Effect of Compaction on Strength and Arching of Cohesive Material in Storage Bins

by

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ABSTRACT

Arching in storage bins for cohesive materials is a common problem in handling bulk solids. The formation of arches in cohesive bulk solids is influenced by many factors, including material properties and storage conditions. An experimental study was carried out to determine the effect of compaction on arching in storage bins for wheat flour with different moisture contents. A model bin 475 mm in height and 600 mm × 375 mm in cross-section was designed and fabricated to conduct tests. A unique feature of this model bin test system was an adjustable hopper which allowed for discharge opening to be increased during test without disturbing the material in the hopper. This feature made it possible to quantify arch spans in the hopper without disturbing the stored material. Wheat flour at two different moisture contents of 8.6% and 14.2% was prepared as the test material. A universal testing machine was used to apply pressure to compact the stored material in the model bin. Compaction pressure was measured in the hopper by using an en masse pressure measuring system. Direct shear tests were performed to determine the angle of internal friction and cohesion of wheat flour subjected to various compaction pressures. The unconfined yield strength was then calculated from the measured values of internal friction and cohesion.

It was observed that the internal friction angles were about the same for the wheat flour at two moisture contents (37.1° vs. 37.5°), but cohesion for 14.2% MC was 72% higher than that for 8.6% MC (1.21 vs. 2.08 kPa). The unconfined yield strength increased from 2.46 kPa to 4.22 kPa, or by 72% as the moisture content of wheat flour increased from 8.6% to 14.2%.

The variation in moisture content of wheat flour had noticeable effect on the arching span. Specifically, arching span increased as the moisture content increased. The required hopper opening for arching-free flow for 14.2% MC was 42% greater than that for 8.6% MC (122 mm vs. 86 mm).

It was observed that the arching span increased with compaction pressure when the compaction pressure was low. Increase in compaction pressure from 0.2 to 5 kPa led to a 64% increase in required hopper opening for arching-free flow for flour at 8.6% MC, and 49% at 14.2% MC. However, compaction pressure had little effect on arch formation after it reached 5 kPa.

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1. INTRODUCTION

Bulk solids storage structures are extensively used to handle bulk materials, such as foodstuffs, pharmaceuticals, chemicals, cement, coal, polymers, and powdered metals. The size of storage bins used in practice varies widely with diameters ranging from less than one meter for the production of some highly-specialized products to well over 30 m for the stockpiling of coal, cement and some food products. It was estimated that hundreds of industrial and farm silos, bins, and hoppers fail in one way or another each year in North America. This high rate of failures associated with bulk solids storage systems can be classified into two categories: structural failures (e.g., denting, collapsing, and foundation failures); and functional failures (e.g., arching, rat holing, flooding, segregation, attrition, implosion, caking). The most common type of functional failure is arching (bridging) in storage bins for cohesive (powder) materials.

Arching is the formation of a stable obstruction (arch) in the material above the hopper outlet so that the flow of the material is stopped. The formation of arch in cohesive bulk solids is associated with the material strength resulted from the inter-particle forces. The design of storage bins for arching-free flow is based largely on the work of Jenike and his co-workers. Jenike's design method gives a set of equations and charts for the determination of the minimum hopper outlet opening for arching-free flow. This minimum opening depends on the properties of bulk solids, hopper wall friction, and the half angle of the hopper. The fundamental material properties that affect the flow of cohesive materials are cohesion, internal friction, and the unconfined yield strength (UYS). These flow properties are affected by many factors, including compaction (bulk density) and moisture content. The scope of this study was to study the effect of compaction and moisture content on the arching behavior of food powdery materials, specifically wheat flour.

Food powdery materials stored in bins are subjected to compaction because of self-weight and other forces imposed by handling operations, such as vibration. The level of compaction varies with the location in the bin; generally higher at the bin bottom and lower at the top. It is a well-known phenomenon that the strength of cohesive bulk solids increases as the material is compacted. The maximum compaction pressure that the material experiences during storage may have significant effect on the strength of bulk solids, and increased strength caused by compaction would raise the probability of arch formation.

Food powdery materials stored in bins may have a wide range of moisture contents. High moisture contents of powdery materials generally lead to reduced flowability due to liquid bridges and capillary forces acting between particles. However, the moisture might also act as a lubricant for improved flow when it was above a certain level. Most studies conducted so far on the flow of food powders have been focused on the assessment of flow parameters (internal friction and cohesion) as affected by moisture content and compaction, but few on the actual formation of arches in storage. The goal of this study was to investigate not only the influence of moisture and compaction on the material flow properties (internal friction, cohesion, and UYS), but also the effect of changing flow properties on the formation of arches in storage bins.

2. OBJECTIVES

(1) To conduct direct shear tests to determine the effect of moisture and compaction pressure on the strength (internal friction, cohesion, and unconfined yield strength) of wheat flour.

(2) To conduct model bin tests to determine the relationship between the compaction pressures and the formation of arch of wheat flour at different moisture contents.

3. LITERATURE REVIEW

3.1. Flow properties of food powdery materials

Many researchers have studied the flowability of food powders (Peleg et al., 1973; Peleg, 1978; Teunou et al., 1999; Fitzpatrick et al., 2004a & 2004b; Domian and Poszytek, 2005; Juliano, 2006; Landillon et al., 2008). The two fundamental forces that affect the flow of powders are cohesion and internal friction (Dawoodbhai and Rhodes, 1989). Jenike (1963) studied the arching problem in hoppers and provided practicing engineers with the design criteria for hoppers, as so-called flow-no-flow criteria. The criteria indicate that the maximum stress in an arch has to be greater than the unconfined yield strength of the material to break the arch in order to cause flow to occur. In essence, the UYS represents the combined effect of cohesion and internal friction on the flowability. From the point view of mechanics, the UYS is the level of the major principle stress that causes the bulk material in an unconfined (unsupported) state to fail. The UYS for cohesive bulk solids tends to increase when subjected to compaction. The relation between UYS and the compaction pressure P_1 can be explained by considering a sample of bulk material uniformly consolidated by a vertical consolidating pressure P_1 in a container with frictionless wall. The container is removed after compaction, and a vertical compressive load is applied increasingly and recorded until the sample is crushed. The obtained compressive load is the unconfined yield strength of the bulk material f_c (Fig. 3.1). The yield strength is a direct function of compaction pressure P_1; greater strength is associated with higher compaction. When the material is stored in a bin, the degree of compaction becomes greater as the depth of stored material increases;

therefore, the strength of the stored material is proportional to the distance from the bottom to the top of the bin (Jenike 1964).

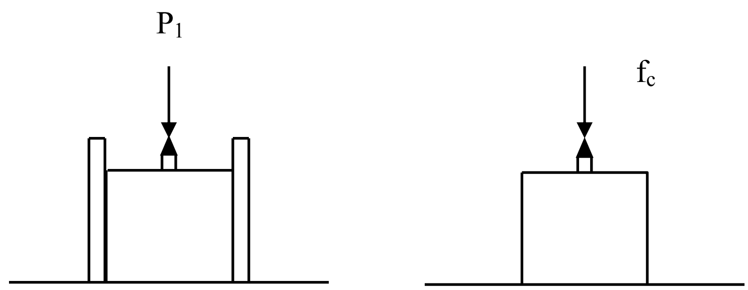

Figure. 3.1. Unconfined yield strength of bulk solid materials.

Peleg et al. (1973) tested a number of food powders for flow properties and observed that cohesion usually increased with compaction pressure, but some powder such as starch did not change their cohesion solely by applying compaction pressure and a combination of increasing moisture and applying compaction pressure was required to change cohesion. Teunou and Fitzpatrick (1999b) evaluated the effect of storage time and consolidation on the flowability of wheat four, tea, and whey permeate and observed that the bulk density and cohesion of the flour and whey permeate powders increased during consolidation, resulting in a more compact and cohesive powder with reduced flowability. The cohesion of the tea powder increased over time even though its bulk density remained unchanged. Domian and Poszytek (2005) experimentally evaluated the storage time and consolidation on the flowability of wheat flour and reported that the flowability was reduced with increasing consolidation time, especially for the higher moisture content flour (16% wb MC). Domian and Poszytek (2005) pointed out that increases in moisture content of powdery materials lead to reduced flowability due to the increase in liquid bridges and capillary forces acting between the powder particles, indicating material strength increases with moisture content. Peleg et al. (1973) measured the tensile strength (TS) as a flowability indicator for powdered onion and sucrose and reported that moisture increased the TS by forming a liquid film on the particles. Dawoodbhai and Rhodes (1989) concluded that the presence of moisture tends to decrease the flow of powders by increasing their TS. Teunou and Fitzpatrick (1999a) evaluated the effect of exposure to humidity in the air on the flowability of wheat flour, tea, and whey permeate and observed that the flowability decreased with increasing relative humidity. Fitzpatrick et al. (2004a) measured the flow properties for 13 food powders and reported that increasing moisture content tended to make powders more cohesive, but the moisture might act as a lubricant for improved flow when it was above a certain level. Fitzpatrick et al. (2004b) reported that exposure of the powders to moisture in air showed a major increase in the cohesion for skim-milk powders, but had little effect on whole-milk and high-fat milk powders. Domian and Poszytek (2005) observed that wheat flour with 16% wb (wet basis) MC (moisture content) was more cohesive than flour at 11% wb mc and the moist flour could cause difficulties in gravity discharge from storage.

The stress-strain behavior of a bulk solid material is generally described by means of the yield and compaction locus. A set of shear and normal stresses below the yield and compaction loci will only give rise to elastic deformations whereas the stresses on the loci will cause irreversible plastic deformations (Maltby et al., 1994). As the shear deformation increases, the material eventually reaches the critical state, which is defined by effective yield loci. Many researchers came up with testing methodologies for investigation of behavior of bulk solid materials. Triaxial test has its extensive application in geotechnical field of study, especially in high-pressure range. In standard triaxial test, the specimen is enclosed vertically by a thin "rubber" membrane and on both ends by rigid surfaces, confined pressure (σ_3) is applied horizontally while the deviatoric stress (σ_1 - σ_3) is applied on the top plate, The pioneering work in bulk solid handling was carried out by Jenike (1964) who introduced the well-known and extensively used Jenike shear cell tester. With this tester, it is possible to determine the mechanical properties of a bulk solid material. Other researchers indicated that Jenike's tester has its limitation and therefore presented biaxial testers, which can provide complete information on the stress and strain states when automatically deforming the sample in two directions (Maltby et al., 1994). Although there are currently different versions of biaxial testers in practice, the main parts consist of a test cell, motors and gears. In the biaxial shear tester the bulk solid sample is constrained in lateral x and y directions by four steel plates. Vertical deformations of the sample are restricted by rigid top and bottom plates (Schwedes, 2001). The friction between plates and sample can be avoided by applying silicon grease, thus, the measured normal stresses and normal strains must be the principle stresses and principal strains. This means that the biaxial testers can be used to fully describe the properties of material in the principal stress space.

3. 2. Arching theories

The term arching is confined to cohesive arching here, which is described as the spontaneous formation of an arch-like supported stagnant mass of bulk material in a bin or hopper upon opening of the outlet or during gravitation flow. Jenike (1961) proposed the first arching theory. The theory is based on the assumption that the bulk material in a hopper can be regarded as a stack of isolated structural members, arches, or domes, and arching may occur if the strength of the members is greater than the weight-induced stresses (Drescher et al., 1994).

In Jenike's arching theory, the worst scenario for the formation of cohesive arch is that the unconfined yield strength developed during compaction just exceeds the forces tending to break it. This means that there are no forces acting on the top surface of the arch and there are no supporting forces underneath it either (Fig. 3.2). The only force that supports the arch is the shear stress (S) developed between the bulk material and the wall and the only force that could cause the arch to collapse is its own weight W.

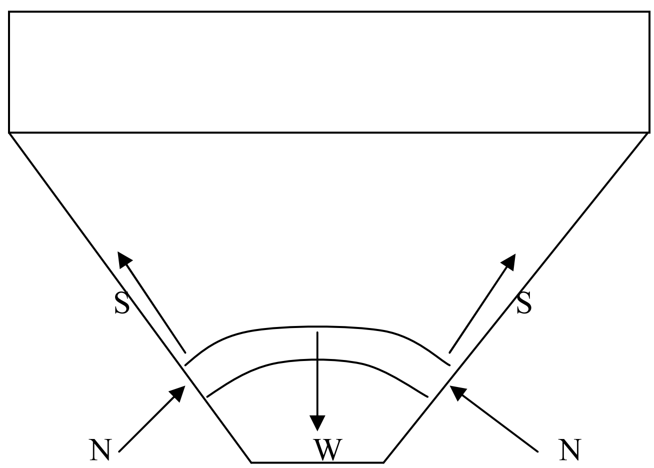

Figure 3.2. Force balance on an arch in bin hopper (Shamlou, 1988).

An arch forms if the shear stress caused by the self-weight is less than the maximum shear strength of the material. The maximum shear strength can be obtained from the Mohr semicircle (Fig. 3.3) and its value is a half of the unconfined yield strength (UYS):

$$S_{max} = f_c/2 \tag{3.1}$$

where:

S_{max} = maximum shear strength

f_c = unconfined yield strength

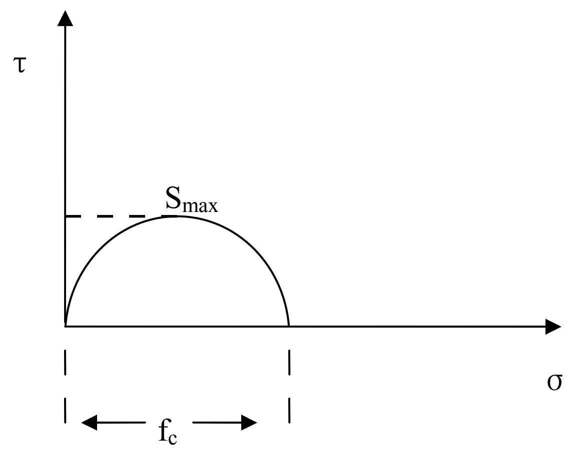

Figure 3.3. Relationship between maximum shear stress and unconfined yield strength on an arch.

The condition for arch destruction is expressed as follows:

$$BLt\ \rho_b g = S_{max} 2Lt \qquad (3.2)$$

where:

B = arch span in a wedge shaped hopper,

L = arch length in a wedge shaped hopper,

t = height of the arch element,

ρ_b = bulk density(kg/m^3), and

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

Re-organizing the above equation yields:

$$B = 2S_{max} / (\rho_b g) = f_c / (\rho_b g) \tag{3.3}$$

Furthermore, the major principal stress σ_s acting along the surface of arch must be equal to the unconfined yield strength when the arch collapses, therefore, we have:

$$B = f_c /(\rho_b g) = \sigma_s /(\rho_b g) \tag{3.4}$$

To consider the variation in the thickness of the arch, Jenike and Leser (1963) modified equation 3.4 as follows:

$$\sigma_s /(\rho_b g B) = H(\alpha) \tag{3.5}$$

where $H(\alpha)$ is directly related to hopper's half angle and geometry:

$$H(\alpha) = \left\{\frac{65}{130+\alpha}\right\}^{i} \left\{\frac{200}{200+\alpha}\right\}^{1-i} \tag{3.6}$$

where

i = 1 for circular and square openings, and

i = 0 for wedge opening (L $\geqslant$ B)

Drescher et all. (1995) examined various arching theories. They generalized the current theories into two groups. One group is based on structural mechanics (SM) approach. In this approach, the stresses that act on the material in hoppers are taken as the compaction pressures and gives rise to the strength of material, and usually, the greatest major principal stress that acts on an arch is assumed as the compaction pressure that directly determines the unconfined yield strength. All SM theories are based on the assumption that the consolidating stresses correspond to large shearing deformation and the effective yield condition can be expressed as a straight line in the τ - σ plan, therefore, the shear stress was proportional to normal stress. The uniaxial compression stress in an arch can be statically determined after the shape of the arch and the supporting conditions are obtained. The arching condition can be established by comparing the principal stress within the arch and the unconfined yield strength of the material. It is postulated that the arching may occur when the unconfined yield strength is greater than the principal stress within the arch. The arching location in a hopper can also be found graphically.

Another theory was originally proposed by Enstad (1975, 1977) and was modified by Drescher (1991). It was based on continuum mechanics (CM) approach in which the global equilibrium of consolidated bulk material mass was considered and the differential slice method was applied as the theoretical solution. In CM based theories, any shape of the instantaneous yield locus is acceptable as long as the effective yield locus becomes linear and passes above the origin of normal stress-shear stress plot, this implies that the cohesion of the bulk solid material is independent of the compaction pressure. The assumptions of continuum mechanics approach lead to stresses acting normally to the material mass in which there exists a slice where the acting stresses changing from compression to tension, the outlet size are determined from the condition $\sigma_3 = 0$, indicating that the mass is in equilibrium without any support from below (Fig. 3.4). In both SM and CM approaches, the bulk unit weight of the material γ, material-wall friction angle ϕ_w are assumed to have constant values.

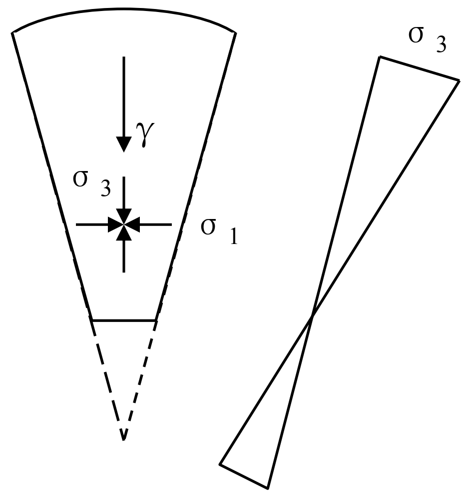

Figure 3.4. Continuum mechanics approach to arching problem (Drescher, 1991)

It should be pointed out that the prediction of the hopper critical openings by theories is usually unsatisfactory. In some cases the outlet sizes found in model or full size hoppers are much smaller than the theory predictions and for some materials the opposite is observed (Stainforth 1973).

3.3. Consolidation analysis

The geotechnical term "consolidation" was first used by Thomas Telform (1809) to describe the process by which soils decrease in volume when stress is applied to a soil that causes the soil particles to pack together more tightly. When this occurs in a soil that is saturated with water, water will be squeezed out of the soil. The consolidation test was invented in 1901 to measure the stress-strain relationship for soils under drained and un-drained conditions. Even though the stress-strain behavior of soil is highly non-linear and non-elastic, soils have been idealized as a linearly-elastic material in most of the previous work. Since the proposal of the one-dimensional consolidation theory by Terzaghi (1925), considerable interest has been shown by many researchers in the consolidation of soil medium. Consolidation was defined as the time-dependent settlement of soils resulting from the expulsion of the water from voids of the soil structure. The total settlement of soil was studied and expressed in three parts: immediate (elastic) compression, primary consolidation and secondary consolidation (Fig. 3.5). Immediate compression is the elastic deformation of soil right after the external load is applied, in this process; there is no change to the moisture content of the soil. The primary consolidation is also called the initial settlement response or the early time response, which is the change in volume of soil by expulsion of fluids from the voids of soil skeleton. During the primary consolidation, the rate of the volume change diminishes with time and the load is continuously transferred from the pore pressure to the soil. The secondary compression occurs when the excess pore water pressure is completely transferred to the soil. It is a very slow process in which the volume of the soil is changed by the adjustment of the soil particles.

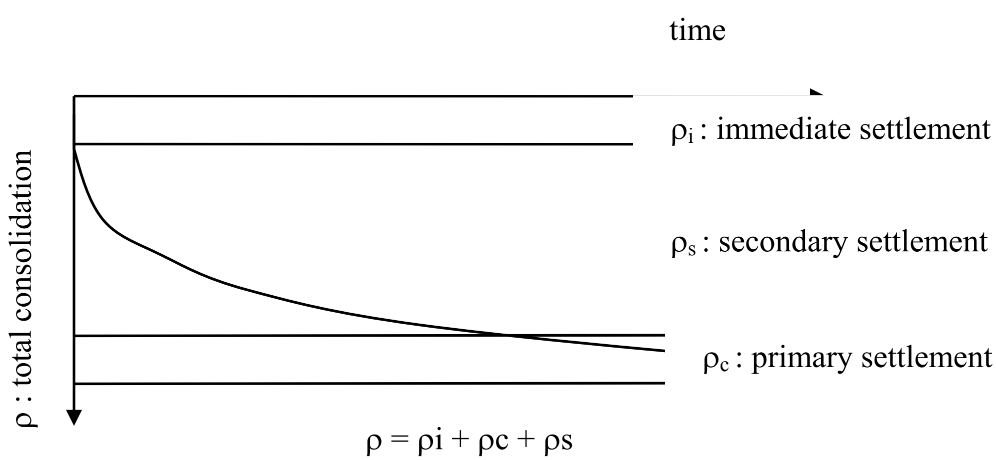

Figure 3.5 An illustration of total settlement of soil.

For compaction of an isotropic bulk material, the material behavior can be described by means of yield and compaction loci (Fig. 3.7). There are no stress combinations possibly existing above the loci if the material is ever subject to a given compaction pressure (Maltby, 1994). The stress combinations under the Mohr circle will only cause recoverable elastic deformation; stresses on the yield loci will result in irreversible plastic deformations. The bulk material will dilate or consolidate depending on which locus it touches. The material tends to dilate if it touches the yield locus until failure occurs, whereas, the material tends to consolidate if it touches the compaction locus. The shape of the transition zone between the yield and compaction loci has so far not been determined (Schwedes, 1975). The two loci were believed to merge at a point where the material will not change in density.

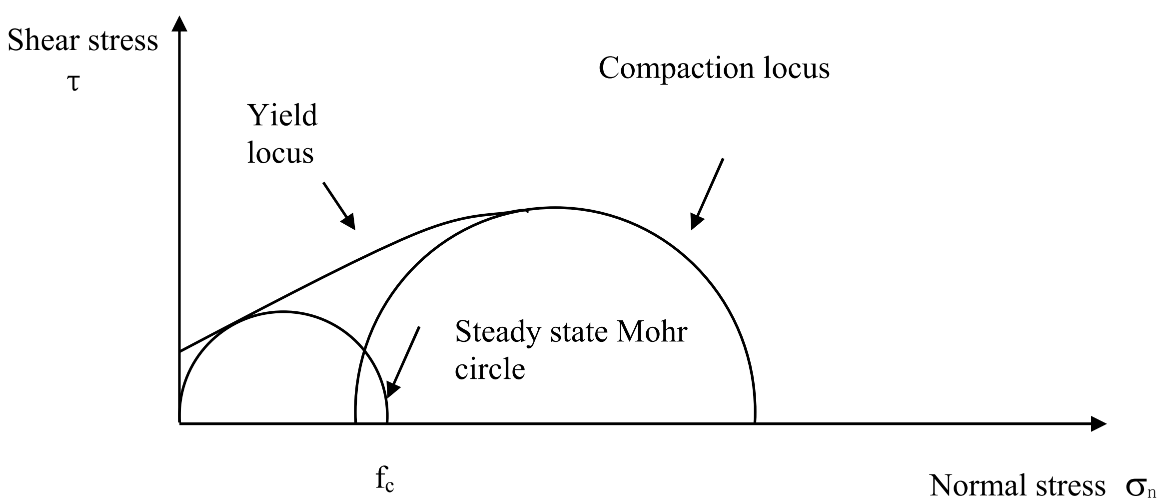

Figure. 3.6. Yield and compaction locus illustrated in shear/normal diagram

3. 4. En masse pressure measurement

Various experimental techniques have been used to measure en masse stresses for various purposes. Deutsch and Schmidt (1969) designed pressure cells to measure overpressures on silo walls during discharge. The diaphragms were instrumented with four miniature strain gauges. During the tests, a drift was experienced, as the output was so small at low pressures that it approached the error range of the cells. Atewologun et al. (1989) developed a diaphragm pressure transducer to measure the normal stresses in grain storage bins. The transducer was held in the granular mass by a rod while external load was applied. Law et al (1992) fabricated a pressure measuring apparatus to evaluate the normal to vertical pressure ratios of wheat and barley in a circular bin. Three pressure sensors (Integrated circuit sensors, Model 81-015G) were fitted into a cube, which is formed by 6 mm cast acrylic plates of 50 mm. The pressure sensors monitored the pressure exerted on the stainless steel diaphragm by utilizing the silicon oil coupled with a piezo resistive sensor.

The presence of a pressure cell in the stored material will change the stress conditions in the surrounding material. Only if the cell and material have the same deformation properties, the measured value could be accurate. Tory and Sparrow (1966, 1967) studied the influence of diaphragm flexibility on the performance of an earth pressure cell. They introduced a flexibility factor, which is defined as a ratio of the elastic modulus of the soil to a measure of the stiffness of the cell diaphragm, and the aspect ratio to establish a relation between flexibility and the cell performance. They showed that for particular ratios of thickness to diameter of the cell and cell stiffness, the measuring errors were negligible, and changes in soil stiffness could be catered for without appreciable errors.

Jarrett et al. (1991) pointed out that the errors due to cell placement have been reported by Hadala et al. (cited in Hvorslev1976), The measured stresses are sensitive to the methods of placement of the pressure cell. Askegaards (1987) found that they vary with each different person that places the cell. Scatters of results between seemingly identical tests were a function of the filling method, the preparation during cell placement, the cell orientation, the stored material, and cell stiffness. Jarrett et al. (1991) reported that only a few experimental investigations were conducted to determine the effects of different methods of placement on measured pressures. Hadala (cited in Hvorslev 1976) recommended placing the cell on a pre-leveled surface of sand deposits. Askegaard (1987) (verbally) recommended leveling the sand with a disk of the same diameter of slightly larger than the cell diameter. The filling method may affect the density of the bulk solid material, thereafter, affects the stress distribution within the storage bin. Various methods of bin filling result in different densities of the bedding and different spatial orientations of individual granules (Molenda et al. 1996). Moysey(1984) found that sprinkle filling increased the density of the storage material, which resulted in an increase in the angle of internal friction, a decrease in lateral pressure, and an increase in vertical floor pressure. Kwade et al. (1994) reported that filling method significantly influenced the magnitude of measured values of the stress ratio. They conducted the tests using four granular solids, the stress ratio was the lowest for sprinkle filling and highest for circumferential filling, and the value was in between for central filling and filling by placing small portions of the granular materials over the crossing-section of the test apparatus. They suggested that the variation of the measured stress ratio was a result from various configurations of shear planes developed during filling.

4. METHODOLOGY

4.1 Model bin test system and test material

A model bin test system was designed and constructed to conduct the arching experiment (Figs. 4.1a and b). The system consisted of a rectangular model bin and slot hopper, a universal testing machine, and a pressure measurement device for measuring en masse pressure in the materials The hopper had a half angle of 45° and the minimum outlet opening of 50 mm. The universal testing machine was used to apply external forces to simulate the equivalent compaction pressures exerted by the stored bulk solid material. A pressure measuring system made of a flexible rubber tube and a solid state pressure transducer was used to record the en masse pressure in the hopper.

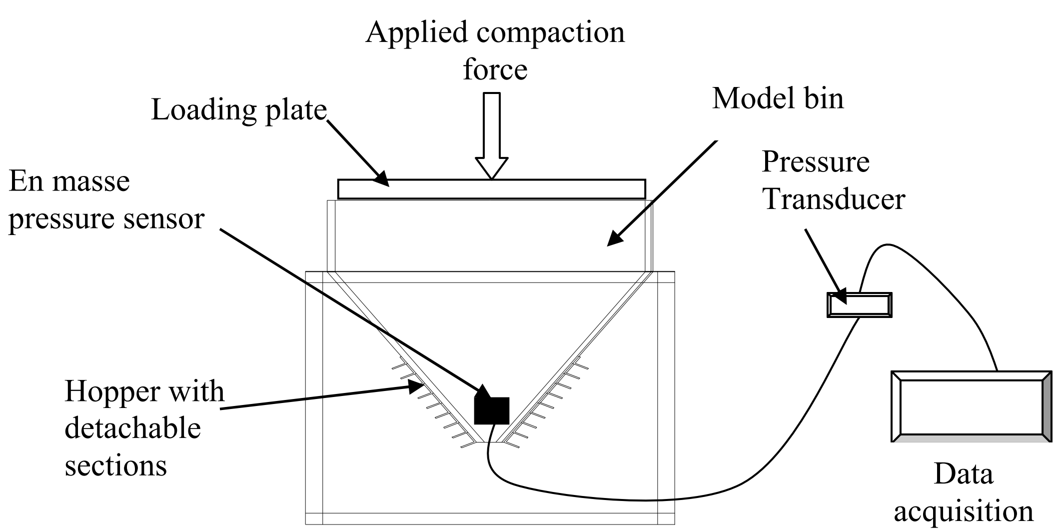

Figure 4.1a Schematic illustration of model bin test system.

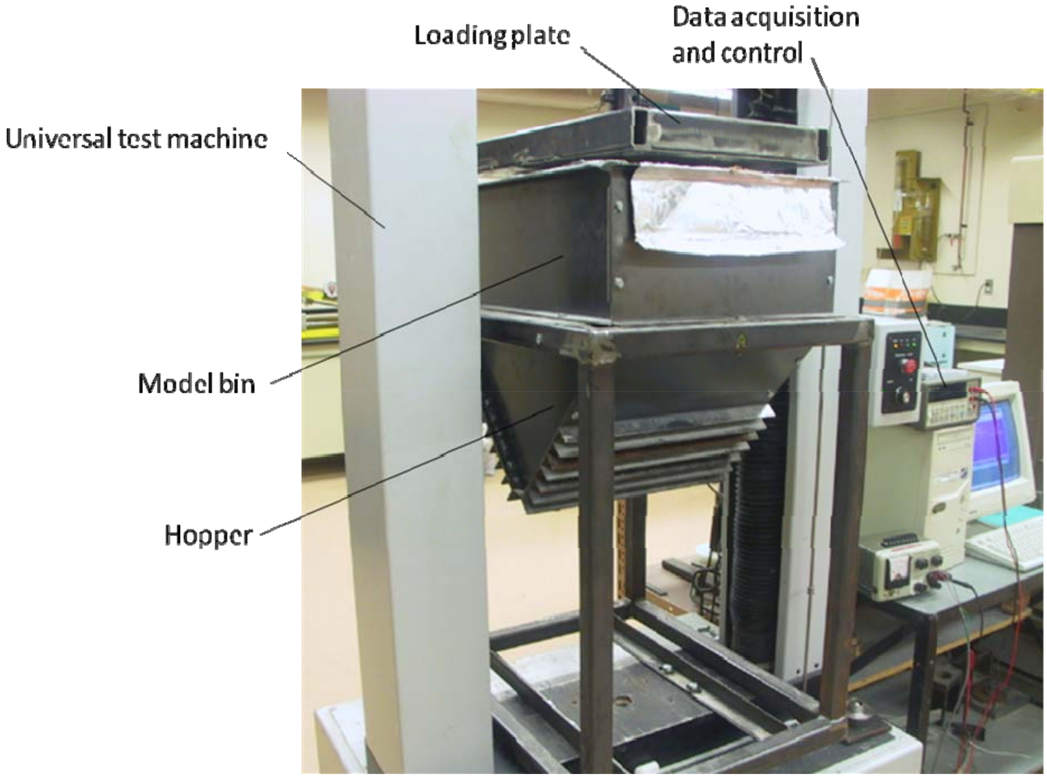

Figure 4.1b Photograph of model bin test system.

4.1.1. Model bin

A 475 mm high model bin with a 600 × 375 mm cross-section was made of 1.88 mm thick sheet steel (Fig. 4.2). A relatively shallow hopper (45°) was used intentionally to create arching. A unique feature of the model bin was that the lower part of the hopper was made of six (6) detachable sections, which allowed for changing the hopper opening without disturbing the stored material in the hopper. The hopper had a slot opening 375 mm long, with width adjustable from 50 mm to 266 mm in 36 mm increments by removing detachable sections. The detachable sections had 6 pairs of panels made of angle iron, which had similar rigidity as the material used for the bin construction. The hopper slot opening was 50 mm when all 6 pairs of panels were installed and the opening could be increased by 36 mm by removing (unbolting) a pair of panels. Both ends of each panel were bolted to flanges welded on the bin. This mounting configuration allowed for removing panels to change the hopper opening without disturbing the stored material in the hopper.

Because different materials were used for bin and the detachable sections and small gaps between panels in the detachable sections, there might be differences in surface friction between the bin and detachable sections. The bin and hopper were lined with aluminum foil in order to make the inside wall surface with uniform friction property. Aluminum foil was selected because it could be easily to remove in the attached sections when the hopper opening was increased.

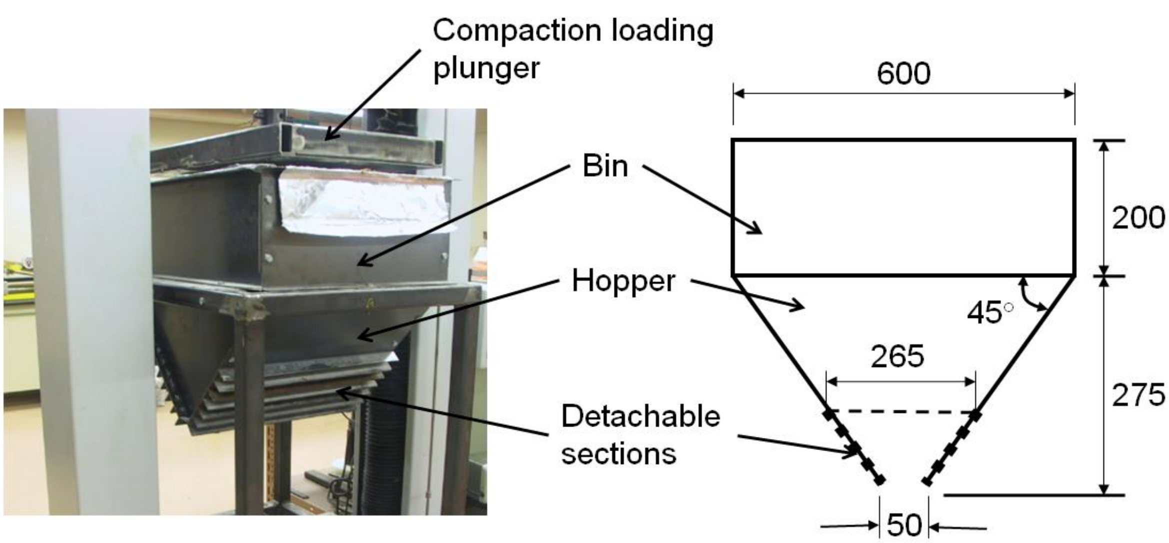

Figure 4.2. Photograph and schematics of model bin test system (dimensions are in mm).

4.1.2. En masse pressure measuring system

When compaction pressure was applied on the top surface of the material in the bin, some pressure was transferred to the material in the hopper where arches might form, and the remaining would be carried by the bin and hopper walls. Only the portion of pressure transferred to the material in the hopper would affect arch formation. In order to establish a relationship between compaction pressure and the resulted arching spans, a special pressure-measuring device was designed to measure the en masse pressure in the hopper. As discussed in the Literature Review, the presence of a pressure sensor in the stored material would change the stress conditions in the surrounding material. Only if the sensor and material have the same deformation properties, the measured value could be accurate. Therefore, in this study, a flexible pressure sensor was designed, constructed, and used to minimize the presence of pressure on the stress condition in the material. The device consisted of a flexible rubber tube 44 mm in diameter filled with water as the pressure sensor. The tube was connected to a solid state pressure transducer (P × 240A Series, Omega, Stamford, CT) that was fixed at the same height as the flexible tube. The water pressure, which represented the en masse pressure in the stored material, was sensed by the pressure transducer, and the output signal was fed to a digital voltmeter and recorded by a data acquisition unit (HP 3852A, Hewlett-Packard, Santa Clara, CA). The data recording rate of was set at 20 readings per second.

The pressure measuring system was calibrated using a water chamber and a water column (Fig. 4.3). The flexible tube was sealed in the water chamber, and a water column of 3.5 m in height was used to create calibration pressure. In each calibration trial, water was added to the water column incrementally from 0 to 3. 5 m at 0.1 m increments to apply hydrostatic pressure to the pressure sensor (rubber tube), and the height of water column was recorded. The voltage output from the solid state pressure transducer was also recorded at the same time. The water column height date was converted to pressure (pressure = column height × density of water × gravitational constant), and the pressure data were then plotted against the voltage data from the pressure transducer to obtain the calibration equation (Fig. 4.4). Based on three replications, the following calibration equation was obtained to relate the pressure measured by the en masse pressure sensor (rubber tube) to the voltage output from the solid state pressure transducer:

$$p = 6.594V - 7.623 \qquad R^2 = 0.999 \tag{4.1}$$

where:

p = pressure measured by the en masse pressure sensor (rubber tube) (kPa)

V = voltage output from the solid state pressure transducer (V)

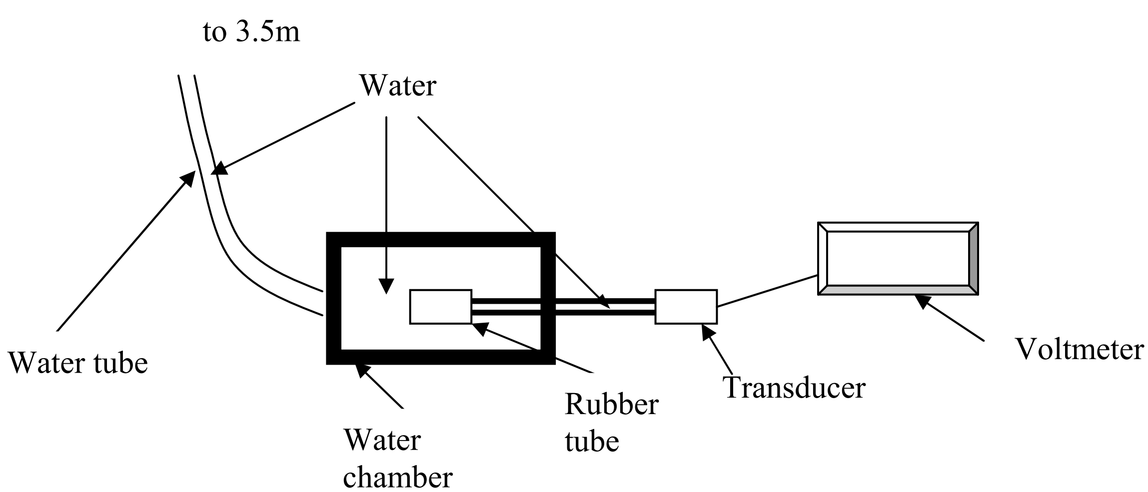

Figure 4.3. Calibration set-up for the pressure measuring system.

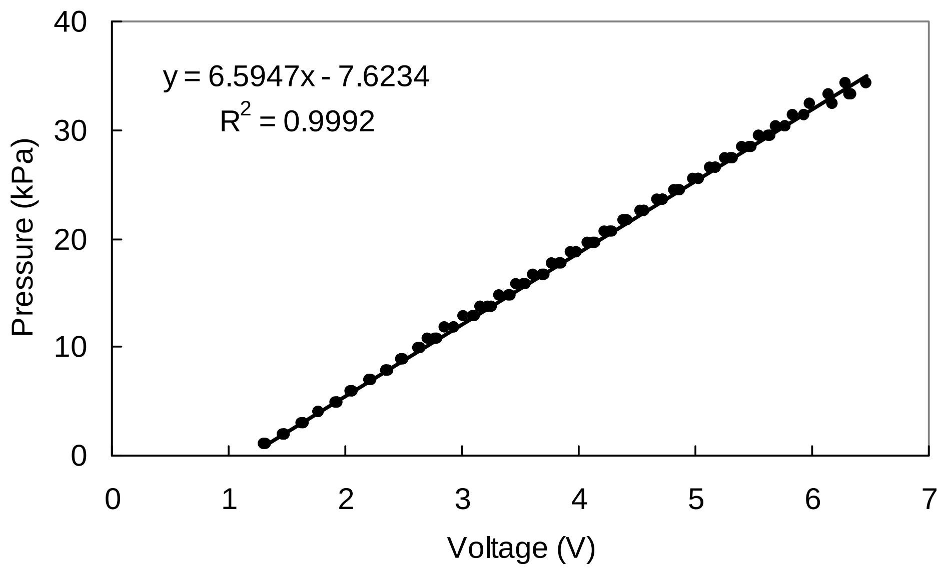

Figure 4.4. Calibration result for the en masse pressure measurement device (3 replications)

4.1.3. Test material

Commercial grade wheat flour (No Name(R)) was used in the experiments. The initial moisture content of the flour was 6.0% wb (wet basis). The moisture content of the wheat flour was measured according to the ASAE (1993) procedure, in which the flour samples (10 g) were kept in an oven at 130°C for 19 hours, and the moisture content was determined on wet basis with 3 replications as follows:

$$MC = \frac{W_{wet} - W_{dry}}{W_{wet}} \times 100\% \qquad (4.2)$$

where:

MC = moisture content of wheat flour (wb)

W_{wet} = wet mass of the sample (before drying)

W_{dry} = dry mass of the sample (afer drying)

In typical storage conditions, the moisture content of wheat flour may be as high as 14% (CGC, 2004). To study the moisture effect on arching, higher moisture content samples (targeted levels of 9% and 14%) were prepared by spraying distilled water onto the wheat flour and thoroughly mixing it in a portable cement mixer with a 28.3 L revolving drum (BigCat Mixer, Red Lion, Winnipeg, Manitoba, Canada). After the flour was loaded in to the drum, the calculated amount of distilled water was manually sprayed onto the flour slowly while the drum was rotating to avoid agglomeration. The resulted samples had actual moisture contents of 8.6% and 14.2% wb, respectively. During the experiments, the wheat flour was kept in a sealed plastic pail to prevent the moisture content from changing. The moisture content was checked and re-adjusted if necessary after each test to enable the consistency of the testing results.

The apparent (uncompacted) bulk densities of wheat flour were determined by weighing the mass of samples in a 4L measuring cup. The filling method and settling time could affect the density measurement. The same filling method as described for model bin tests was used to fill the measuring cup, the measured minimum compaction pressure 0.2 kPa and maximum compaction pressure 9.1 kPa (pressure/force conversion) were applied through a lid to the wheat flour. The sample was allowed for 2 minutes to settle in the measuring cup. The density measurement results are summarized in Table 4.1.

Table 4.1 Physical properties of wheat flour

Physical properties	8.6% MC	14.2% MC
Bulk density, kg/m^3	630	601
Angle of internal friction*, degree	37.6°	37.5°
Friction angle of flour on wall surface, degree	20.0°	21.5°
Cohesion of flour*, kPa	1.21	2.08
Unconfined yield strength*, kPa	2.46	4.22

*Unconfined yield strength measured for samples pre-consolidated at a normal pressure of 9.1 kPa

Friction of the flour on the inside wall surface (with aluminum foil) was determined using a tilt table device (Mohsenin, 1986). A surface sample (aluminum foil of 0.1 mm) was fixed on the table, and then the wheat flour was filled into a shear box sitting on the tilt table. A motor tilted the table and the tilting angle was recorded at the moment when the shear box started to slide. This angle was equal to the friction angle between the material and bin wall surface and the results are summarized in Table 4.1.

Direct shear tests were conducted to determine the angle of internal friction and cohesion of the wheat flour. The details are described in section **4.3 Direct Shear Test** and the results are summarized in Table 4.2.

4. 2. Model bin test procedure

4. 2.1 En masse pressure test

Since the placement of pressure sensor in the bin would disrupt material flow, a separate set of tests were conducted prior to the arching tests to establish the relationship between the compaction pressure applied on the top surface of wheat flour in the bin and the en mass pressure in the hopper. The bin and hopper assemble (Fig.4.1) was mounted on a universal testing machine (Series 1410, Applied Test Systems, Inc., PA). With the hopper outlet closed, the model bin was manually filled with wheat flour and the en masse pressure sensor was buried 20 mm above the hoper opening. After the top surface of flour was leveled, a compaction pressure (force) was applied by using the universal testing machine. The force was applied through a steel plate which was slightly less than the bin cross-section (600 × 375 mm) in size (Fig. 4.1) and this plate transformed the applied force to a uniform pressure on the top surface of flour in the model bin. Three replicates were conducted for the pressure rage of 0 to 39 kPa.

4. 2.2 Arching test

The bin filling procedure for arching tests was the same as that for en masse pressure test, but without the en masse pressure sensor buried in the material. After the bin was filled, compaction pressure was applied through the loading plate by using the universal testing machine and maintained for 2 minutes before the hopper gate was opened to discharge the stored flour. Applied compaction pressures ranged from 2.3 to 29.8 kPa, in an increment of 0.5 kPa in the 2.3-10.0 kPa range, and 1.0 kPa in the 10.0-29.8 kPa range. A minimum compaction pressure of 2.3 kPa was dictated by the weight of the loading plate, while 29.8 kPa covers the pressure ranges in typical storage bins. Each compaction condition (pressure) was replicated three times, resulting in a total of 108 tests for each of the two moisture contents.

When the hopper gate was opened to discharge the stored flour, if arching formed, i.e., the flow did not occur at the minimum hopper opening (50 mm), then a panel (angle iron) on the hopper was removed to increase the hopper opening to the next size. This process was repeated until flow occurred. The arching location was determined as the height of the panel that was removed immediately before the flow occurred.

It should be noted that 2-minute compaction time might not be sufficient enough for the material to be consolidated because the behavior of wheat flour was time dependent. It was observed that the measured en masse pressure was still increasing even though no additional pressure was applied, indicating that pressure on the wall was transferred to the bulk material as the compaction was in progress, but the rate of this change was only 2-3 N/minute. For the future studies, longer compaction time is recommended.

4.3 Direct Shear Test

The direct shear test device included a split box (127 mm×127 mm) consisting of an upper and lower cell, a cradle sled of dead weight, a DC motor with speed control, a load cell and a data acquisition (Fig. 4.5). The direct shear tester was a modified version of that was designed and described by Zhang et al. (1994). The unit is consistent with the standard shear apparatus originally developed by Jenike for determination of flow properties, and described in more detail in Mohsenin (1986). The upper and lower cells were constructed of 13 mm thick Plexiglas. The square cells were 127 by 127 mm in cross-section, and 75 mm high. The lower cell was fixed on a steel frame and the upper cell was connected to a liner screw-drive through a load cell. The screw-drive was driven by a DC motor to pull the upper cell horizontally. The motor speed was adjusted through a controller to achieve a shear rate of 0.12 mm/s. The shear (horizontal) force applied on the upper cell was sensed by the load cell and recorded at 1 s intervals using a data acquisition unit (Model 3852A, Hewlett-Packard, Santa Clara, CA). A vertical (normal) force was applied to the top surface of material in the upper cell by using weights slung underneath the unit by means of a cradle sled. A steel ball was used to transfer the force from the cradle sled to the top cover to ensure a uniform weight distribution.

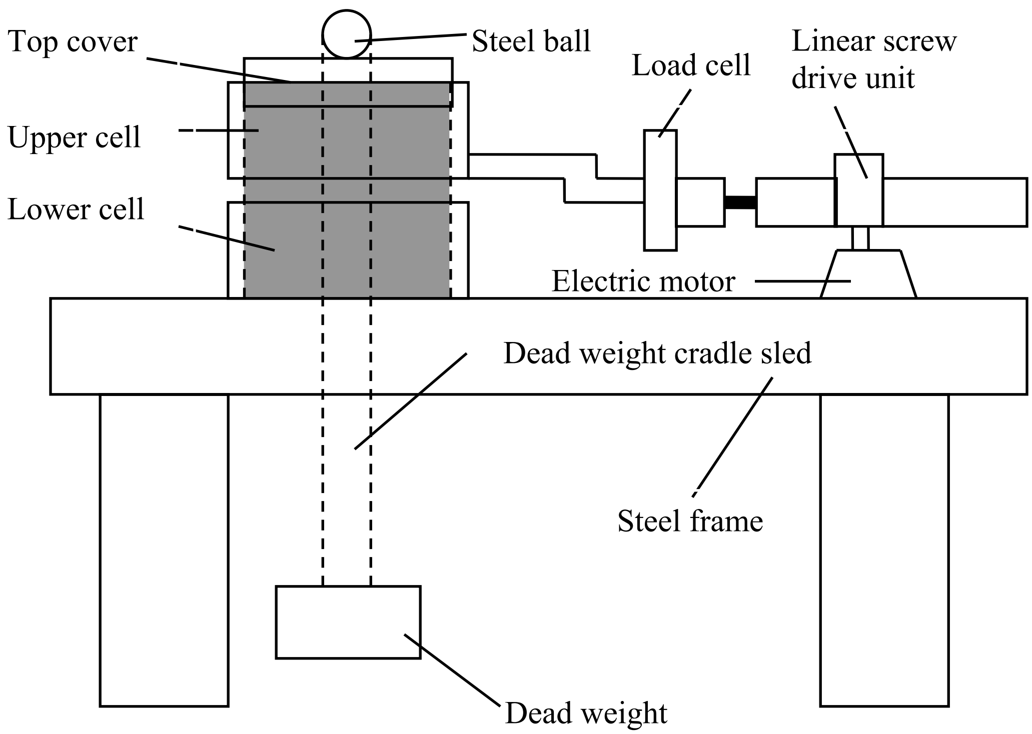

Figure. 4.5. Schematic illustration of direct shear test for measurement of internal friction and cohesion of wheat flour.

When the shear cells were assembled for each test, metal shims were placed at four corners between the upper and lower cells to maintain a clearance of about 2 mm between the two cells. This clearance was necessary to avoid friction between the cells themselves, but bridging prevented the material (flour) from flowing out through the clearance. Once the shear cells were assembled, wheat flour was placed into the cells and a vertical force was applied by placing weights into the cradle sled. The shims were removed after the vertical force was applied (the clearance stayed because friction between the flour and the interior surface of the upper box held up the box). The test began when the DC motor was turn on to pull the upper cell horizontally.

For each test, wheat flour was slowly poured centrally from a container into the boxes. The pouring height was maintained approximately 50 mm above the top of the boxes. Pouring continued until the material spilled over the edges of the top box, and then a dowel was used to remove excess material.

Two sets of direct shear tests were performed. In the first set of tests, a vertical pressure (force) was applied for 2 minutes to pre-compact the sample and then removed before the test force was applied. The pre-compaction pressures were chosen in the range from 0.2 to 9.1 kPa, which corresponded to the measured compaction pressure in the hopper section of the model bin. It should be noted that for a given test condition, pre-compaction pressure was always higher than the vertical (normal) pressure of shear testing. In the second set of tests, flour samples at moisture contents of 8.6% wb and 14.2% wb were tested at a single pre-consolidation pressure of 9.1kPa to compare the strength of flour between the two moisture contents. Each test condition was replicated three times.

For each test, the pulling (horizontal) force and displacements were recorded through the data acquisition system. The peak force was considered to be the shear force at failure and used in calculating internal friction and cohesion. The applied vertical force and the measured horizontal (shear) force at failure were converted to pressures as follows:

$$\sigma = F_n / A \qquad \text{and} \qquad \tau = F_s / A \tag{4.2}$$

where:

σ = normal stress

τ = shearing stress

F_n = applied vertical force

F_s = measured peak horizontal force

A = cross sectional area of shear box

According to the Mohr-Coulomb failure criterion, the strength (failure) is defined by the stress state as follows:

$$\tau = c + \sigma \tan\varphi \tag{4.3}$$

where:

τ = shear stress

σ = normal stress

c = cohesion

ϕ = angle of internal friction angle

By plotting the measured shear (horizontal)(τ) stress against the normal (vertical) stress (σ), the internal friction angle (ϕ) was obtained from the slope and the cohesion (c) as the intercept, whereas the unconfined yield strength (f_c) was determined by drawing a Mohr circle through the origin and tangent to the τ - σ line (Fig. 4.6), or f_c may be determined mathematically as follows:

$$f_c = \frac{c}{\tan(45 - \phi/2)} \tag{4.4}$$

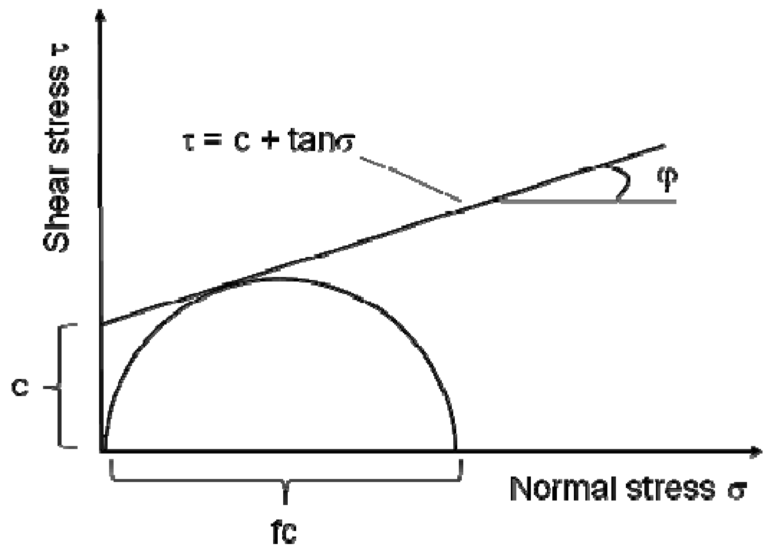

Figure. 4.6. Illustration of relationship between angle of internal friction, cohesion and unconfined yield strength (Shamlou, 1988).

Figures 4.7 and 4.8 show the direct shear test results for 8.6% and 14.2% moisture content, respectively. Values of internal friction angle, cohesion, and unconfined yield strength were obtained from these two figures and are summarized in Table 4.1.

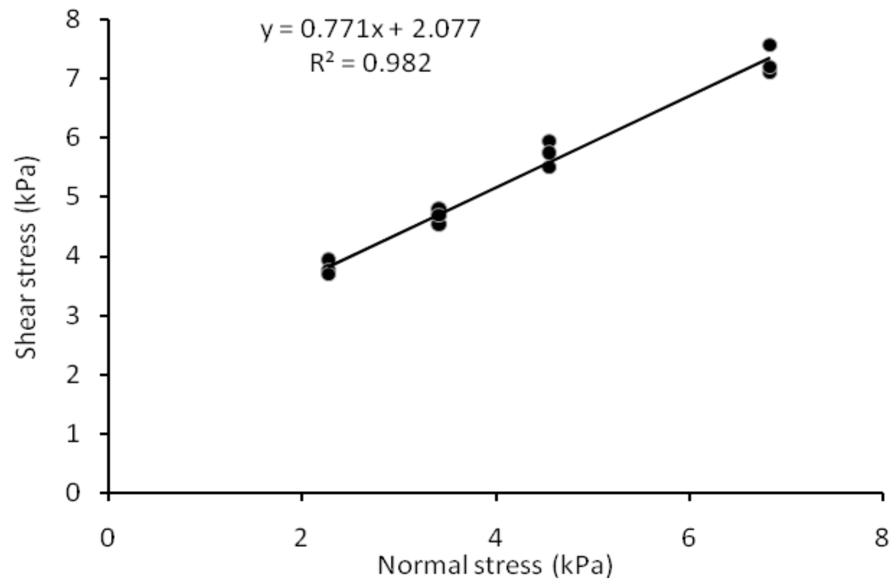

Figure. 4.7. Measured relationship between shear and normal stresses for wheat flour with moisture content 8.6%.

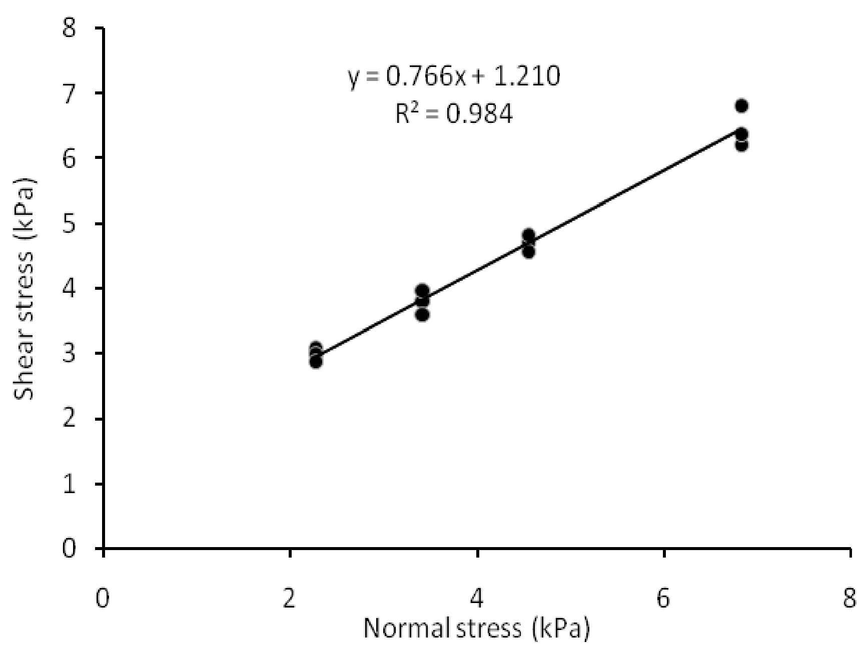

Figure. 4.8. Measured relationship between shear and normal stresses for wheat flour with moisture content 14.2%.

5. RESULTS AND DISCUSSION

5. 1. Compaction pressure

It was observed that the measured pressure in the hopper section increased with the compaction pressure applied at the top surface of the material (Fig. 5.1). A vertical pressure of 0.2 kPa was measured when no additional pressure was applied on the top surface. This initial compaction pressure was caused by the self-weight of the flour. The pressure applied on the top surface of the stored material did not transfer completely to the hopper section where arching occurred. At the maximum applied pressure of 39.13 kPa on the top surface, the measured en-masse pressure was only 6.88 kPa. In other words, only 17.6% of applied pressure was transferred from the top surface to the hopper section and the rest was carried by the bin wall. The percentage of applied pressure carried by the walls is dependent on both wall friction and the hopper angle. The higher the wall friction, the more pressure is carried by the wall; the smaller the hopper angle, the more pressure is carried by the wall (a hypothetical zero hopper angle, or a horizontal hopper wall would carry 100% applied pressure).

Although the overall correlation between the en masse and applied pressures was high (R^2 = 0.95) (Fig. 5.1), there was considerable scattering in data at low pressures. This indicated that the transfer of applied compaction pressure to the material in the hopper was not consistent at low pressures. This was probably due to some instantaneous (random) arches which transferred applied pressure to the walls and these random arches would be broken at high pressures.

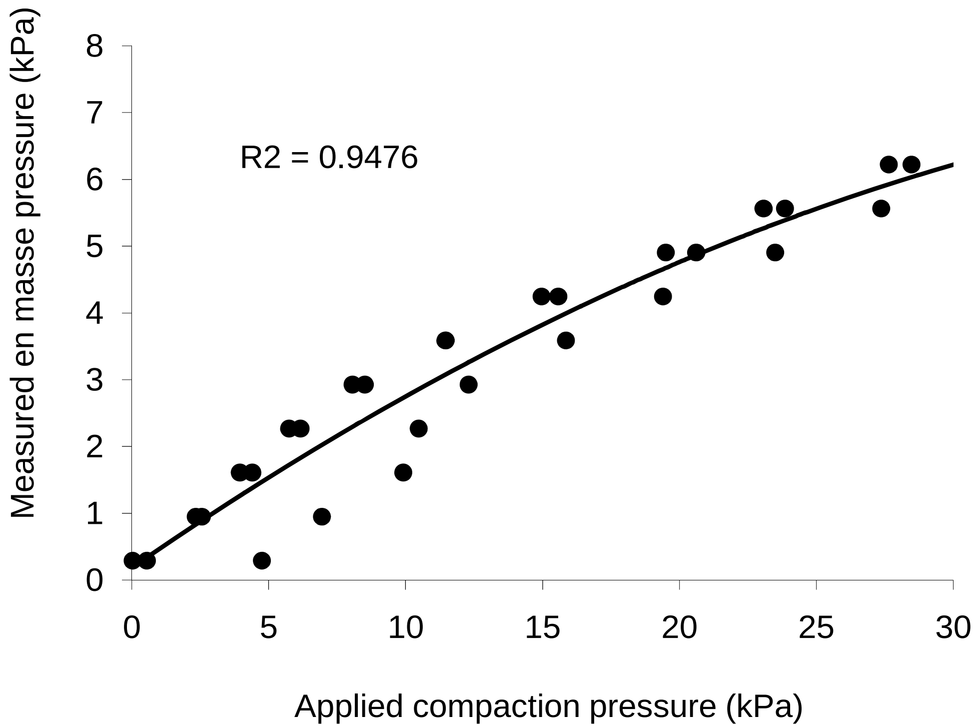

Figure 5.1. Relationship between applied pressure and measured en mass pressure (three replications).

5. 2. Compaction in model bin

Measured compaction (% volume reduction) and compaction rate (% volume reduction per kPa of applied pressure, or %/kPa) are presented in Figure 5.2. As expected for bulk solids, the wheat flour was more compressible at the initial stage; the rate of compaction decreased from 3.5 to 0.5 %/kPa when applied pressure was increased from 0 to 5 kPa. The compaction rate did not change significantly after the pressure was beyond 5 kPa (0.5 %/kPa at 5 kPa vs. 0.3 %/kPa at 21 kPa). Similarly, the bulk density changed quickly at the initial loading stage; it increased from 601 to 640 kg/m^3 when applied pressure was increased from 0 to 5 kPa. A semilog model has been used by several researchers to describe the relationship between bulk density and compaction pressure for food powders (Peleg et al., 1973):

$$\rho = a + b \log p \quad (5.1)$$

By regression analysis, the two constants were determined to be: a = 613 kg/m^3; b = 17.9, with R^2 = 0.89, for wheat flour at 14.2% MC.

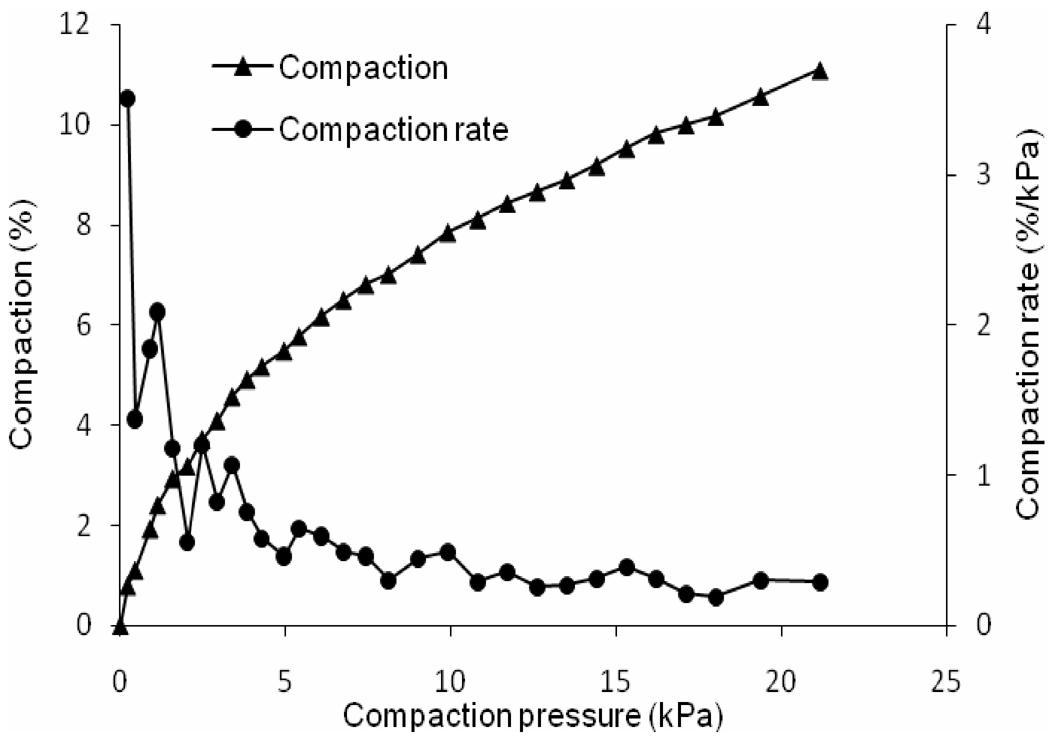

Figure 5.2. Relationship between applied compaction pressure and compaction for wheat flour at 14.2% MC (moisture content) (each data point represents the average of three replications).

5.3. Effect of moisture content on material strength

An increase in moisture content from 8.6% to 14.2% had little effect on the internal friction. The $\sigma - \tau$ curves for 8.6% and 14.2% moisture contents appeared parallel as presented in Figure 5.3, i.e., the internal friction angles were about the same for the two moisture contents (37.6° vs. 37.5°). The 95% confidence interval (CI) of the internal friction angle were (34.9° – 39.9°) for 8.6% MC and (34.9° – 40.2°) for 14.2% MC and there was no statistically significant ($P > 0.05$) difference in internal friction angle between the two moisture contents. The cohesion for 14.2% MC (2.08 kPa, 95% CI: 1.74 – 2.41) was 72% higher than that for 8.6% MC (1.21 kPa, 95% CI: 0.90 – 1.52), and the difference was statistically significant ($P > 0.05$). This observation is important in understanding how the moisture content affects the formation of arches. It can be seen the Mohr-Coulomb criterion (equation 4.3) that the shear strength of material consists of a part that is independent of the normal stress - cohesion, and a part that is normal stress dependent - internal friction angle. As discussed in the literature review, arch formation is dictated by the unconfined yield strength (UYS), which is a measurement of material strength when no normal stress is applied. This means that among the two strength parameters, cohesion is more closely related to arching than internal friction. Therefore, moisture content would have a major effect on arching because it is closely associated with cohesion.

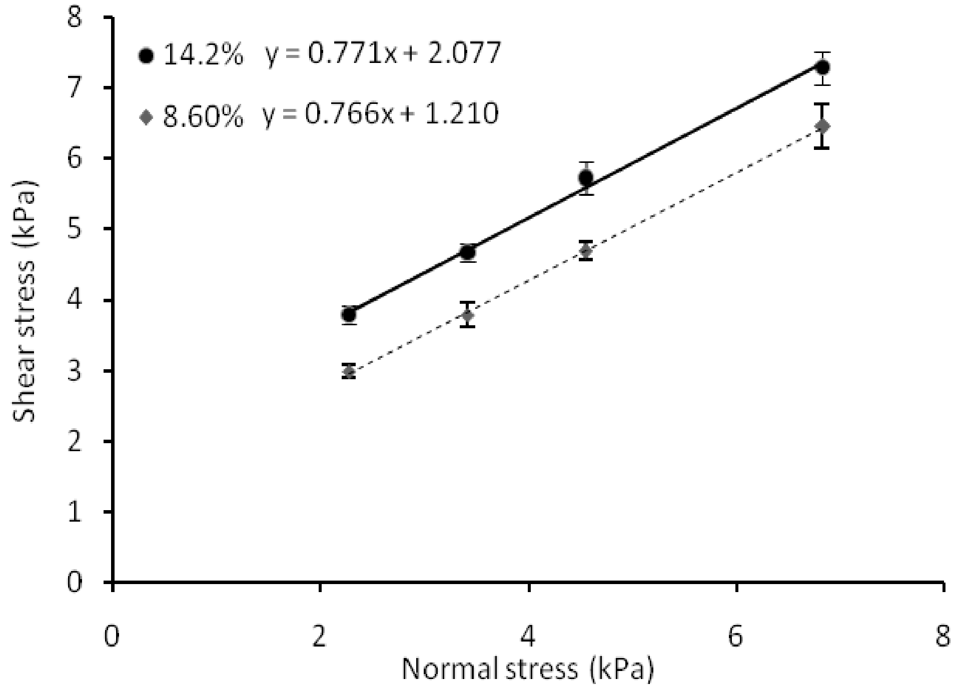

Figure 5.3. Measured relationship between shear and normal stresses for wheat flour at moisture contents of 8.6% and 14.2%. Samples were pre-consolidated at a normal stresses of 9.1 kPa.

The UYS represents the combined effect of cohesion and internal friction on the flowability. From the measured values of cohesion and internal friction, the UYS was calculated with equation 4.4 to be 2.4 and 3.1 kPa for 8.6% and 14.2% MC, respectively. In other words, the UYS increased 29% when the moisture content increased from 8.6% to 14.2%. This observation agreed with what has been reported by many researchers in the literature. For example, Domian and Poszytek (2005) reported that wheat flour with 16% wb (wet basis) MC moisture was more cohesive than flour at 11% wb MC and the moist flour could cause difficulties in gravity discharge from storage. Teunou and Fitzpatrick (1999) evaluated the effect of exposure to humidity in the air on the flowability of wheat flour, tea, and whey permeate and observed that the flowability of all these materials decreased with increasing relative humidity.

Decrease in flowability at increased moisture content might be attributed to the increase in liquid bridges and capillary forces acting between the powder particles (Domian and Poszytek, 2005). For dry powders the dominant interparticle force is van der Waals (Israelachvili, 1992). Capillary forces often dominate when particle size is between 40 and 400 μm (Johanson et al., 2003). When moisture is added to a powder material, the liquid is held as a point contact in a bridge neck between particles. The strong boundary forces resulting from the surface tension of the liquid draw the particles together and capillary pressure is resulted from the curve liquid surfaces of the bridge.

It should be noted the moisture might also act as a lubricant for improved flow when it was above a certain level (Fitzpatrick et al., 2004a), and some materials are more sensitive to moisture than other materials depending on how moisture changes the interaction between particles. Fitzpatrick et al. (2004b) reported that exposure of the powders to moisture in air showed a major increase in the cohesion for skim-milk powders, but had little effect on whole-milk and high-fat milk powders.

5.4 Effect of compaction on material strength

Experiments showed that both internal friction angle and cohesion of the wheat flour varied with compaction (Fig. 5.4). The wheat flour had very low strength if not compacted. For example, the internal friction angle was only 6.5° and cohesion 1.4 kPa (Fig. 5) when no compaction pressure was applied. At a compaction pressure of 1.3 kPa, the internal friction rose quickly to 36.9°. It is, however, interesting to note that the internal friction angle changed little at higher compaction pressures. Significant changes in cohesion did not occur until the compaction pressure reached 3.9 kPa. Cohesion increased from 1.5 to 2.1 kPa, or 40%, when pressure was increased from 3.9 to 6.8 kPa. Continuing increase in compaction pressure caused little change in cohesion (Fig. 5.4.1).

The UYS increased with the compaction pressure (Fig. 5.4) until the pressure reached 6.8 kPa. Because of the sharp increase in internal friction at initial compaction, the UYS also increased sharply from 1.6 to 2.9 kPa, or 55%, when compaction pressure increased from 0.2 to 1.3 kPa. The UYS increased gradually from 2.9 to 4.2 kPa as the compaction pressure was raised from 1.3 to 6.8 kPa, and changed little after 6.8 kPa (Fig. 5.4).

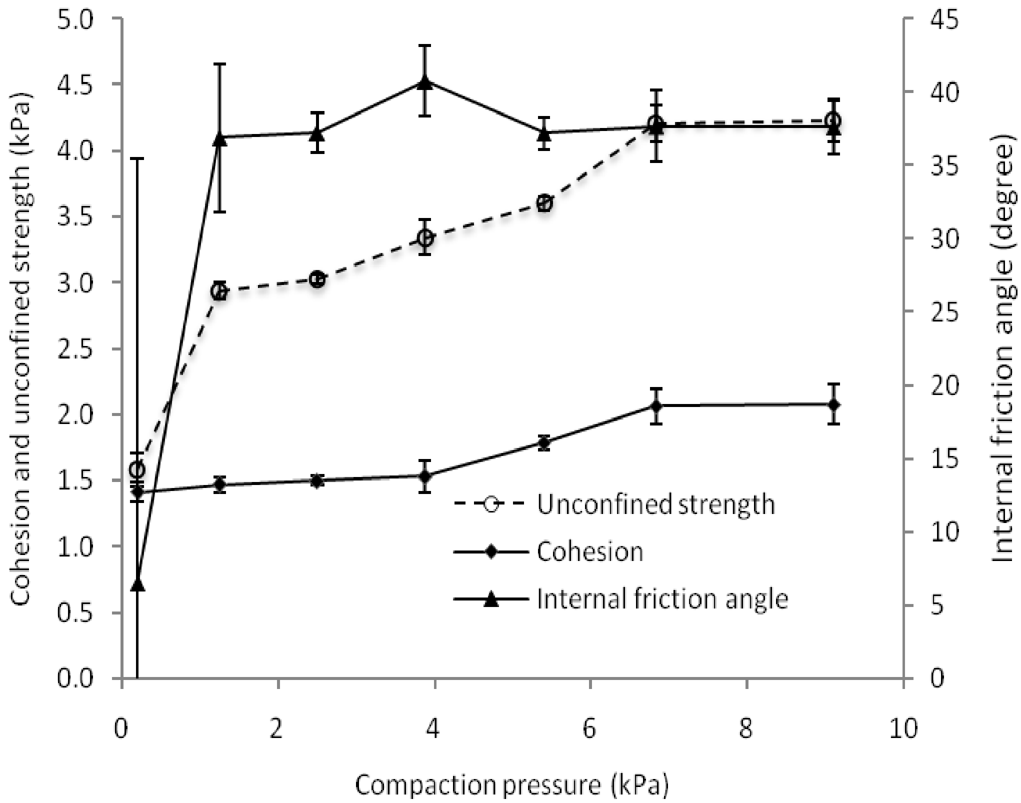

Figure. 5.4. Variation of internal friction, cohesion and unconfined yield strength with compaction pressure for wheat flour at 14.2% MC (moisture content) (each data point represents the average of three replications).

5. 5. Effect of compaction on arching

The moisture content had a noticeable effect on arch formation (Fig. 5.5). The minimum hopper opening for no arching was 122 and 86 mm for 14.2% and 8.6% MC, respectively. In other words, the hopper opening for 14.2% MC was 42% greater than that for 8.6% MC. This was attributed to the effect of moisture content on the strength of wheat flour.

For wheat flour at moisture content of 14.2%, an arch formed at hopper opening of 50 mm even if the material was not compacted (no compaction pressure was applied besides the self-weight). The material started to flow when the hopper opening was increased to 82 mm, but the flow was not reliable. As the compaction pressure increased, the hopper opening had to be increased to avoid arching. The true arch-free flow was achieved when the hopper opening reached 122 mm. Compaction pressure had little effect on arching after the pressure reached 5.3 kPa. This agreed with the measured material strength shown in Fig. 5.4 where the material had reached its maximum strength after a certain compaction pressure. Therefore, further increases in compaction pressure did not affect arch formation.

When wheat flour at 8.6% MC was not compacted, no arching occurred at the minimum hopper opening of 50 mm (Fig. 5.5). When the compaction pressure was increased to 4.3 kPa, an arch formed near the discharge outlet, with a span of 62 mm. No arching was observed after the hopper opening reached 86 mm, i.e., the hopper opening for arch-free flow was 86 mm for 8.6% MC. Compaction pressure had little effect on arch formation after compaction pressure reached 4.8 kPa.

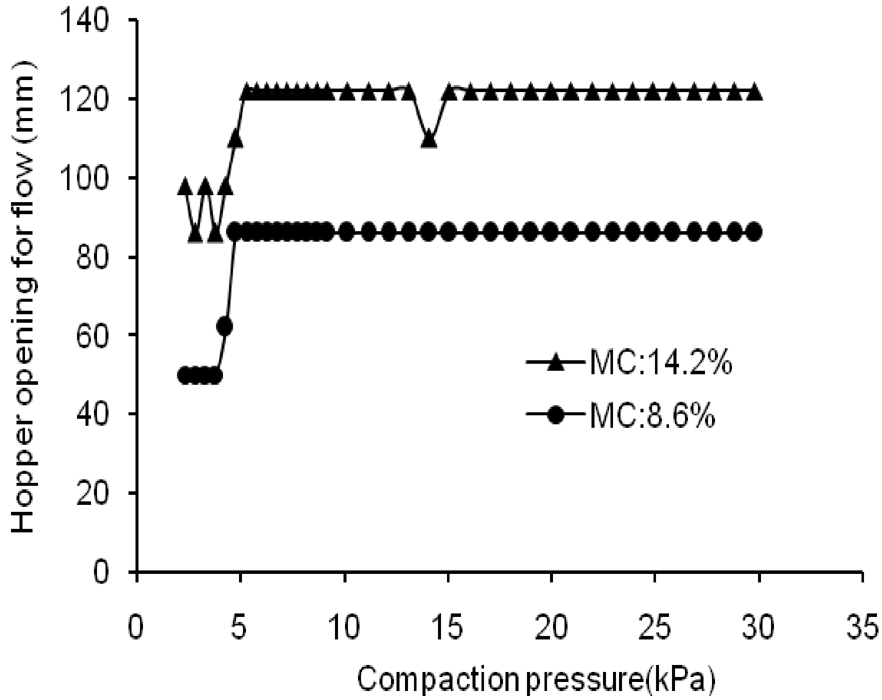

Figure 5.5. Hopper opening for flow of wheat flour at 8.6% and 14.2% MC (moisture content) under different compaction pressures (each data point represents the average of three replications).

Based on the measured values of unconfined strength, the measured arching spans were compared with theoretical predictions (equation 3.5). The results are summarized in Table 5.1.

Table 5.1 Comparison between measured and predicted arch spans

Conpaction pressure (kPa)	Unconfined yield strength (kPa)	Measured arching span (m)	Predicted arching span (m)
0.20	3.14	0.05	0.62
1.25	5.87	0.098	1.16
2.50	6.30	0.121	1.25
3.88	6.69	0.121	1.33
5.40	7.20	0.121	1.43
6.80	8.31	0.121	1.65

It can be seen that the measured arching spans were much smaller than theoretical predictions, at the compaction pressure of 0.20 kPa, for instance, the measured arching span was 11.4 times smaller than the calculated arching span using Jenike's method of estimation. This would be expected that Jenike did neither account for the possibility that the arch across the outlet would slide along the wall due to the low friction nor for the fact that the arch, in addition to its own weight, would have to sustain the weight of the stored material above (Enstad, 1975).

6. CONCLUSIONS

1. The moisture content of wheat flour had a noticeable effect on arching. The hopper opening for arch-free flow for 14.2% MC was 42% greater than that for 8.6% MC.
2. Compaction led to increases in minimum hopper opening required to initiate material flow; the opening increased from 50 to 82 mm for 8.6% MC and from 82 to 122 mm for 14.2% MC when compacted at about 5 kPa. However, compaction pressure had little effect on arch formation beyond 5 kPa.
3. Higher moisture content resulted in higher strength and cohesiveness of the wheat flour in the tested moisture range (8.6% - 14.2%), but the moisture content had little influence on the internal angle of friction.
4. The strength of the wheat flour increased with compaction pressure; however compaction had little effect on strength after it had reached a certain level. The internal friction of the wheat powder showed a major increase initially with increasing compaction, and compaction had only a minor influence on cohesion.
5. Experimental evidence showed that the measured arching spans were much smaller than the calculated arching spans using Jenike's method.

7. RECOMMENDATIONS FOR FURTHER RESEARCH

Arching in storage bins for cohesive bulk solids is a complex problem. Much research effort is needed to understand the mechanism of arch formation. The current research revealed that the moisture content of material and the degree of compaction the material was subjected to had noticeable effect on arching in wheat flour. Further research is recommended to foster the understanding of moisture and compaction effect on arching formation.

1. In a narrow range of moisture content investigated in this study, the flowability decreased with increasing moisture content, but moisture at high levels could also increase the flowability. It is recommended that a wider moisture range be investigated.
2. Most food powdery materials are visco-elastoplastic, and thus the compaction process would be time dependent. In this research, compaction pressures were applied to the wheat flour for a very short time period (2 minutes). It recommended that the time effect on compaction and arching formation be investigated.
3. In the arching test, six detachable panels were used to change the hopper opening in an increment of 36 mm. It was noticed that this increment in hopper opening was too large to accurately quantify the arch spans. In the future research, more detachable section panels or smaller hopper opening increments should be used to accurately determine the minimum openings for free flow.
4. The food powdery materials may react differently to moisture in terms of changes in flowability, depending on how moisture affects the particle interactions. This

study dealt with wheat flour. It is recommended that other food powdery materials be studied and compared to better understand the mechanisms of moisture effect on arching.

5. In this research, the measured arching spans were compared with theoretical predictions; the results indicated the measured arching spans were much smaller. A more reliable arching theory or equation is desired for the future research.

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APPENDIX A. DIRECT SHEAR TEST RESULTS

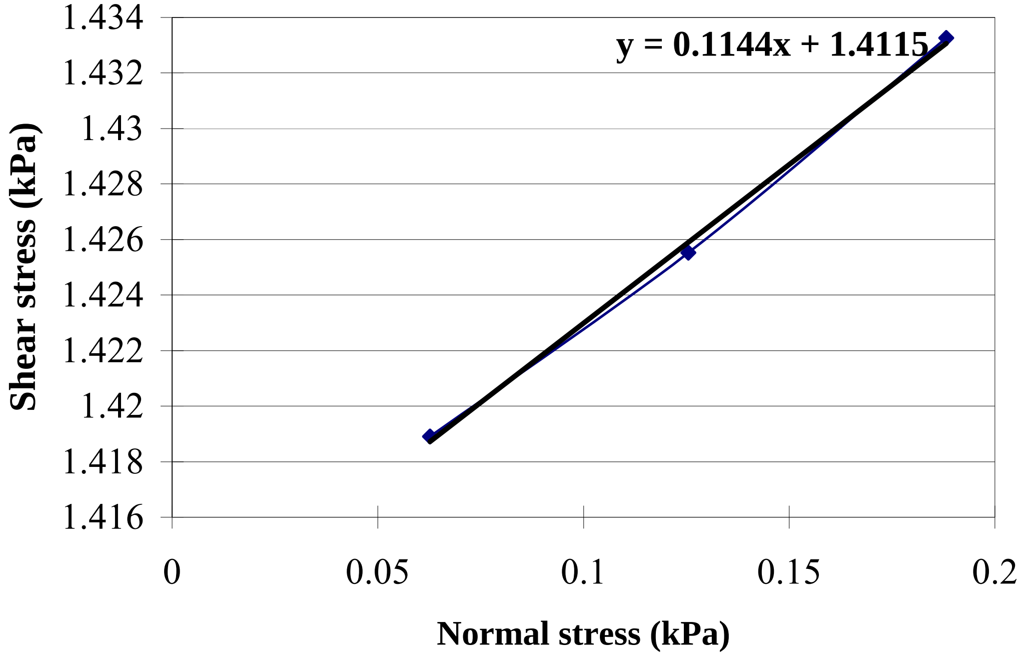

Figure A. 1. Direct shear test result at compaction pressure of 0.2 kPa

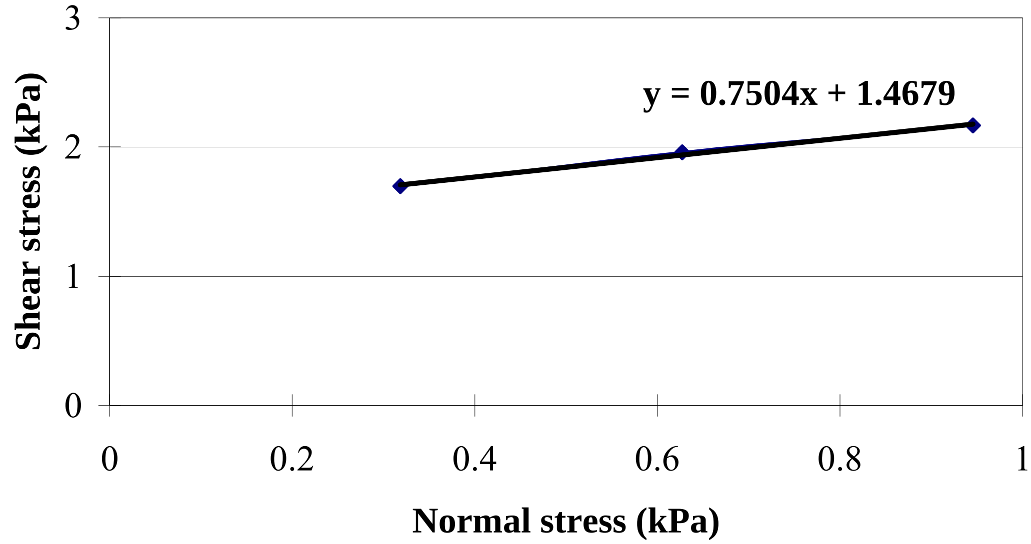

Figure A. 2. Direct shear test result at compaction pressure of 1.25 kPa

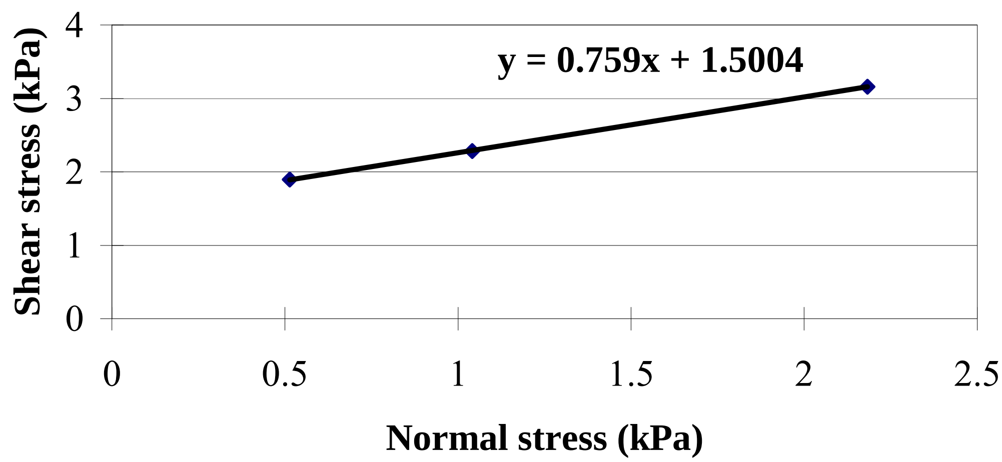

Figure A. 3. Direct shear test result at compaction pressure of 2.50 kPa

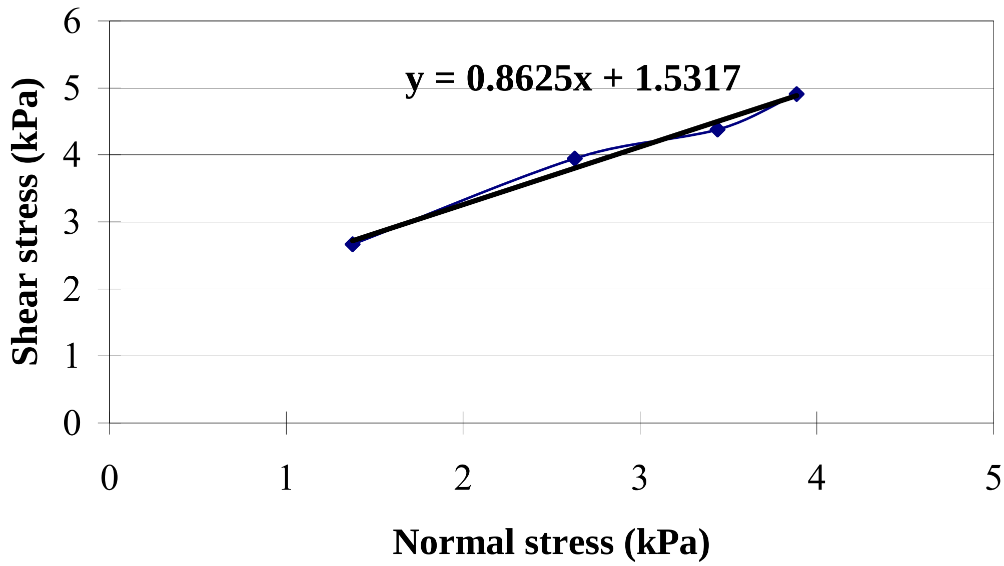

Figure A. 4. Direct shear test result at compaction pressure of 3.88 kPa

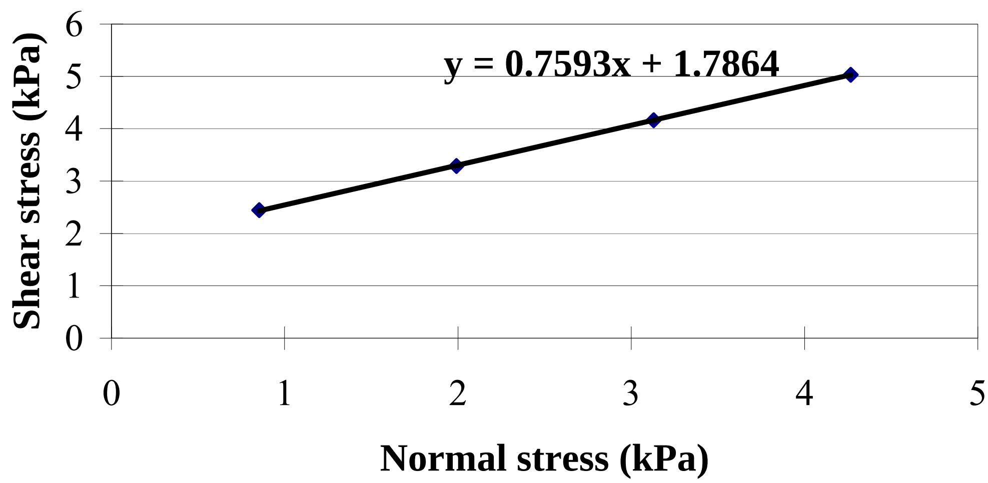

Figure A. 5. Direct shear test result at compaction pressure of 5.40 kPa

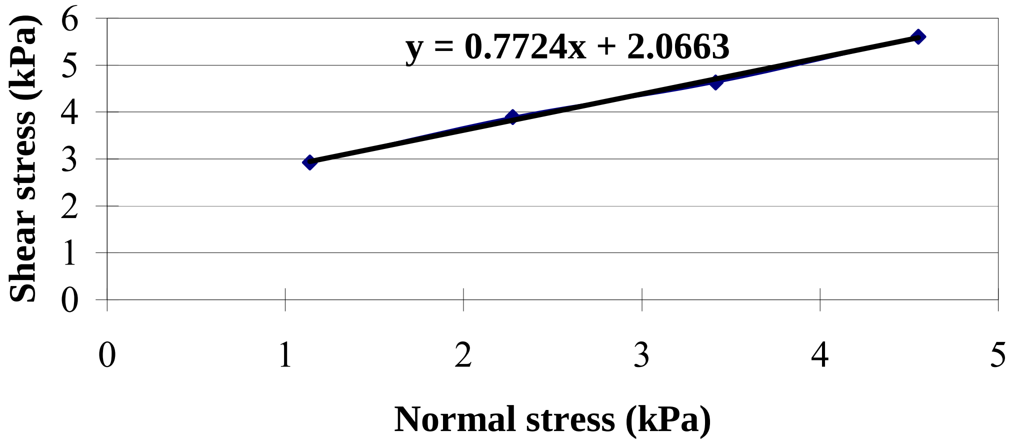

Figure A. 6. Direct shear test result at compaction pressure of 6.83 kPa

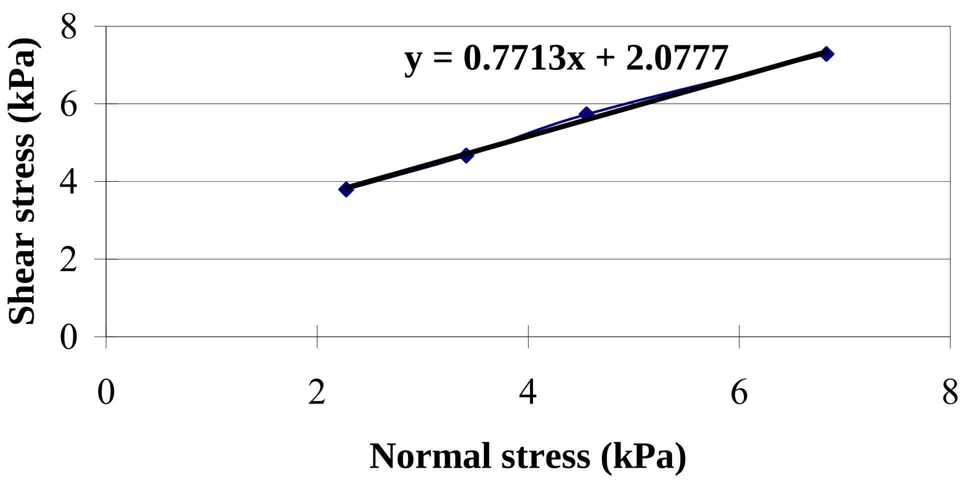

Figure A. 7. Direct shear test result at compaction pressure of 9.10 kPa