# Influence of particle size on strength of pelleted feed

Carlos Salas-Bringas[1], Nevena Mišljenović[2], Trude Wicklund[3], Odd-Ivar Lekang[1] and Reidar Barfod Schüller[3]

[1]Dep. Of Mathematical Sciences and Technology, Norwegian University of Life Sciences, P.O. Box 5003, N-1432 Ås, Norway

[2]Faculty of Technology, University of Novi Sad, Bulevar C. Lazara 1, 21000 Novi Sad, Serbia

[3]Dep. Of Chemistry, Biotechnology and Food Science, Norwegian University of Life Sciences, P.O. Box 5003, N-1432 Ås, Norway

## ABSTRACT

It is known that particle size of raw materials (e.g. cereals) affect the strength of pelleted feed. Previous research used pellet presses for these comparisons. However, pelleting pressure and temperature are affected by particle size, meaning that it is not possible to compare the effect of the different size fractions separately using the same pressure, temperature and moisture content. This research uses a new laboratory pelleting press to analyse the effects of particle size on pellet strength under the same pressure, temperature and moisture content.

## INTRODUCTION

Preceding pelleting of animal feed, it is required a size reduction of grains like wheat, barley or corn. Different particle sizes are recommended for the nutritional intake of different animals, for example coarse particles are required for ruminants while other organism like shrimp required smaller particle sizes. Besides the nutritional requirements, it is important to manufacture the pellets with enough strength to withstand the stresses during handling. The smallest fractions of broken pellets created by fracture and attrition during handling, are avoided by many animals or they can be dissolved in water, causing environmental and economical problems[1].

During grinding, the different parts of the grain are reduced (i.e. endosperm, germ and brand). These parts have different composition, for example the endosperm contains complex carbohydrates, B-complex vitamins and proteins, the germ contains essential fatty acids, vitamin E, B-complex vitamins and trace minerals while the Bran contains fibres, B-complex vitamins, trace minerals and phytonutrients[2].

Hammer mills grind by impact and in lower level by attrition[3, 4]. These stresses affect differently the different parts of the grain because they are chemically different as described previously, and for this reason they must be rheologically different (e.g. different yield strength, E-modulus, etc). As a result, since the different parts of the grain have different strengths and deformation characteristic, a same grinding process is likely to produce different size reductions for the different parts of the cereal. For example the same impact strength could break an endosperm, but might only inflict a minor damage in a loose fibre.

Besides the different size reductions caused by the different rheological properties of the constituents of a grain, the different constituents will also produce different bonds in the pellet. It is widely known that during pelleting process and steam conditioning, the main components of the feed (starch, proteins and fibres) suffer chemical modifications which are caused by the thermo-mechanical work (moisture level, temperature, pH, pressure, shear and residence time). The intensity of these changes influences the physical quality, for example it is widely agreed that starch can act as binder when is gelatinized by heat and moisture[5, 6].

The main goal of the present article is to study the effects of the different size fractions over the strength of pelleted feed. This study uses ground wheat grain by hammer mill and the differences in pellet strength are planned to come only by the effects of the size fractions. Consequently, the study requires the manufacture of pellets under equal conditions of pressure and temperature for all different size fractions which is impossible to be achieved in an industrial pellet press. The reason is because pelleting pressure and temperature depends on the size fractions. Furthermore, pressure is difficult to be measured in a pellet press[7]. During an industrial pelleting process, all particle sizes are part of a recipe (mixture), and consequently all particles are produced at the same temperature and pressure, but they cannot be produced at the same conditions if they are pelleted separately, reason why this research uses a new laboratory pelleting equipment[8-10].

## MATERIALS AND METHODS

### Raw material

Ground wheat was obtained from the Centre for Feed Technology pilot plant (FôrTek), located at the Norwegian University of Life Sciences, Ås, Norway. Wheat was ground in an 18 kW hammer mill having a 3 mm mesh (Münch-Edelstahl, Wuppertal, Germany).

The moisture content in the ground wheat and fractions was determined gravimetrically in a scale after drying for 20 hours in an oven (Termaks, Norway) at 105 °C.

### Preparation of the size fractions

To select the size fractions that were used to produce the pellets, it was first done a mapping of the particle size distribution of the ground wheat obtained from FôrTek pilot plant (see Fig. 1). This analysis was performed with a vibrating sieving set to 1.5 mm amplitude during 60 seconds. The screens used were 0.1 mm, 0.5 mm, 1 mm, 1.6 mm and 2 mm. A collector was used at the bottom to gather the particles < 0.1 mm. According to this analysis (see Fig. 1) it was decided to separate the sample in the following four different fractions, F, as follows: F1 < 0.5 mm, 0.5 mm < F2 < 1 mm, 1 mm < F3 < 1.6 mm and 1.6 mm < F4. The criterion for choosing these four fractions is included in the section for results and discussions. The fractions can be seen in Fig. 2.

### Pelleting method

All pellets used in this research were produced in the laboratory die pelleting rig presented by Salas-Bringas et al [8, 9]. The rig was assembled in a Lloyd LR 5K Plus texture analyzer. This equipment has been previously used to produce wood[8, 9] and buttermilk[10] pellets. The die pelleting rig consists of a barrel made of brass having a compressing channel along the center. The compressing channel has a diameter of 5.5 mm and a 5.4 mm diameter rod was used to press the samples against a blank die. Using this configuration, the system can produce compacting stresses up to 218 MPa. To release the pellets from the compressing channel, the blank die was disassembled from the barrel.

The barrel was heated by a jacket heater of 550 W which is controlled by a PID connected to a thermocouple in contact with the barrel surface.

The temperature was set to 82 ºC to manufacture all pellets. 81 ºC is the minimum temperature that is required in Norway[11] to disable *Salmonella* and to reduce the number of bacteria. However, the feed industry normally uses a minimum of 82 ºC as an assurance. This is the reason why 82 ºC was chosen in our experiments.

### Compressibility of ground wheat

To produce pellets having a density of similar magnitude to the ones coming from pellet presses, it was necessary to measure the density of pellets rich in wheat from the pelleting line at FôrTek pilot plant. Since pellets are fractured by knives at the exit of pellet presses, the cylindrical pellets have irregular ends making it difficult to estimate an accurate length, and consequently only the diameter could be determined with confidence. To obtain a better estimation of density, an average density was calculated based on a cylindrical volume for each of the 18 pellets per group with the standard error of the mean (± SE).

To know which compressive stress can be used to produce pellets of similar density to the ones from FôrTek pilot plant, a mapping was first done of the pellet densities at different compressive stresses for all different fractions (shown in Fig. 3). 18 pellets were manufactured for each of the compressive stresses shown in Fig. 3. The Lloyd LR 5K texture analyzer was set to compress with the following forces: 125, 250, 500, 750 and 1000 N. The average density for each group is presented in Fig. 3 with the SE in the error bands.

### Influence of particle size on pellet strength

Once the compressibility data was obtained for the ground wheat (referred as "entire particle size distribution" - EPD), it was done a curve fit to EPD data to find the compressive stress that can produce pellets with a similar density to the pellets produced at FôrTek pilot plant (ref. Fig. 3). Thereafter all fractions (F1, F2, F3 and F4) of ground wheat were compressed to this compressive stress to analyze the resulting pellet strength.

A length to diameter (L/D) ratio of 2 was chosen to manufacture the pellets because L/D ≥ 2 are commonly found in commercial pelleted feed.

The manufactured pellets were stored in plastic bags and used for the stress analysis the day after to ensure an even temperature between the core and surface.

### Strength tests

The strength tests were performed in diametral compression because it has been shown [12] that the diametral compression test produced a smaller dispersion in the results than the uniaxial test. In addition, the diametral compression test is the most common stress analysis used on pelleted feed.

### Statistical analysis

To analyse significant differences among the strength means of the fractions, the ANOVA - Tukey method in Minitab software (Minitab Inc, USA) was used. The SE was also calculated for these averages.

## RESULTS AND DISCUSSIONS

### Raw material

The initial moisture content in the ground wheat (EPD) was 15.27 ± 0.05 ($n$ = 3, where $n$ is the number of samples). The moisture content found on each fraction is presented on Fig. 1.

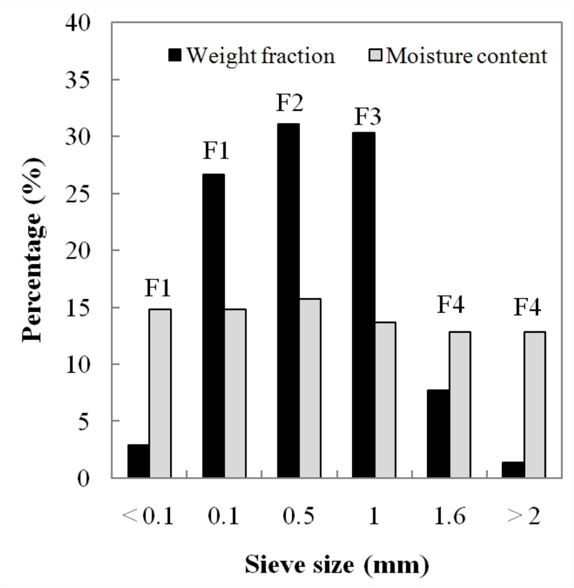


Figure 1: Particle size distribution and average moisture content of wheat grains ground in a hammer mill. F1, F2, F3 and F4 represent the size fractions used to manufacture the pellets.

Fig. 1 shows that the moisture content among the fractions were relatively similar, however it is possible to observe that the larger size fractions (F3 and F4) have slightly less water. It is assumed that 20 hours of drying at 105 °C is enough time to diffuse all water trapped at the inside of the grains and therefore these differences might be attributed to a higher drying of the small fractions during the grinding process. The raw materials after hammer mills normally have an increased temperature that last for relatively short time. The diffusion of water through the smaller particles is quicker than through the larger particles and this could explain the small differences in moisture.

Preparation of the size fractions

The analysis of the particle size distribution from EPD is shown in Fig. 1. The figure shows that the particle sizes were normally distributed.

The criterion for selection of the size fractions was based on the particle sizes obtained in Fig. 1 and by a visual classification. The size fractions can be observed in Fig. 2.

Compressibility of ground wheat

The compressibility of EPD, F1, F2, F3 and F4 is shown in Fig. 3. The compressibility of the fractions was relatively similar and they can be analyzed in detail from Table 1. The only size fraction that presented a different ($p < 0.05$) density for the same pressure was F4 when compressed until 10.92 MPa. The lower densities achieved in F4 compared to all other groups at compacting stresses below 10 MPa can be explained by the differences between the mechanisms of densification.

The mechanism of densification during pressure agglomeration includes as a first step, a forced rearrangement of particles requiring little pressure followed by a steep pressure rise during which brittle particles break and malleable particles deform plastically [13, 14].

At low pressure, rearrangement of the particles takes place, leading to a closer packing. At this stage, energy is dissipated mainly overcoming particle friction, and the magnitude of the effect depends on the coefficient of inter particle friction. In the case of fine powders (e.g. F1 fraction), cohesive arches may collapse at this stage [14].

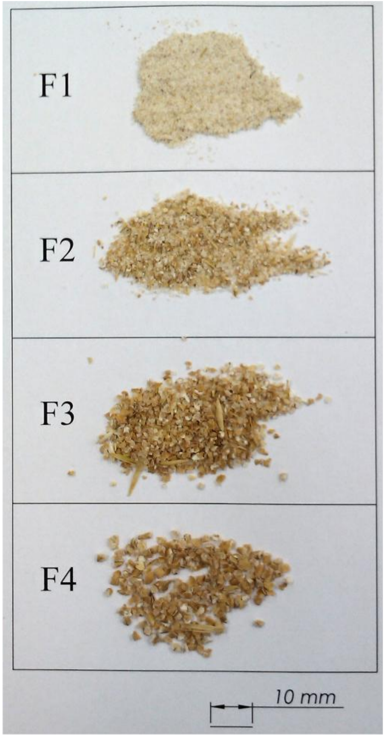


Figure 2: Photograph of the size fractions

At higher pressures, elastic and plastic deformation of the particles may occur, causing particles to flow into void spaces and increasing the area of inter particle contact. Interlocking of particles may also occur.

High pressure continues until the density approaches the true density of the material when all spaces are filled with material. This can be seen in Fig. 3 as density starts presenting a plateau at compaction stresses higher than ~30 MPa in the power shaped curve of Fig. 3.

Elastic compression of the particles and entrapped air will be present at all stages of the compaction process [14].

The mechanisms discussed may occur simultaneously. The relative importance of the various mechanisms and the order in which they occur depend on the properties of the particles and on the speed of pressing [14].

The density range of the pelleted feed (rich in ground wheat ingredient) produced in

FôrTek is shown by the grey band in Fig. 3 (1218.2 ± 17.9 kg $m^3$ ($n$ = 18)). The bands are included in the figure to have an idea of the pressures used by a pellet press. The compacting pressures during pelleting are unknown [7] since it is very difficult to measure it. Also compacting pressures have not been estimated in literature. Following Fig. 3, it is possible to see that to achieve a range of densities similar to the ones from a pelleting process for EPD, the compressing stresses are in the range between 10 to 14 MPa.

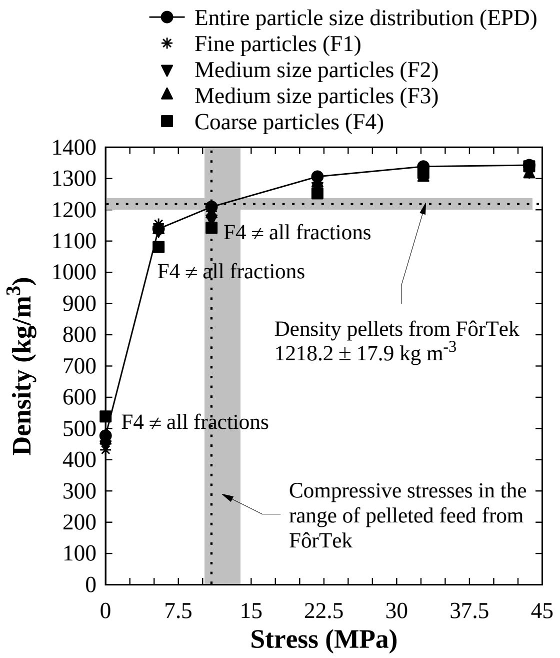


Figure 3: Compressibility plot of ground wheat grain and fractions. Data points are averages ($n$ > 6). Significant differences within the groups are indicated with symbol ≠. The grey bands indicate the range of densities and possible compressive stresses of the pellets manufactured in FôrTek pilot plant. The dotted lines indicate the estimated pressure to produce pellets of similar density to the ones from FôrTek.

Influence of particle size on pellet strength

Pellets were made from the four fractions F1, F2, F3 and F4 using the same compressive stress, even though the different fractions presented different compressibility leading to different densities (see Fig. 3 and Table 1). The reason for using the same compressive stress for all fractions is because the aim was to investigate the effects of particle size on pellet strength focusing on industrial pelleting process. In an industrial pellet press die hole, the fractions are compressed at the same stresses because they are part of a mixture forming the pellets.

Table 1: Differences in compressibility for the different size fractions. Different letters (superscript) indicate significant differences ($p < 0.05$).

| Stress (MPa) | Fraction | Average density (kg $m^{-3}$) |
|---|---|---|
| 0 (bulk density) | EPD* | 477.0 $^{b}$ |
| 0 (bulk density) | F1 | 431.7 $^{d}$ |
| 0 (bulk density) | F2 | 448.3 $^{c\,d}$ |
| 0 (bulk density) | F3 | 462.1 $^{b\,c}$ |
| 0 (bulk density) | F4 | 538.4 $^{a}$ |
| 5.46 | EPD* | 1139.0 $^{a}$ |
| 5.46 | F1 | 1154.9 $^{a}$ |
| 5.46 | F2 | 1135.0 $^{a}$ |
| 5.46 | F3 | 1135.7 $^{a}$ |
| 5.46 | F4 | 1080.8 $^{b}$ |
| 10.92 | EPD* | 1209.3 $^{a}$ |
| 10.92 | F1 | 1195.2 $^{a\,b}$ |
| 10.92 | F2 | 1171.3 $^{b}$ |
| 10.92 | F3 | 1186.5 $^{a\,b}$ |
| 10.92 | F4 | 1142.2 $^{c}$ |
| 21.83 | EPD* | 1306.2 $^{a}$ |
| 21.83 | F1 | 1268.8 $^{b}$ |
| 21.83 | F2 | 1275.4 $^{a\,b}$ |
| 21.83 | F3 | 1285.7 $^{a\,b}$ |
| 21.83 | F4 | 1252.6 $^{b}$ |
| 32.75 | EPD* | 1338.5 $^{a}$ |
| 32.75 | F1 | 1320.5 $^{a\,b}$ |
| 32.75 | F2 | 1330.6 $^{a}$ |
| 32.75 | F3 | 1303.5 $^{b}$ |
| 32.75 | F4 | 1318.0 $^{a\,b}$ |
| 43.66 | EPD* | 1342.9 $^{a}$ |
| 43.66 | F1 | 1334.9 $^{a\,b}$ |
| 43.66 | F2 | 1324.0 $^{a\,b}$ |
| 43.66 | F3 | 1314.4 $^{b}$ |
| 43.66 | F4 | 1339.2 $^{a}$ |

*EPD represents the entire particle size distribution

The results presented in Fig. 4 showed that the largest difference in strength ($p < 0.05$) was found for the pellets made with the largest particle sizes (F4). This fraction produced the weakest pellets. At the same time, but now analyzing Fig. 5, is possible to see that this fraction of pellets made with the largest particles breaks with the lowest ($p < 0.05$) deformation (~2.5 % strain).

The large difference in strength given by F4 cannot be explained by differences in density as shown in Fig. 4 because F4 and F2 did not produce pellets with different densities ($p > 0.05$). Consequently, the differences could be explained by either the differences in chemical composition among the fractions, which led to different binding strengths or by the differences in the surface contact among particles since at this compacting stress (~10.9 MPa), the pellets still doesn't reach its true or maximum density (the volume was not filled entirely) and the contact surface among particles and distribution of voids is probably different for the different fractions.

The manufacture of pellets in the laboratory press was done under conditions of low water (~15%) and a temperature of 82 ºC. Consequently gelatinization in a great extent did not occur, and therefore the influence of the starch as binder can be excluded.

Taking into account that starch is not a major contributor of the pellet strength under our experimental conditions, it is reasonable to believe that other feed constituents, such as proteins acted as a binder. Wood[5] showed that a partial protein denaturation caused by the combined effects of shear, heat, residence time and moisture content, can increase the hardness and the durability of pelleted feed.

During pelleting process, the molecular structure of proteins is broken down (i.e. protein denaturation), but later, during cooling, the denatured proteins re-associate forming new bonds (e.g. covalent bonds, electrostatic interactions, van der Waals interactions or hydrogen bonds)[15].

Denaturation temperature for most proteins is usually below 100 ºC, but it is highly affected by the moisture content. Wheat gluten, as a major protein component, can be easily denatured under mild conditions. Hoseney[16] reported that wheat gluten structure can unfold at 16% of moisture at room temperature and can contribute to the physical quality of feed pellets. Additionally, the shear forces during processing contribute to denature proteins at lower temperatures when compared to shear-less processes. This can be explained because shear also causes molecular breakdown[17-20]. In our system, shear is present among particles and at the walls during pressing.

If voids are present in the pellets, the most probable is that the contact surface among the large particles of F4 is smaller than the contact surface among the finer particles of the other groups (F1, F2 and F3).

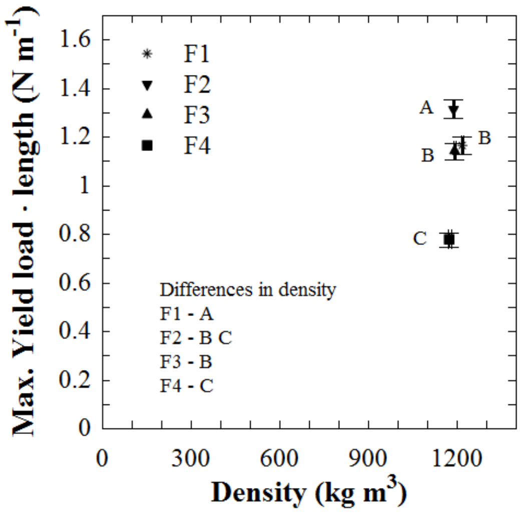


Figure 4: Max. yield load times length (N $m^{-1}$) for the different sizes fractions. Different letters indicate significant differences ($p < 0.05$). Letters beside the data points indicate significant differences in *y* - axis ($p < 0.05$). Error bars represent the standard error of the mean (*n* = 40).

Fibres in cereals can be divided into two groups: soluble and insoluble fibres. Water soluble fibres can improve pellets quality as they can act as filler in the voids. These fibres embed coarse particles producing higher durability and hardness in the pellets. Insoluble fibres can have double effect on the physical pellet quality. Insoluble fibres can entangle and fold among different particles or strands of the fibre and contribute to better particle adhesion in the pellet. Otherwise, large fibres, due to stiffness and elasticity, can avoid good contact between particles and present weak spots in the pellet[21]. Fibres were mostly present in F3 and F4 fractions as it can be seen in Fig. 2.

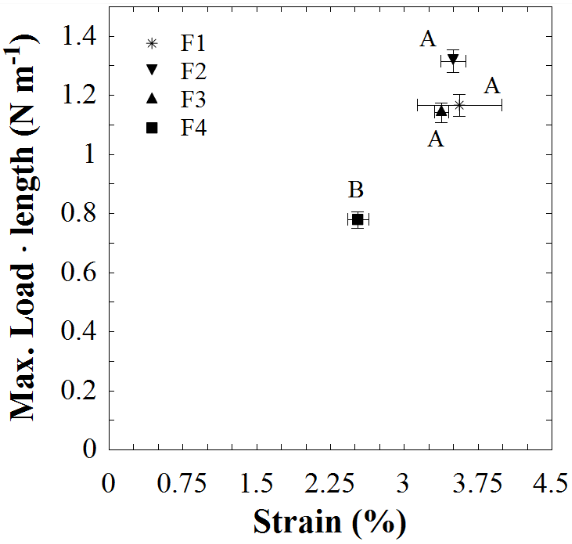


Figure 5: Max. yield load times length (N $m^{-1}$) for the different size fractions showing the different levels of strain (%) at the moment of the main failure. Error bars represent the standard error of the mean (*n* = 40).

The significantly strongest pellets ($p < 0.05$) were produced with the fraction F2, this can be seen from Fig. 4 and Fig. 5. This fraction is likely to have large amounts of protein and fibres and less endosperm (starch) content than F1 (see Fig. 2). The mechanical reason of having strength differences for F4 and F2 can be explained by differences in the following three strength components of the pellet: (a) the strength component provided by the binder substance (e.g. starch, proteins, etc), (b) the strength provided by the particle boundary, which is the strength caused by adhesion between binder and particulate solids forming the pellet, and (c) the strength component of the particulate solids forming the agglomerate. The weakest component is the responsible for the failure of the pellet.

It was impossible to determine with confidence which one of these mechanisms was or were the responsible for the differences in strength among the fractions. However due to the small contact areas among the particles of F4 compared to the other fractions, it is likely that this group of pellets were broken by a failure in the binding - particle area which was small (type b), so the forces could have been distributed in smaller areas increasing the stresses. Instead the binding strength from F2 fraction is likely to have come from a different component. This could have been by the strength of the binder (type a) or by the strength component of the particulate solids (type c).

## CONCLUSIONS

It is concluded that the strength of pelleted feed based on cereals is affected by the size of the particles when are manufactured under the same conditions of temperature and pressure. The coarser particles produced the weakest pellets. These pellets are able to withstand smaller deformations when compared to pellets made of finer particle sizes. In an industrial pelleting process, all particle sizes are under the same pressure and temperature because they are part of a mixture.

## AKNOWLEDGEMENTS


The centre for feed technology, FôrTek, is acknowledged for providing the ground wheat used in this research.


## REFERENCES


1. Salas-Bringas, C. and O.I. Lekang. *Final Report Pellet Quality Project*, Norwegian University of Life Sciences, 2007

2. Willis, B. and M. Okos, *Stress and Breakage in Formed Cereal Products Induced by Drying, Tempering, and Cooling*, in *Characterization of Cereals and Flours*, G. Kaletunc and C.J.B. Brimelow, Editors. 2003, Mercel Dekker, Inc.: NY. p. 267-310. 0-8247-0734-6.

3. Ortega-Rivas, E., P. Juliano, and H. Yan, (2005) "Food Powders". NY: Springer. 372, 0306478064

4. Salas-Bringas, C., O.I. Lekang, and R.B. Schüller, (2008), "Rheology in Feed Production", *Annual Transactions of the Nordic Rheology Society*, **16**: p. 229-237.

5. Wood, J.F., (1987), "The functional properties of feed raw materials and their effect on the production and quality of feed pellets", *Animal Feed Science and Technology*, **18**: p. 1-17.

6. Zimonja, O. and B. Svihus, (2009), "Effects of processing of wheat or oat starch on technical pellet quality and nutritional value for broilers", *Animal Feed Science and Technology*, **149**(3-4): p. 287-297.

7. Salas-Bringas, C., W.K. Jeksrud, O.I. Lekang, and R.B. Schüller, (2007), "Noncontact Temperature Monitoring of a Pelleting Process Using Infrared Thermography ", *Journal of Food Process Engineering*, **30**(1): p. 24-37.

8. Salas-Bringas, C., T. Filbakk, G. Skjevrak, O.I. Lekang, O. Høibø, and R.B. Schüller, (2010), "Assessment of a new laboratory die pelleting rig attached to a texture analyzer to predict process-ability of wood pellets. Energy consumption and pellet strength", *Annual Transactions of the Nordic Rheology Society*, **18**: p. 77-86.

9. Salas-Bringas, C., T. Filbakk, G. Skjevrak, O.I. Lekang, O. Høibø, and R.B. Schüller, (2010), "Compression rheology and physical quality of wood pellets pre-handled with four different conditions", *Annual Transactions of the Nordic Rheology Society*, **18**: p. 87-94.

10. Salas-Bringas, C., E.O. Rukke, L. Saga, O.I. Lekang, and R.B. Schüller, (2010), "Rheological properties of buttermilk pellets manufactured by a new die pelleting rig of a texture analyzer", *Annual Transactions of the Nordic Rheology Society*, **18**: p. 101-106.

11. *Avd. for Matpolitikk, Mattilsynet. FOR 2005-12-23 nr 1703: Forskrift om kontroll av Salmonella og andre matbårne zoonotiske smittestoffer. LMD (Landbruks- og matdepartementet)*, 2005, Lovdata, http://tinyurl.com/kontroll-av-Salmonella (Last accessed March 2011)

12. Salas-Bringas, C., N. Mišljenović, O.-I. Lekang, and R.B. Schüller, (2011), "Comparison between diametral and uniaxial compression tests of pelleted feed", *Annual Transactions of the Nordic Rheology Society*, **19, submitted**.

13. Pietsch, W., (2002) "Agglomeration Processes". Darmstadt, Germany: Wiley-VCH 3527303693

14. Shinohara, K., *Fundamental and Rheological Properties of Powders*, in *Handbook of Powder Science and Technology*, M.E. Fayed and L. Otten, Editors. 1997, Springer: NY. p. 96-145. 0412996219.

15. Howell, N.K., *Protein – protein interactions*, in *Developments in Food Proteins* B.J.F. Hudson, Editor. 1991, Elsevier: Amsterdam. p. 231-270.

16. Hoseney, R.C., (1994), "Effect of heat moisture treatment on the structure and physicochemical properties of cereal, legume and tuber starches", *Carbohydrate Research* **252**: p. 33-53.

17. Dogan, H. and J.L. Kokini, *Rheological Properties of Foods*, in *Handbook of Food Engineering*, D.R. Heldman and D.B. Lund, Editors. 2007, CRC Press/Taylor & Francis: Boca Raton, Fla. p. 1-124. 978-0-8247-5331-3.

18. Figura, L.O. and A.A. Teixeira, (2007) "Food Physics". Berlin: Springer. 550, 3540341919

19. Heldman, D.R. and D.B. Lund, (2007) "Handbook of Food Engineering". Boca Raton, Fla: CRC Press/Taylor & Francis. 1023 978-0-8247-5331-3

20. Steffe, J.F., (1996) "Rheological methods in food process engineering". East Lansing, Mich.: Freeman Press. XIII, 418., 0-9632036-1-4

21. Thomas, M., T. Van Vilet, and A.F.B. Van der Poel, (1998), "Physical quality of pelleted animal feed 3. Contribution of feedstuff components", *Animal Feed Science and Technology*, **70**: p. 59-78.