellets were dropped from

Based on this graph, the total breakage of pellets can be computed as below:

$$Bx = 0.0521x - 0.093$$

$$Total\ Breakage = \int_0^{21} \rho A Bx \, dx = \rho A \int_0^{21} Bx \, dx = \rho A \int_0^{21} (ax + b) \, dx =$$

$$\rho A \int_0^{21} (0.0521x - 0.093) \, dx$$

$$Total\ Breakage = \rho A (0.5 * 0.0521x^2 - 0.093x) \Big|_0^{21}$$

where $\rho = 1200 \text{ kg/m}^3$ while projection area can be either rectangular or circular. In our case, $A(\text{rectangular}) = 0.0001512 \text{ m}^2$ and $A(\text{Circular}) = 3.11567 \text{E} - 05 \text{ m}^2$. Therefore,

i) Breakage of pellet with rectangular projection is

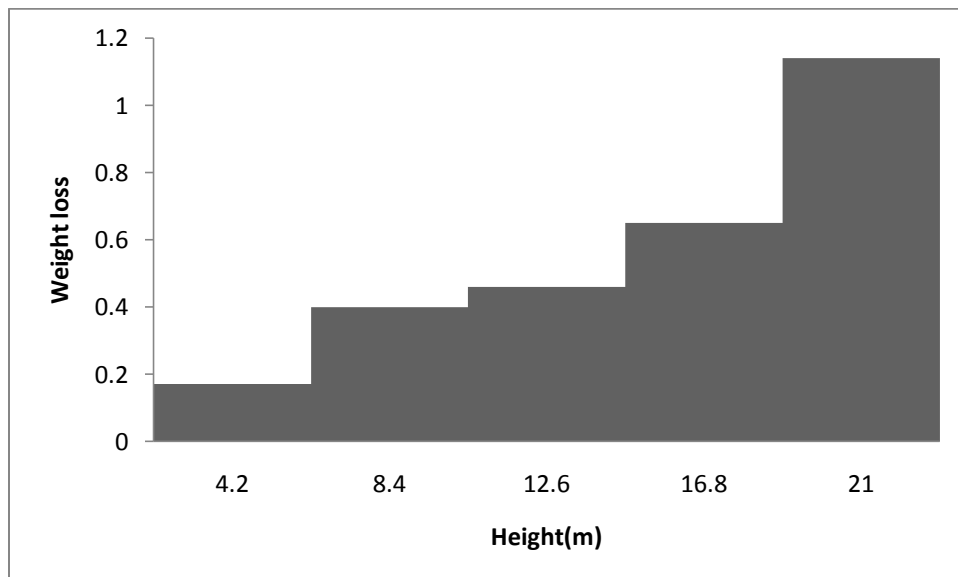
$$\text{Total Breakage} = 1200 * 0.00011512(0.5 * 0.0521 * 21^2 - 0.093 * 21) = 1.31$$

ii) Breakage of pellet with circular projection area is

$$\text{Total Breakage} = 1200 * 3.11567 \text{E} - 05(0.5 * 0.0521 * 21^2 - 0.093 * 21) = 0.36$$

Hence, the average weight loss is 0.83%.

B) The total breakage is calculated by right-end point method



i) Breakage of pellet with rectangular projection are

$$\text{Projection area of pellet (m}^2\text{)} = 0.0063 \text{m} \times 0.024 \text{m} = 0.0001512$$

$$\text{Accumulative of weight loss} = 0.17 + 0.4 + 0.46 + 0.65 + 1.14 = 2.82$$

$$\begin{aligned} \text{Total Weight loss} &= \rho * A * \Delta x * \text{accumulative weight loss} = 1200 * 0.0001512 * 4.2 * 2.82 \\ &= 2.15\% \end{aligned}$$

ii) Breakage of pellet with circular projection area

$$\text{Projection area of pellet (m}^2\text{)} = (0.0063/2) * (0.0063/2) * 3.14 = 3.11567E - 05$$

$$\begin{aligned} \text{Total Weight loss} &= \rho * A * \Delta x * \text{accumulative weight loss} = 1200 * 3.11567E - 05 * 4.2 * 2 \\ &= 0.44\% \end{aligned}$$

$$\text{Average weight loss} = 1.3\%$$