An Investigation into the Flowability of Flours and Evaluation of testing methods of Powder Flow Tester

Thesis submitted in the partial fulfillment
Of the requirements for the degree of

Master of Engineering
In
Thermal Engineering

By

Gourav Saluja

Registration No.: 801683010

THAPAR INSTITUTE
OF ENGINEERING & TECHNOLOGY
(Deemed to be University)

Under the Supervision of

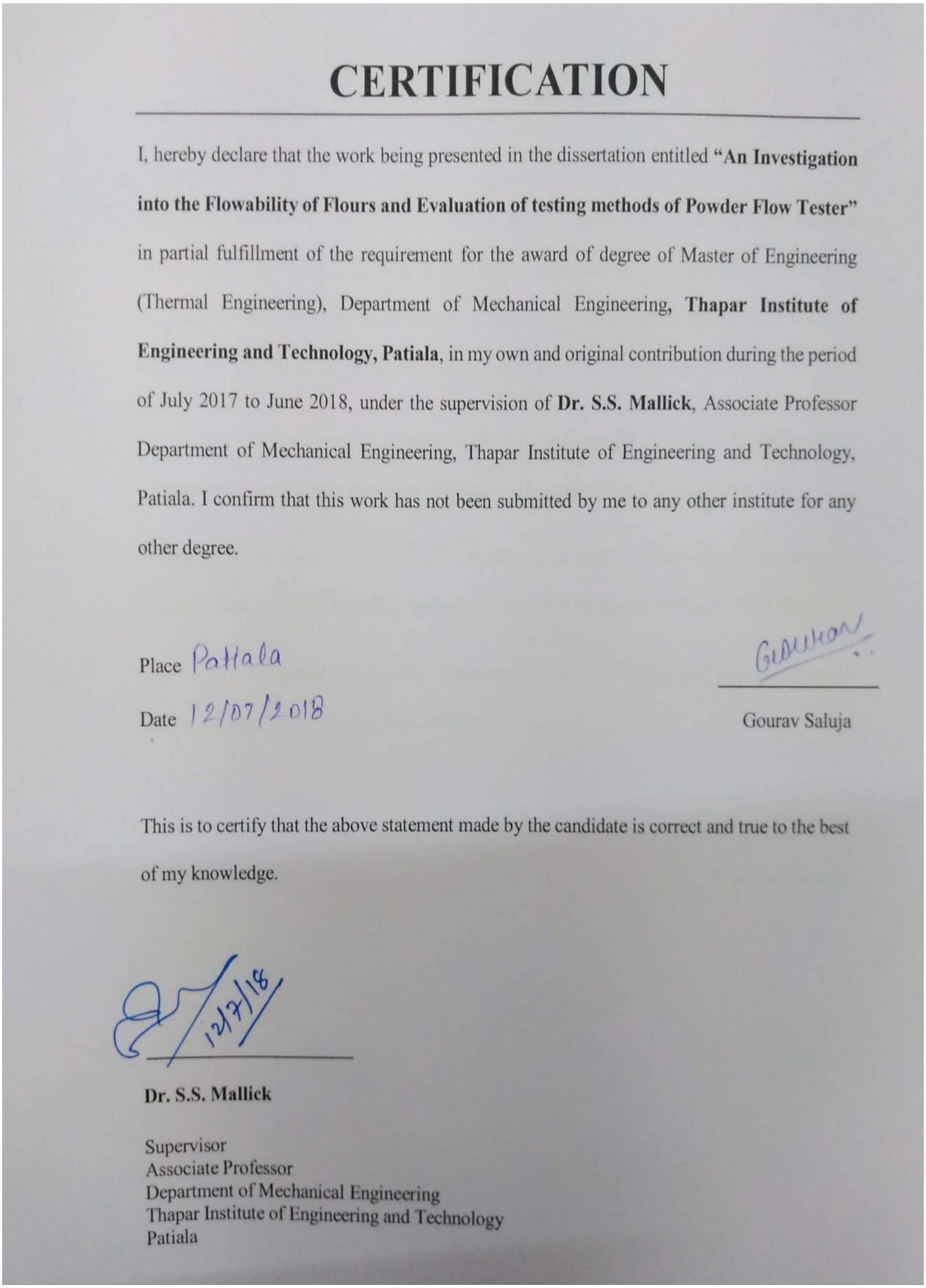
Dr. S.S. Mallick

Associate Professor

Department of Mechanical Engineering

Thapar Institute of Engineering and Technology Patiala

July, 2018



CERTIFICATION

I, hereby declare that the work being presented in the dissertation entitled **"An Investigation into the Flowability of Flours and Evaluation of testing methods of Powder Flow Tester"** in partial fulfillment of the requirement for the award of degree of Master of Engineering (Thermal Engineering), Department of Mechanical Engineering, **Thapar Institute of Engineering and Technology, Patiala**, in my own and original contribution during the period of July 2017 to June 2018, under the supervision of **Dr. S.S. Mallick**, Associate Professor Department of Mechanical Engineering, Thapar Institute of Engineering and Technology, Patiala. I confirm that this work has not been submitted by me to any other institute for any other degree.

Place Patiala

Date 12/07/2018

Gourav Saluja

This is to certify that the above statement made by the candidate is correct and true to the best of my knowledge.

12/7/18

Dr. S.S. Mallick

Supervisor
Associate Professor
Department of Mechanical Engineering
Thapar Institute of Engineering and Technology
Patiala

Acknowledgement

First of all, I would like to thank my supervisor, **Dr. S.S. Mallick** for his guidance and constant support during this work. The study presented here could not have been accomplished without his patience and motivation. He taught me to be concise and correct in my approach from the formulation of ideas to the presentation of the results.

I would also like to express my gratitude to **Mr. Atul Sharma, Dr. Anu Mittal and Mr. Kapil Sharma** who never turned me down whenever I approached them for any kind of help.

Words fail me to express my thanks to my family and friends who have always supported me and have been a source of strength and inspiration to me during the entire period of the work.

I also want to thank **Mr. Sambhrant Srivastav** who motivated me to grab the opportunity to pursue my Masters in Thermal Engineering.

Gourav Saluja

Abstract

Food processing industries encounter several problems regarding powder fowability, such as arching or no flow, inconsistent flow, segregation, flooding etc. due to the lack of fundamental understanding of the physical properties of the bulk solids to its flowability and the subsequent influence of the same on the selection of critical hopper parameters. In this study, the physical and flow properties of wheat and chickpea flour were studied. Flow properties were tested using powder flow tester (PFT) with standard and custom (with separate samples) test methods along with different options (geometric spacing, even spacing, doubling progression, tangent to Mohr circle). Results of instantaneous flow property tests showed that wheat flour falls in the cohesive region and chickpea flour in very cohesive region. There was no considerable effect of time consolidation on the flowability of wheat flour, whereas the flowability of chickpea flour decreased considerably to non-flowing state. A significant difference was observed between the "standard" and "custom" (with separate samples, geometric spacing and tangent to unconfined Mohr circle) instantaneous flow function test results at higher stresses for chickpea flour. The "custom" test method provided better flow function results than that of "standard" methods. The conical shape hopper was found to be more suitable for wheat flour with a hopper half angle of 32°. Wedge shaped hopper for chickpea flour with a hopper half angle of 20° was considered to be a more judicious choice.

Keywords: Wheat and chickpea flour, Flow property, Time consolidation, Hopper half angle, Powder flow tester.

Table of Contents

Contents

CERTIFICATION i

Acknowledgement ii

Abstract iii

Contents iv

List of Tables vi

List of Figures vii

Nomenclature ix

CHAPTER 1: Introduction & Objectives

1.1 Introduction 1

1.2 Objectives 4

Chapter 2: Literature Review

2.1 Common problems with bulk solids 5

2.2 Review of the previous research on powder flowability 9

Chapter 3: Materials and Methods

3.1 Materials 19

3.2 Physical Properties 19

3.3 Flow properties 21

Chapter 4: Result and Discussion

4.1 Physical Properties 25

4.2 Flow Properties 28

4.3 Hopper design for mass flow 45

Chapter 5: Conclusion & Future Scope

5.1 Conclusion 49

5.2 Future Scope 50

References 51

Communications 55

List of Tables

Sr. No.	List of Tables	Page No.
1.	Physical properties of wheat flour and chickpea flour	27
2.	Moisture content of fresh and time consolidated wheat flour and chickpea flour	28
3.	Flow properties of wheat and chickpea flour using different test methods in Powder Flow Tester (PFT)	33
4.	Wall friction test results for wheat and chickpea flour	38
5.	Bulk density test results for wheat and chickpea flour	42
6.	Time consolidated flow function test results for wheat and chickpea flour	41

List of Figures

Sr. No.	List of Figures	Page No.
a.	Arching	5
b.	Funnel flow	6
c.	Flooding	7
d.	Non-uniform discharge	8
e.	Segregation	8
f.	Buckling	9
1.	Schematic representation of Mohr circles and yield locus from flow testing	23
2.	SEM images of fresh wheat flour and chickpea flour	27
3.	SEM images of time consolidated wheat flour and chickpea flour	28
4.	Flow function curves of wheat flour using standard test method and custom test method with different options	30
5.	Flow function curves of chickpea flour using standard test method and custom test method with different options	31
6.	Effective angle of internal friction versus major principal consolidating stress for wheat flour	34
7.	Effective angle of internal friction versus major principal consolidating stress for chickpea flour	35

8.	Effective angle of wall friction versus major principal consolidating stress for wheat flour	36
9.	Effective angle of wall friction versus major principal consolidating stress for chickpea flour	37
10.	Bulk density versus normal stress for wheat flour and chickpea flour	41
11.	Time consolidated flow function curves for wheat and chickpea flour	43
12.	Hopper half angle versus hopper outlet diameter for wheat flour and chickpea flour (conical and plane shape hoppers) with time consolidation effects	46
13.	Hopper half angle versus hopper outlet diameter for wheat flour using instantaneous standard flow function and different wall friction (for conical hopper)	47
14.	Hopper half angle versus hopper outlet diameter for chickpea flour using instantaneous custom flow function with separate samples geometric spacing and tangent to unconfined Mohr circle flow function and different wall friction (for plane hopper)	48

Nomenclature

Greek Symbol

ρ_{lb}	Loose-poured bulk density, kg/m^3
ρ_p	Particle density, kg/m^3
ρ_t	Tapped density, kg/m^3
d_{50}	Average particle size, µm
σ_1	Major principal consolidating stress, kPa
σ_c	Unconfined yield strength, kPa
δ_j	Effective angle of internal friction, °
ϕ_w	Effective angle of wall friction, °
θ	Hopper half angle, °

Abbrevation

S	Span
SSA	Specific surface area, m^3/kg
P	Porosity
HR	Hausner Ratio
CI	Compressibility Index
MC%	Moisture Content
$D_{arching}$	Hopper opening size, m
ff_c	Flow index
SEM	Scanning Electron Microscope

Chapter-1

Introduction and Objectives

1.1. Introduction

Wheat (Triticum) flour and chickpea (Bengal gram; Cicer arietinum) flour are two popular staple food powders that are commonly used in South East and South Asia, especially in the Indian sub-continent due to their large scale availability, affordable price and associated benefits of healthy living [1]. India is the largest producer of pulses and the second largest producer of wheat having a wide variety due to 46 different types of soil and 26 different types of climatic conditions at which the wheat is cultivated [2]. Wheat flour is a universal flour which is milled from wheat grains having varieties in itself and categorized in two types: high gluten and low gluten flour. They can be also categorized as: whole wheat flour, self-rising flour, cake or pastry flour, bread flour, gluten flour and semolina flour. Chickpea flour is milled from Bengal gram, which is a type of chickpea. Such large quantities of flour coming from food processing industry require efficient handling of the bulk solids for size reduction, pneumatic transport, compaction, mixing, packaging and storage in bins and hoppers [3, 4 and 5]. The bulk powders trying to pass through such mechanical bulk-powder handling equipment or processes often face challenges of arching, rat-holing, agglomeration, segregation, flooding, funnel flow and non-uniform discharge [3-6, 8-10]. A major reason behind the occurring of these problems is the lack of understanding of flow properties of bulk solids and their dependencies on the physical characteristics of the powders at the bulk and particle level, which subsequently lead to inadequate design of flow chutes, hoppers, bins etc. [3]. Therefore, it is mandatory to monitor the flowability variation at each unit of the processing plant with close precision [11] and take appropriate measures to ensure that the desirable powder flowability is maintained.

To investigate into the flowability of different powders through various equipment, the standard procedure is to perform laboratory scale test based on Jenike's principle [3]. The method comprises of calculating flow function coefficient and generating flow function curves under instantaneous and time consolidation stresses [12]. Other parameters (such as unconfined yield strength, cohesion and angle of internal friction) can be calculated by analyzing the Mohr's circle with the knowledge of major principal or consolidated stresses [5]. There are various powder characteristics, such as particle size distribution, particle shape, surface structure, particle density, bulk density, water content and chemical composition on which flowability of powder depends. To characterize the flow properties of the powders, shear cell technique is widely used [13] in designing storage bins and hoppers that are widely used in industries, such as for detergent, cement, certain type food powders etc. [10, 13-17]. However, it seems that there is a limited amount of information available in the literature on the flowability of flour, especially for wheat and chickpea powders that are grown and consumed in South East and South Asia. Therefore, a comprehensive study is required to be carried out on the flow properties and wall friction characteristics of these flours (wheat and chickpea flours) and to compare the results with respect to the physical properties of the powders.

Majority of powder flowability studies that have been undertaken in the past [4, 5, 8, 9, 12-17] have reported results of instantaneous flow function only. Under practical circumstances, there is a likelihood that the powders are stored in storage hoppers, silos and chutes due to line stoppages (such as maintenance, blockages, overnight storage due to the end of shift etc.). This would result in product being consolidated with time and could cause changes in physical and surface properties of the bulk powders, such as moisture content, microbial growth, liquid layer bridging etc. [3, 10]. While it is well known that such time-consolidation of powders generally leads to a loss of powder flow properties (requiring a more favourable hopper outlet opening), the exact underlying causes (such as changes in moisture content and particle structure/size etc.) and the extent of loss of flow property with respect to time are rarely reported. Therefore, there is a requirement to study the effect of time consolidation on the flow properties of bulk solids.

The Brookfield Powder Flow Tester (PFT) was developed to perform tests following the basic Jenike's methodology [18], but in a reduced time duration yet with meaningful results. The algorithm of the software provided with PFT (Powder Flow Pro) has two test methods: "Standard" and "Custom" with various options (geometric and even spacing, use of separate samples, tangent to Mohr circle etc.). The "standard" mode does not allow for any change in the option, while the "custom" tests allows to change the options up to a certain maximum value [18]. In the "standard" test, the time consumption is less, but it does not allow to change the sample for each consolidation stress. Use of a fresh sample with pre-shear is the recommended practice as per Jenike's methodology [19]. The "custom" test with separate samples requires fresh samples at each consolidation stress. As a result, it also takes a great degree of effort and time for the tests to be completed. Previously, PFT was used by Bian et al., [5] studied the flow properties of hard red winter and soft white winter wheat flour. Amagliani et al., [13] investigated the flow properties of rice protein powders. Crowley et al., [14] to study the flow properties of milk protein concentrate powders having 7 different concentrations of protein. Saw et al., [20] examined the flow properties of a variety of bulk solids, such as 13 milled, 2 spray dried lactose powder, 3 sand and 3 refractor dust samples.

Lee et al., [21] studied the flow properties of black soybean powders of different particle size. Mallick et al., [22] studied the flow properties various samples of fly ash from different fields of power plants. Rohilla et al., [23] used 7 different fly ash samples from 7 different consecutive ESP fields of a thermal power station. Garg et al., [24] studied the flow properties of calcium sulphate and di-calcium phosphate. It is evident that although the various researchers in the past have used Powder Flow Tester (PFT) for the flow property testing of various bulk solids, very few independent studies have been carried out to compare the differences in the test results depending on the choice of test method (i.e. “standard” versus “custom”) and addressing the same for estimation of hopper half angle. Therefore, an independent study needs to be conducted to address the differences in test results obtained depending on the choice of test method in the Powder Flow Tester (PFT) equipment.

1.2. Objectives

(i) To investigate into the flow properties of wheat flour and chickpea flour under instantaneous flow condition;

(ii) To investigate into the effect of time consolidation on the flow behaviour of both the above mentioned flours and to address the loss of power flowability with the corresponding changes in physical condition of the bulk powders;

(iii) To determine critical hopper half-angle and opening size for mass-flow condition;

(iv) To evaluate the differences in the test results depending on the choice of test method (i.e. “standard” versus “custom”).

Chapter-2

Literature Review

2.1. Common problems with bulk solids

During the establishment of any food industry or food processing unit, a lot of thought hasnot been put towards silo or hopper design. At that particular time this small mistake or negligence affect the performance of the plant in the long run. People working in the plant encounters a lot of problems regarding bulk solid storage and its handling. The most common problems which are encountered are mentioned below

1. Arching

   Arching is a phenomenon which takes place due to the cohesive strength of the powders. The particles of the powder due to its cohesiveness forms a bridge in the shape of an arc near the outlet of the hopper and the flow of the bulk solid stops.

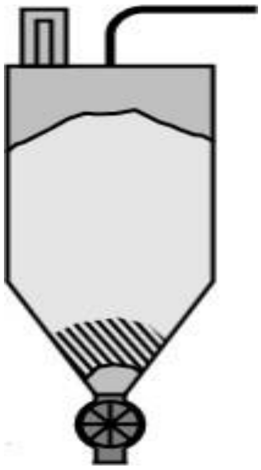


Figure a: Arching (Schulze, 2008)

2. Funnel flow and rat-holing

   Generally, funnel flow develops because of large hopper half angles and high wall friction. When hopper angles are large the material near the hopper wall stays motionless and as time goes by it gains strength and becomes like a wall for the fresh material, guides it to the outlet through a funnel like structure.

   Rat-holing is the phenomenon occurs because of the same conditions mentioned for the funnel flow the only difference is that during this problem there is a formation of tunnel like structure which seems to be a rat hole.

Figure b: Funnel flow (Schulze, 2008)

3. Flooding

   During the funnel flow sometimes due to the lack of de-aeration fine powder start flowing like fluid and excess amount of material start coming out of the silo. It is a reason behind the dust generation. Flooding is shown in the figure below

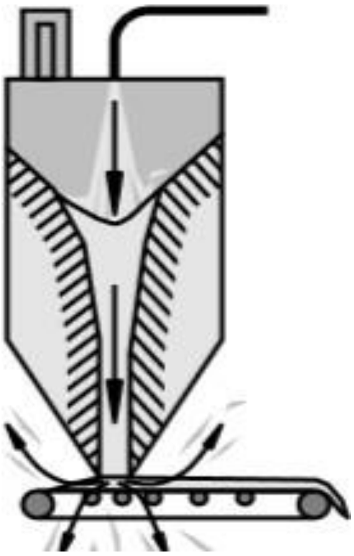


Figure c: Flooding (Schulze, 2008)

4. Non-uniform discharge

   Commonly the problem of non-uniform discharge emerges in the hoppers with screw feeders, material at the extreme left gets discharge continuously but material in the rest of the portion of feeder does not get discharged.

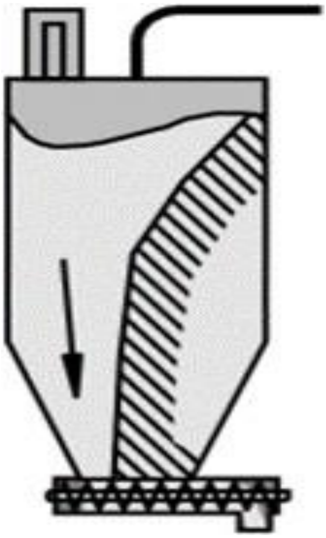


Figure d: Non-uniform discharge (Schulze, 2008)

5. Segregation

   During segregation in a silo or hopper the fines present in the powder gets amassed at the centre of the silo while the coarse particles gathers near silo walls and when the discharge of the powder starts fine particles flows out at first followed by coarse particles. Segregation is a vital problem in chemical and pharmaceutical industries because the particle size of the powder for different medicines is different.

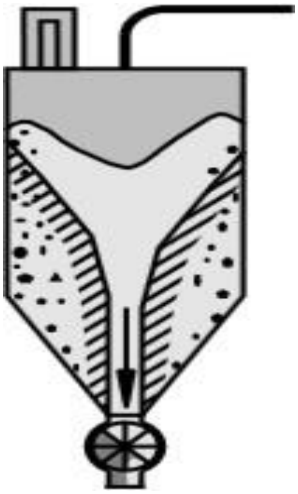


Figure e: Segregation (Schulze, 2008)

6. Buckling

   Due to unsymmetrical loading, during the discharge from the silo or hopper buckling can take place and it can also effect the flow pattern.

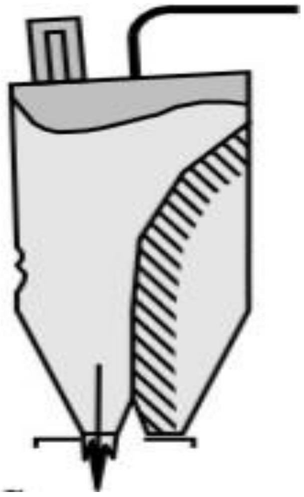


Figure f: Buckling (Schulze, 2008)

To deal with the problems mentioned above Jenike has developed a methodology which is a guide for designing the optimum hoppers or silos according to the bulk solid, as the parameters required for hopper design (hopper half angle and hopper outlet diameter) depends on the flow properties of a bulk solid which differs powder to powder.

2.2. Review of the previous research on powder flowability

Teunou et al. [1998] examined the flow properties of 4 different food powders flour, skim-milk, tea and whey-permeate. The flow properties of these powders were tested using an annular shear tester. Physical properties of these powders were also investigated to know their characteristics. The flow properties were measured and discussed with the help of physical properties and these flow properties were then used in estimating the mass flow hopper dimensions. The influence of relative humidity and temperature was analysed using the flow function curves. Tea powder is hygroscopic and have smaller particle size because of which it can have problems during flow at high relative humidity. Flour is cohesive in nature and is difficult to flow but there has not been any significant change in flowability when relative humidity is varied. The skim-milk and whey protein does not absorb much water i.e. why there has not been any significant increase in the flow function but it is noticed that skim-milk and whey protein have caking problems at low relative humidity.

Fitzpatrick et al. [2004] has analysed the flow properties (flow function, effective angle of internal friction and wall friction) and powder physical properties (particle size, moisture, bulk and particle density) of 13 food powders were measured using Jenike shear cell. Some powders with small particle size and increased moisture content showed poor flowability but this was not universal. The internal friction angle was discovered in a range of 40° to 60° for the powders having the particle size in range of 12 μm to 320 μm and particle density of maximum 2200 kg/m^3 and minimum 1490 kg/m^3. The wall friction angle plays a dominant part in determining the hopper angle and internal friction angle for flow function. It was also reported that this methodology has given low values of failure strength of the powder and hopper outlet dimension.

Domian et al. [2005] studied the effect of water activity, time of storage and consolidation on the flow behaviour of wheat flour. The instantaneous flow function was measured using Jenike shear tester at the water activity of 0.33 and 0.8 which was maintained by using a moisture chamber and the time consolidation tests were conducted on the powder for the consolidation time of 1 and 7 day for both the water activity flours. The time consolidation tests resulted in the reduced flowability of the powder with increase in moisture content. Bulk density and cohesion in the flour was also increased when the flour was consolidated resulted in more compaction of the powder. The moist flour can cause more problem during gravitational out flow as greater the moisture content greater the cohesiveness of the powder.

Iqbal et al. [2006] studied how different storage conditions temperature, relative humidity and storage time effects the wall friction characteristics and hopper dimensions of food powders flour, tea and whey permeate. These powders were tested for the range 22-66 % of relative humidity and for a storage time of seven days and concluded that the wall friction increases with temperature for flour and tea but decreases for whey permeate. The powders were absorbing moisture when subjected to the air with the relative humidity resulted in the increase in hopper dimensions and all friction.

Ganesan et al. [2008] has reported the influence of many different parameters for instance pressure, temperature etc. on the flow properties of the bulk solids. Distilled dried grains with soluble (DDGS) were used for the experimentation. It was discovered while the testing of different flow properties for example angle of wall friction, internal friction using different shear testers like ring shear tester, direct shear tester and compressibility index that the prediction of flow behaviour using the results of the shear tester were more accurate.

Emami et al. [2008] studied the physical properties and chemical composition of chickpea flour. The starch and protein fraction of chickpea flour was analysed and its internal friction coefficient and external friction coefficient were calculated with different materials as surface which are steel, concrete, teflon and polypropylene. The cohesion and adhesion were also analysed. It was determined that chickpea flour has highest coefficient of external friction with concrete as compared to other surfaces. Chickpea flour has highest internal friction coefficient and starch fraction has highest cohesion. All samples has highest external friction coefficient with concrete and lowest with polypropylene surface. Chickpea flour and protein fraction has highest adhesion with concrete and starch fraction has highest adhesion with steel.

Crowely et al. [2014] analysed seven different milk protein concentrate powders having different concentration of milk protein in it from 35 to 90 %. The physical properties such as particle size distribution, specific, surface area, bulk density etc with the flow properties such as flowability, internal and wall friction, compressibility were determined and the bulk density and wall friction data was used for the determination of mass flow hopper dimensions. It is observed that different protein concentration in the milk protein concentrate powders effect the physical characteristics of the powder which means that the physical characteristics of the milk protein concentrate powder varies with the protein concentration. This difference in the physical properties will in turn effect the flow properties of the powder, higher the concentration of the protein in the powder steeper will be the hopper walls and larger will be the outlet diameter. The reduced flowability of the powder can be due to the high specific surface area of the high protein concentrate powders.

Bian et al. [2015] has examined the physical and flow properties of two different types of wheat flours in this study i.e. HRW (Hard red winter) & SWW (Soft white winter) having average particle size of 48.77 μm and 48.20 μm respectively and found that the bulk and tapped density of HRW is greater than that of SWW flour. The wall friction angle for SWW was larger than that of HRW flour which concludes that the SWW flour shows cohesive flow behaviour than HRW flour.

Lee et al. [2015] investigated the effect of particle size on the flowability of black soybean powders at a constant moisture content using consolidation method and image analysis and determined hopper half angle and the minimum hopper opening size without causing arching, based on the flowability data and concluded that black soybean powders with the smallest particle size showed poor flowability and required larger values of the hopper angle and a larger minimum size of the hopper opening. Finer the powder, will show the more cohesive flow behaviour during flowability tests and the bulk density will increase sharply as the major principal consolidating stress increases. The effect of both particle size and shape will reflect in the results of effective angle of internal friction. The highest and lowest particle size sample used was of 1180-1400 μm and 425-600 μm respectively. The finer the powder smaller the angle of internal friction. The influence of particle size is generally more on the finer particles than particle shape.

Liu et al. [2015] has examined the influence of particle size on the results of flow function curves of pulverised, which was separated in 7 different samples using sieve analysis of different particle size varies from 223.8 μm to 17.7 μm. The flow properties of the different samples of pulverised coal were tested using an annular shear tester and their discharge behaviour was analysed using a transparent hopper of Plexiglas. To differentiate between the coarse and fine samples bulk density tests were conducted. The samples having particle size greater than 100 μm were designated as coarse and those having particle size smaller than 100 μm were listed as fine because the bulk density attains a constant value for the samples greater than particle size of 100 μm. The angle of internal friction and wall friction were significantly affected in case of samples listed as fine but the samples represented as coarse does not had any substantial effect of particle size. The results of the flow properties were used to determine the hopper design parameters according to Jenike's methodology. The sample having fine particle size 17.7 μm has the steepest hopper angle of 13.41° and the sample have coarse particle size 223.8 μm has the large value of hopper angle 21.68°, relatively to fine particle sample. The relative flow of the samples having different particle sizes from Plexiglas hopper was compared and the effect of particle size on flow was analysed. Stable region, unstable region and arching region are three types of discharge behaviours classified on the basis of discharge patterns. No flow condition was observed due to arching phenomenon in the samples having particle size below 40 μm which comes under the arching region, relatively higher flow rate was observed in the samples having particle size ranging from 40-100 μm and the samples having particle size above 100 μm showed stable discharge from the hopper.

Koynov et al. [2015] examined the effect of consolidation stress and tester type on eight responses obtained using the shear cell: cohesion, unconfined yield stress, major principal stress, pre-shear stress, flow function coefficient, bulk density. Three different shear cells are used and there results has been compared. The RST-XS (Dietmar Schulze, Wolffenbuttel, Germany), FT4 (Freeman Technology, Tewkesbury, Gloucestershire, UK), and PFT (Brookfield Engineering Laboratories, Inc., Middleboro, MA, USA) shear cells were used and concluded that The Schulze and Brookfield both measure the applied normal force at the top of the powder bed while the FT4 measures this at the bottom of the powder bed. Results are based on only two materials, coarse and fine alumina, and three common shear cells. The shear cell is less suitable for free-flowing materials. Shear cells can be used to identify a material as free-flowing, but care should be taken in ranking materials within the free-flowing regime. Each of the three shear cells tested can distinguish between cohesive and free-flowing materials. The flowability of a material is not a constant but is dependent upon several factors. The flow function may not always be linear.

Saw et al. [2015] has examined a variety of bulk solids, 13 milled, 2 spray dried lactose powder, 3 sand samples and m refractor dust having particle size 28.9-223 μm , 35.8 and 102.2 μm, 28.7-76.9 μm and 23.3-66.6 μm respectively. Shear testing was done to determine the flow behaviour of the various samples. The lactose samples which were milled have fine particle size of 28.9 and 58 μm demonstrated very cohesive flow and cohesive flow respectively when tested. The sand and refractor dust samples showed free flowing nature regardless of their particle size which explains that particle size cannot be referred to as the absolute benchmark to decide that the powder is cohesive or not. A correlation has been provided between the values of Hausner Ratio and Cohesion for the Pre Shear Stress values from 0.31-4.85 kPa, another correlation was provided to predict the ratio of major principal consolidation stress (σ_1) and unconfined yield strength (σ_c) by utilising Hausner Ratio. The correlation's prediction for cohesive and very cohesive powders well but for easy flowing and free flowing powder error was too high.

Manikantan et al. [2015] has studied the influence of moisture content on the physical properties of coconut flour specifically those which effect the flow properties of the powder. Two different coconut flours were tested with three different moisture content value for each which are coconut milk residue flour with moisture content 4.53, 6.23 and 8.18 wet basis and virgin coconut oil cake four with moisture content 3.85, 6.01, 7.98%. It was observed that the bulk density of both the flours decreases with increase in moisture content. The value of bulk density and tapped density of virgin oil coconut cake flour is higher when compared to that of coconut milk residue flour. The compressibility index and angle of repose was higher in case of coconut milk residue flour which means that the coconut milk residue flour will have poor flow behaviour than virgin coconut oil cake flour. All the physical properties essential for the powder flow i.e. compressibility index, angle of repose, Hausner ratio, coefficient of static friction and rolling friction showed increasing trend with increasing moisture content. The friction coefficient tested against three different surfaces plywood, acrylic, plastic and steel sheet out of which plywood demonstrated the higher coefficient of static and rolling friction of them all.

Xantakis et al. [2015] investigated into the flow properties of Nano-powders using Brookfield Powder Flow Tester. The Nano-powders used were titan, alumina and silica based. Nano-powders examined in the study had both hydrophobic and hygroscopic nature with same particle size. These powders were transformed into hydrophobic powders using surface hydrophobization. Even though the Nano-powders used had same base material and same particle size but significant difference was observed in the flowability when flow function test was conducted. It was observed that the slope of the flow function curve of hydroscopic powders was greater than the slope of hydrophobic powders.

Amagliani et al. [2016] studied the physical properties of a range of rice protein powders and explained how the physical properties effects the flow properties of these powders. It was explained that the flowability of the powder gets reduced as there is reduction in the particle size because finer particles has more area of contact which increases the cohesion and frictional forces. It is reported that the flowability of the powder also depends upon the shape of the particle. Powders with more spherical shape will show better flowability and will be less compressible. The surface roughness can lead to mechanical interlocking and higher Van-der waals forces results in more cohesive flow. It was discovered that the applied major principal consolidating stress also effect the flow properties of the powder, which explains that the powder have different flow behaviour in different areas of the hopper. The flowability of the powder is also effected by the fill height of the hopper. The difficulty in flow of the food powders can also be due to the presence of fat on the surface of the particles which leads to the liquid bridging. The higher the fat content in the powder there will be more flow problems. The analysis of the results conferred that the chemical composition, particle shape and surface characteristics have more influence on the flow behaviour of the powder than the particle size. It was also inspected that the friction properties especially the wall friction plays a dominant role in calculating the hopper dimensions.

Enriquez et al. [2017] has demonstrated the effect of moisture content and water activity on the flow behaviour of the powders. The hygroscopic powders which were used in the study were malto-dextrin, starch, pectin. It was discovered that as the water content in the powder increases the flow behaviour of the powder tends towards more cohesive flow. Also, the water activity and absolute moisture content were linearly correlated with the flow factor, which lead to the conclusion that the water activity of the powder is a better predictor of the flow behaviour of a food powder than the absolute moisture content.

Ji et al. [2017] explored the adhesive forces of the bulk solids because the flow problems in finer bulks solids are often due to the presence of adhesive forces. Generally, adhesive forces come into picture due to the Van-der Waals interaction between the particles, which also depends upon the particle size and the inter-particle distance. The smaller the distance between the particles higher will be the influence of the Van-der Waals forces, which will become the source of higher adhesive forces during the rearrangement of particles. It has also been said that spherical shaped particles has shown better flow behaviour than that of non-spherical particles. It has also been discovered that decreasing the particle size will result in higher wall friction angle inconsiderate of the normal stress applied. Bulk solids with larger wall friction angles are the type to show segregation in hopper because the particles in the centre moves faster than the particles near the wall.

Chapter-3

Materials and Methods

3.1. Materials

The powders used in this study (wheat flour and gram flour) were acquired from a flour mill, Patiala, Punjab (India). These powders were contained in the air-tight containers to prevent them from attracting moisture.

3.2. Physical Properties

Particle Size Distribution and Specific Surface Area

The assessment of particle size and specific surface area of the samples was done using laser beam diffraction with the help of Malvern's Mastersizer 2000 (Malvern Instruments, Worcestershire, UK) with a dry dispersion unit, which has a measurement range of 0.020 to 2000 μm with particle refractive index of 1.52 and absorption index of 1.0.

Bulk and Particle Density

Loose poured bulk density is measured by pouring a known mass of a powder in a graduated cylinder and by taking its mass by volume ratio. Powders having strong inter-particle bonding and high friction between particles are likely to show low bulk density due to their resistivity towards the rearrangement of particles for attaining high packing density. On the other hand, powders having low inter-particle bonding and less friction between particles would result in a higher value of bulk density. Less friction between particles would allow them to get rearranged easily, which would result in even higher value of bulk density [13]. Porosity and Compressibility Index was calculated by using the formulae mentioned below:

$$\text{Porosity} = 1- (\rho_{lb}/\rho_{p}) \quad (1)$$

$$\text{Compressibility Index} = 100 \times [1- (\rho_{lb} /\rho_{t})] \quad (2)$$

Particle density (ρ_p) of the samples was determined using water displacement method. Hausner Ratio is described as the ratio of tapped bulk density to loose-poured bulk density, which also helps in understanding the flow behaviour of a powder as it is a measure of cohesiveness [25].

$$\text{Hausner Ratio} = (\rho_{t} /\rho_{lb}) \quad (3)$$

Scanning Electron Microscopy

Powder samples were analyzed after placing them on Aluminum stubs using double-sided adhesive carbon tape and sputter cloaked with a 5 nm layer of gold/palladium (Au: Pd = 80:20) in JSM-5510 Scanning Electron Microscope (JEOL Ltd, Tokyo, Japan) operated at an accelerating voltage of 15 kV at Sophisticated Analytical Instruments Laboratory of Thapar Institute of Engineering & Technology, Patiala.

Moisture Content

The determination of the moisture content in the powder samples was done by oven-drying a known mass of the sample up to 105°C for 1.5 hour. The porcelain evaporating dish, which was used for heating the samples, was placed in a desiccator after the drying process was completed to prevent moisture getting absorbed in the sample from the atmosphere. This method was repeated 3 times per sample for the fresh and timeconsolidated samples of both the powders. An average of the result of these repeat tests are shown in Table 2.

$$\text{MC\%} = \frac{(\text{Mass of the sample before drying} - \text{Mass of the sample after drying}) \times 100}{\text{Mass of sample before drying}} \tag{4}$$

3.3. Flow properties

The equipment used in this study to analyze the flow properties of the samples is Powder Flow Tester (PFT) from Brookfield Engineering Laboratories, Inc., Middleboro, MA, USA at the Laboratory for Particle and Bulk Solid Technologies, Thapar Institute of Engineering & Technology, Patiala. PFT provides an axial speed of 1.0 mm/s and a torsional speed of 1 rev/h. The testing of the samples uses an annular shear cell made up of aluminum having a volume of 230 cm^3 and an internal diameter of 15.2 (which is called as trough). The samples were prepared in the trough using the scraper assembly provided with the kit at a temperature of 22 to 27°C, which is used to level the powder profile curved or flat for flow function test or wall friction test, respectively. Two different types of lids were used: vane type for flow function test and flat type for wall friction test, which are made up of 304 SS with a 2B surface finish of the flat profiled lid having an external diameter of 15.2 cm. These lids are likely to be attached to the compression plate before starting the tests and the mass of the powder was measured using a weighing scale beforehand. The equipment is provided with a Powder Flow Pro software, which was used to record the readings.

Flowability or flow function

According to Jenike's method, the flow function has been described as failure function which is determined by powder shearing at different consolidation stresses which is fixed by different pre-consolidation stress [3, 19 and 27]. "Standard flow function" tests were conducted for measuring the flowability of both the samples, which involves 5 uniaxial normal stresses (varies from 0.2 and 4.8 kPa) and 3 over-consolidation stresses at each value of major principal consolidation stress. Firstly, the sample was consolidated with a known value of normal stress and an essential shear stress was applied, which brought it to failure. Subsequently, the four more normal stresses lower than the consolidating stress were applied on the sample, along with the consolidating stress itself. Failure shear stress values were plotted with respect to normal stresses at each of the consolidating stresses, which helped in establishing the best-fit yield locus. This method was repeated for 5 different consolidating stresses to obtain 5 yield loci (Figure 1). To develop a flow function curve two specific Mohr circles were analyzed from each yield locus for the value of unconfined failure strength and major principal consolidating stress and the developed curve is known as the instantaneous flow function curve. The angle of the line from the horizontal axis, which begins at the origin and is tangent to the Mohr circle of major principal consolidating stress represents effective angle of internal friction [3, 14 and 18]. The flow function test was also conducted using "Custom test method" using fresh samples for each consolidation level, which strictly follows Jenike's methodology[19] and the stresses were kept same as the standard method for the comparison between standard and custom test results. The custom tests were also conducted in the combination different options: even spacing, geometric spacing and tangent to Mohr circle. The time required to conduct a single custom test is about 3 to 4 times that of a single standard test. Time consolidation test was conducted using the "Standard" time consolidated flow function test option provided in PFT, which includes 4 uni-axial normal stresses (varying from 0.2-2.409 kPa) and 3 over consolidation stresses. PFT requires about 12 hours for the completion of a single time consolidated flow function test, which provides us with two curves having 4 locus points for a single powder. The result from this test provides a comparison between instantaneous and time consolidated flow behaviour of the powder. All tests were repeated 5 times to ensure reproducibility of test data.

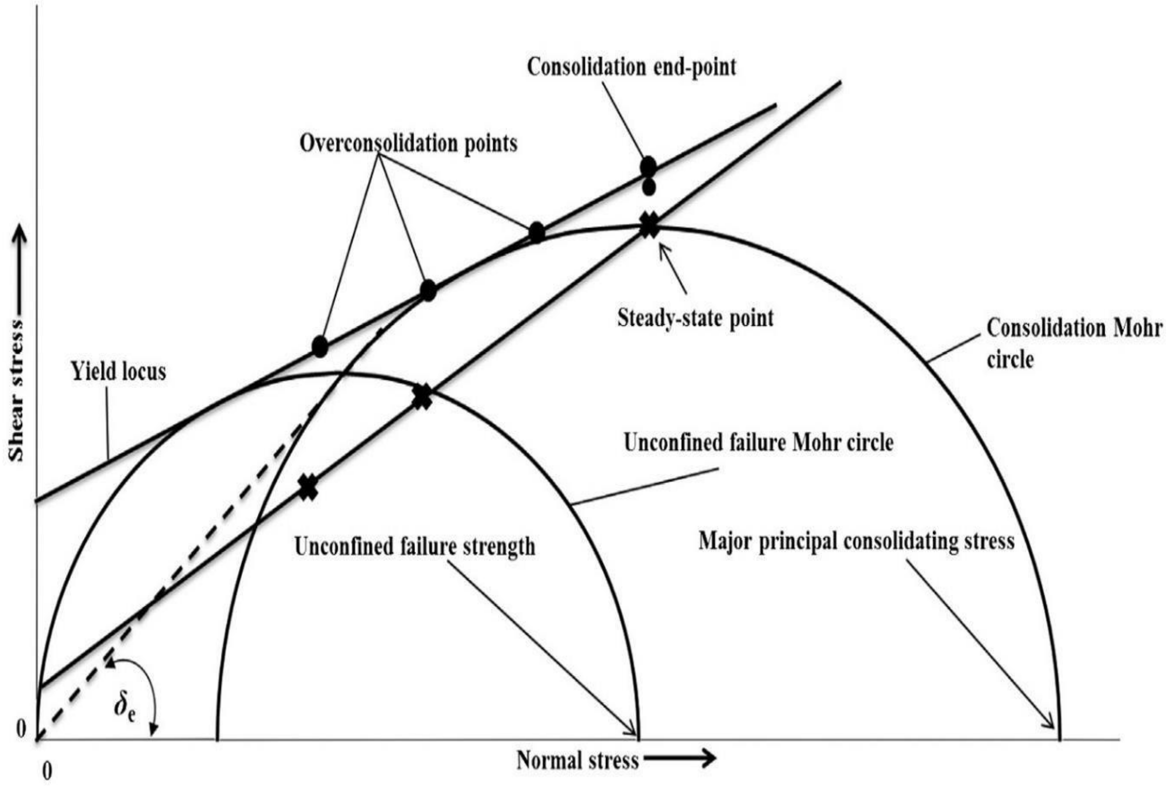


Figure 1. Schematic representation of Mohr circles and yield locus from flow testing.

Wall friction angle and Bulk density

The wall friction angle (ϕ_w) was measured by conducting the standard and custom wall friction tests on PFT with even spacing (displacement of 0.100 m) and spacing in doubling progression (displacement of 0.399 m), which allowed to test the samples on 2 displacement levels at 10 different normal stresses varying from 0.48 kPa to 4.8 kPa. Shear stress was applied to move the sample against a stainless steel surface under the above mentioned range of normal stress in descending order. Using the maximum shear stress between the powder sample and the wall material a wall yield locus was developed for each sample at each normal stress value. A straight line was plotted which begins at the origin and intersects the point of wall yield locus at normal stress and the coefficient of wall friction (μ) was calculated from its slope [3, 14 and 18]. The value of ϕ_w was calculated for each normal stress using the following equation below:

$$\phi_w = \tan^{-1}(\mu) \tag{5}$$

Chapter-4

Results and Discussion

4.1 Physical Properties

The several physical properties of wheat flour and chickpea flour are mentioned in Table 1. Average particle size of wheat flour is greater than that of chickpea flour which signifies that chickpea flour has larger Specific Surface Area (SSA) than wheat flour, which could result in higher Van-der Waals force of attraction between the particles [13]. Also, due to the larger SSA chickpea flour can experience more resistance to flow [3]. Hausner Ratio (HR) and Compressibility Index (CI) of wheat flour is greater than that of chickpea flour (Table 1). HR and CI indicates towards the compression capability of a powder and the interaction between the particles [25, 26]. According to the HR and CI values provided in Table 1, wheat flour and chickpea flour exhibits very poor and poor flow behavior, respectively. HR value of wheat flour is in the range of 1.46 to 1.59 and that for chickpea flour is in the range of 1.35 to 1.45 [26, 28 and 29]. CI value of wheat flour is in the range of 32 to 37 and that for the chickpea flour is in the range of 26-31 [15, 28 and 29].

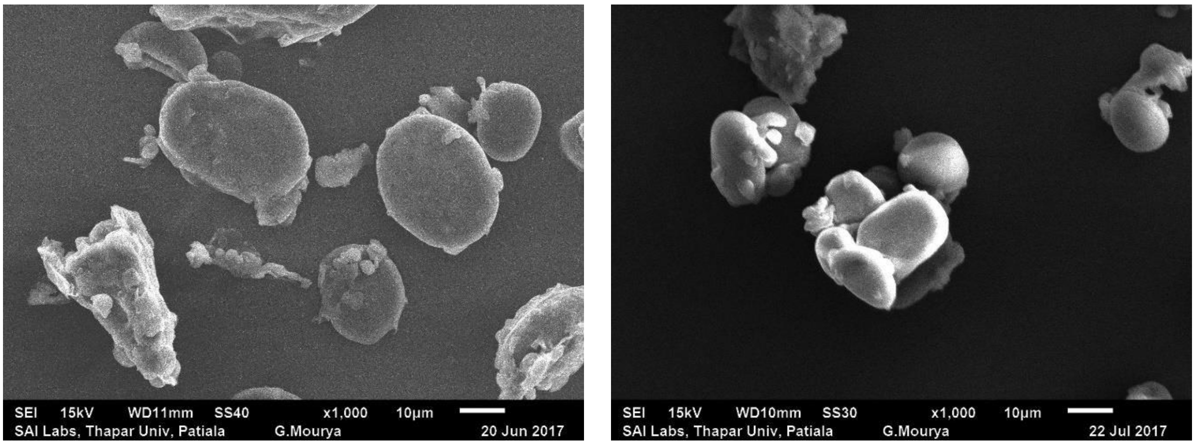
Table 1. Physical properties of wheat flour and chickpea flour

Symbol	**Wheat flour**	**Chickpea flour**
d_{50}, µm	136	85
S	2.307	3.37
SSA, m^3kg^{-1}	108	172
ρ_{lb}, kg m^{-3}	531	314
ρ_p, kg m^{-3}	1558	1370
ρ_t, kg m^{-3}	798	433
P	0.66	0.77
HR	1.50	1.38
CI	33.24	27.42

Table 2. Moisture content of fresh and time consolidated wheat flour and chickpea flour

State	Wheat flour [MC%]	Chickpea flour [MC%]
Fresh	6.78	7.47
Time Consolidated	9.21	8.59

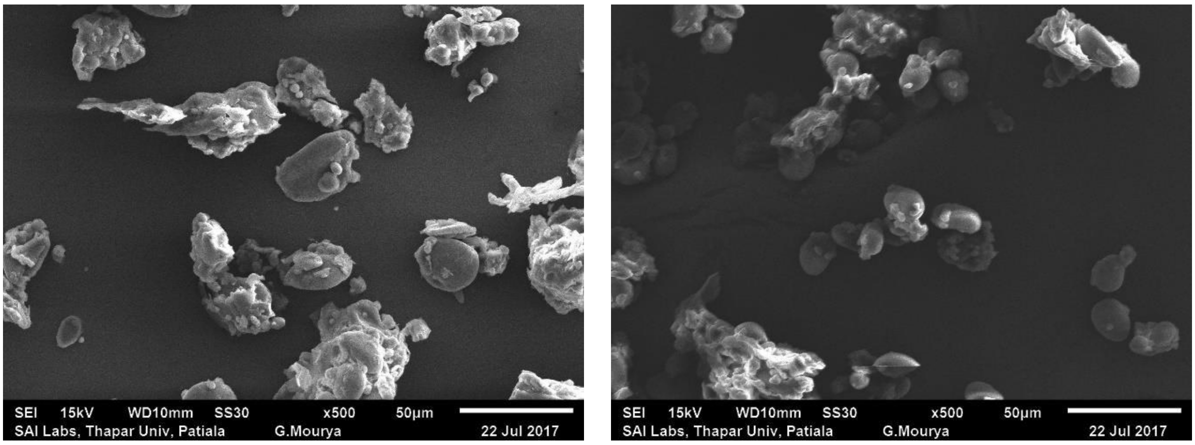
The SEM images of fresh and time consolidated flours are shown in Figures 2 and 3, respectively. The SEM images of fresh and time consolidated flours show that there is more agglomeration in the chickpea flour as compared to wheat flour. The reason for more agglomeration in the chickpea flour could be due to its small particle size and large specific surface area.



Fresh Wheat Flour

Fresh Chickpea Flour

Figure 2. SEM images of fresh wheat flour and chickpea flour



Time consolidated Wheat Flour

Time consolidated Chickpea Flour

Figure 3. SEM images of time consolidated wheat flour and chickpea flour

4.2 Flow Properties

Flow Function

The flow function curves of wheat flour and chickpea flour for “Standard” and “Custom” test options have been plotted between major principal consolidating stress (σ_1) and unconfined failure strength (σ_c) (see Figures 4 and 5 for wheat flour and chickpea flour, respectively). The flow function plots are divided into four regions according to Jenike’s flowability criteria [3, 19]. These four regions were according to the flow index (ff_c) values: $ff_c < 1$ for the non-flowing region, $1 < ff_c < 2$ for the very cohesive region, $2 < ff_c < 4$ for the cohesive region, $4 < ff_c < 10$ for the easy flowing region and $ff_c > 10$ for the free flowing region. The following different configurations of tests were performed:

Standard: Standard Instantaneous flow function

Custom I: Custom Instantaneous Flow Function using Separate Samples with Even Spacing

Custom II: Custom Instantaneous Flow Function using Separate Samples with Geometric Spacing

Custom III: Custom Instantaneous Flow Function using Separate Samples with Even Spacing and Tangent to Unconfined Mohr Circle

Custom IV: Custom Instantaneous Flow Function using Separate Samples with Geometric Spacing and Tangent to Unconfined Mohr Circle

The average values of 5 repeat tests with individual setting were taken (see Table 2 for wheat and chickpea flour) and plotted with the error bars (with standard deviation at 95% confidence level). In Figure 4, at lower values of major consolidation stresses, wheat flour is in the very cohesive region and after the second locus point it enters into the cohesive region (at the higher values of major consolidation stress). This trend is found to be the same for all the different test methods. In Figure 5, at lower values of major consolidation stresses, chickpea flour is in the very cohesive region and after the second locus point it enters into the cohesive region (at the higher values of major consolidation stress). Once again, this trend is found to be similar all the different test methods. The results obtained using even spacing i.e. “Custom I and III” shows lower strength values at higher consolidation stresses compared to the case where geometric spacing i.e. “Custom II and IV” was considered for both the powder samples [18]. No significant difference was observed between “Standard” and “Custom IV” test results when all the options selected in PFT were the same in custom method (using “separate samples”) and standard test for wheat flour. The tangent to unconfined Mohr circle option helps in limiting the extrapolation of the values of strength which can be seen in Figure 4 by comparing "Custom I and III” and “Custom II and IV” options. There is a significant difference observed amongst the “Custom” tests done using fresh samples of wheat flour for each consolidation stress with and without the option of tangent to unconfined Mohr circle. Also, a significant difference of 0.5 kPa was noticed at higher consolidation stresses between the “Standard” and “Custom IV” test results of chickpea flour. It was observed that the chickpea flour shows loss in strength after the fourth locus point. So, the “custom separate sample” test with the options of geometric spacing and tangent to unconfined Mohr circle setting is recommended for the hygroscopic powders having fine particle size.

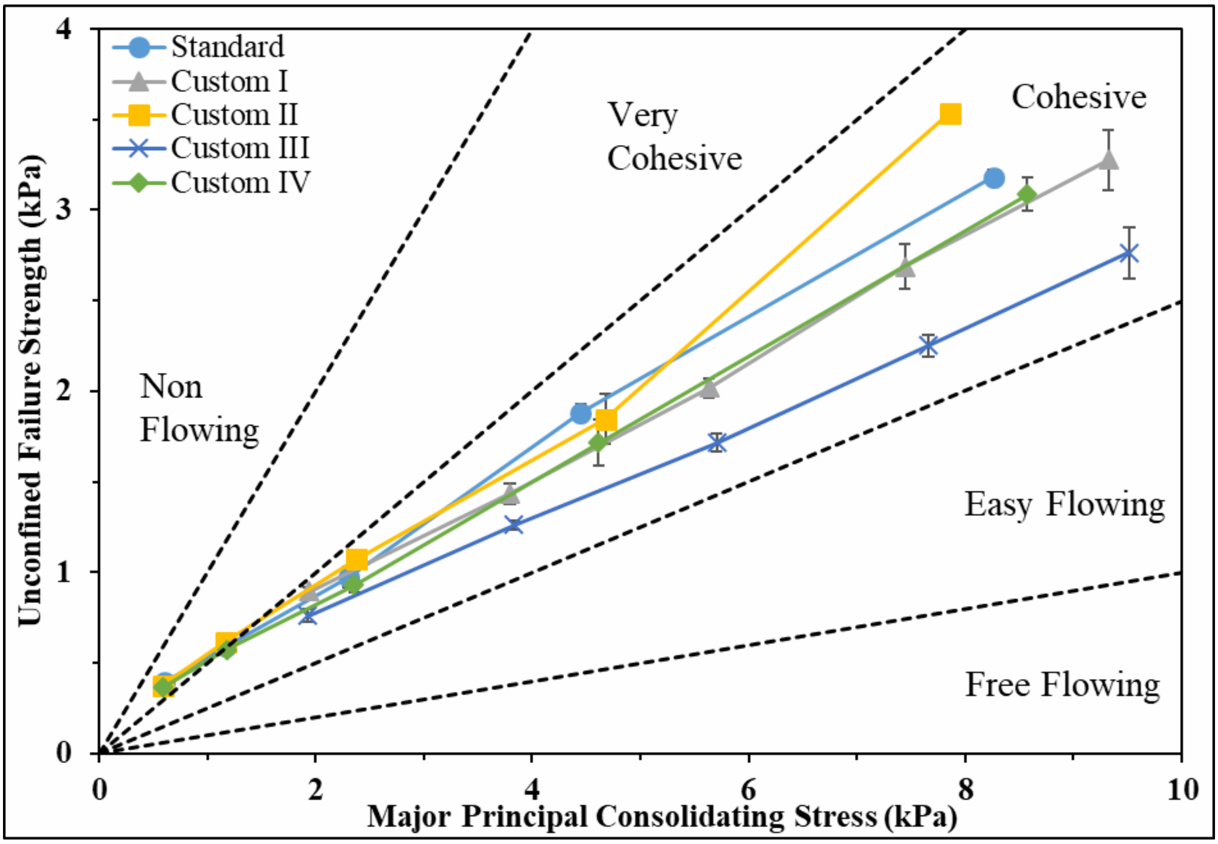


Figure 4: Flow function curves of wheat flour using standard test method and custom test method with different options

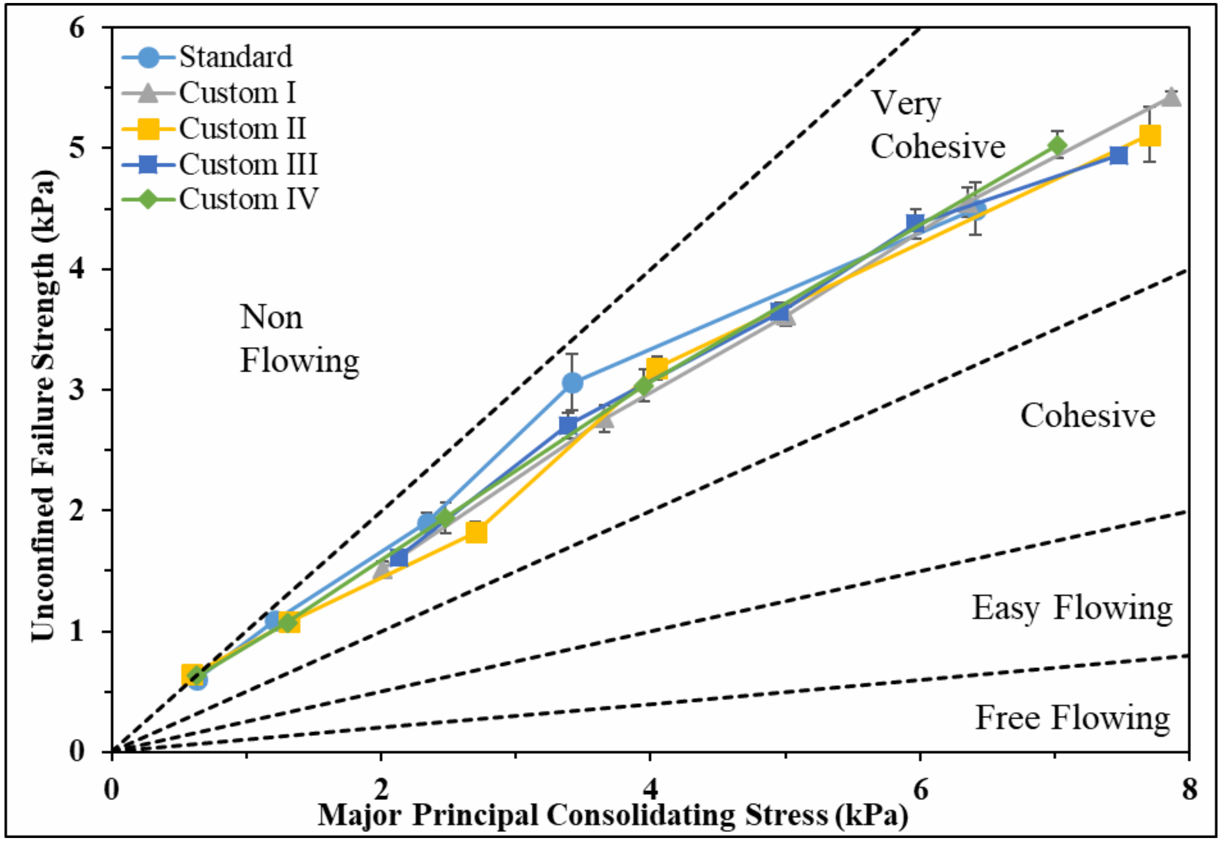


Figure 5. Flow function curves of chickpea flour using standard test method and custom test method with different options

Table 3. Flow properties of wheat and chickpea flour using different test methods in Powder Flow Tester (PFT).

σ_1 (kPa)	σ_c (kPa)	ρ_b (kg/m$_3$)	δ_j (°)	Cohesion (kPa)
Standard (wheat flour / chickpea flour)				
0.598 / 0.633	0.394 / 0.603	623 / 457.02	50.98 / 77.90	0.119 / 0.174
1.163 / 1.210	0.591 / 1.090	656.54 / 507.06	45.38 / 69.08	0.173 / .338
2.299 / 2.339	0.973 / 1.901	714.12 / 560.86	42.26 / 60.34	0.284 / .5832
4.447 / 3.416	1.880 / 3.063	753.90 / 609.88	38.32 / 62.56	0.599 / 1.174
8.258 / 6.410	3.181 / 4.501	793.86 / 626.92	35.12 / 43.76	1.054 / 1.761
Custom I (wheat flour / chickpea flour)				
1.939 / 2.010	0.892 / 0.372	697.70 / 518.83	43.86 / 57.27	0.258 / 0.454
3.793 / 3.656	1.434 / 0.614	743.96 / 566.77	41.8 / 53.30	0.407 / 0.930
5.632 / 5.002	2.018 / 1.072	767.26 / 603.07	40.74 / 51.23	0.577 / 1.236
7.441 / 6.350	2.688 / 1.846	783.60 / 617.60	40.24 / 49.47	0.781 / 1.580
9.321 / 7.863	3.276 / 3.535	789.06 / 648.83	38.78 / 47.80	0.978 / 1.884
Custom II (wheat flour / chickpea flour)				
0.584 / 0.593	0.372 / 0.644	612.43 / 429.13	49.83 / 90	0.113 / 0.198

1.164 / 1.311	0.614 / 1.076	651.37 / 492.07	46.33 / 63.53	0.179 / 0.306
2.369 / 2.699	1.072 / 1.822	693.17 / 546.9	43.87 / 57.07	0.309 / 0.555
4.676 / 4.046	1.846 / 3.181	735.17 / 586.87	41.63 / 54.23	0.533 / 1.113
7.855 / 7.702	3.535 / 5.116	769.50 / 639.67	40.17 / 45.8	1.107 / 1.798
Custom III (wheat flour / chickpea flour)				
1.9282 / 2.132	0.760 / 1.615	656.26 / 506.67	42.46 / 57.13	0.215 / 0.483
3.8312. 3.386	1.262 / 2.702	699.24 / 566.23	40.7 / 56	0.354 / 0.953
5.7062 / 4.958	1.714 / 3.642	720.48 / 603.03	39.84 / 50.6	0.479 / 1.280
7.6576 / 5.966	2.251 / 4.375	733.66 / 623.4	39.28 / 48.5	0.6352 / 1.609
9.5148 / 7.476	2.764 / 4.945	748.38 / 647.73	39.06 / 45.3	0.7822 / 1.762
Custom IV (wheat flour / chickpea flour)				
0.5875 / 0.633	0.363 / 0.629	595.50 / 432.10	49.075 / 85.07	0.109 / 0.183
1.177 / 1.302	0.573 / 1.074	635.32 / 489.23	45.15 / 63.5	0.165 / 0.310
2.356 / 2.478	0.930 / 1.942	676.52 / 536.23	42.475 / 58.7	0.263 / 0.614
4.6115 / 3.951	1.715 / 3.034	714.10 / 583.90	40.15 / 52.8	0.506 / 1.072
8.575 / 7.019	3.087 / 5.030	744.55 / 646.60	36.7 / 46.87	0.968 / 1.847

Effective angle of internal friction

The ratio of major principal consolidating stress and minor principal consolidating stress acting on the powder is known as the effective angle of internal friction [19]. Fig. 6 and 7 show the variation in the effective angle of internal friction with respect to major principal consolidating stress for wheat flour and chickpea flour, respectively. The values of effective angle of internal friction (Table 3) are higher at lower consolidating stress values for both wheat flour and chickpea flour. However, these values are much higher in case of chickpea flour when compared to wheat flour indicating that the adhesive forces acting between the particles in case of chickpea flour is higher which further proves that the chickpea flour will have more cohesive tendencies than wheat flour.

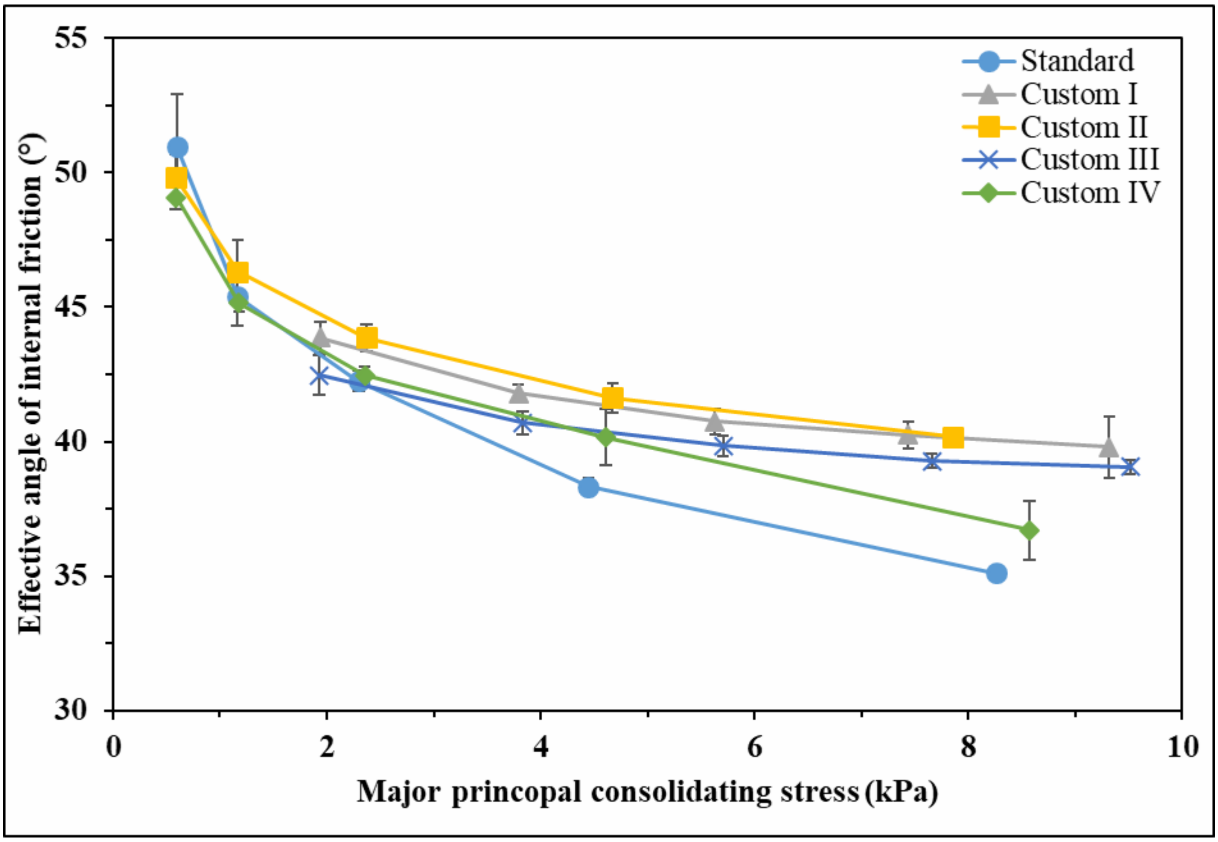


Figure 6. Effective angle of internal friction versus major principal consolidating stress for wheat flour

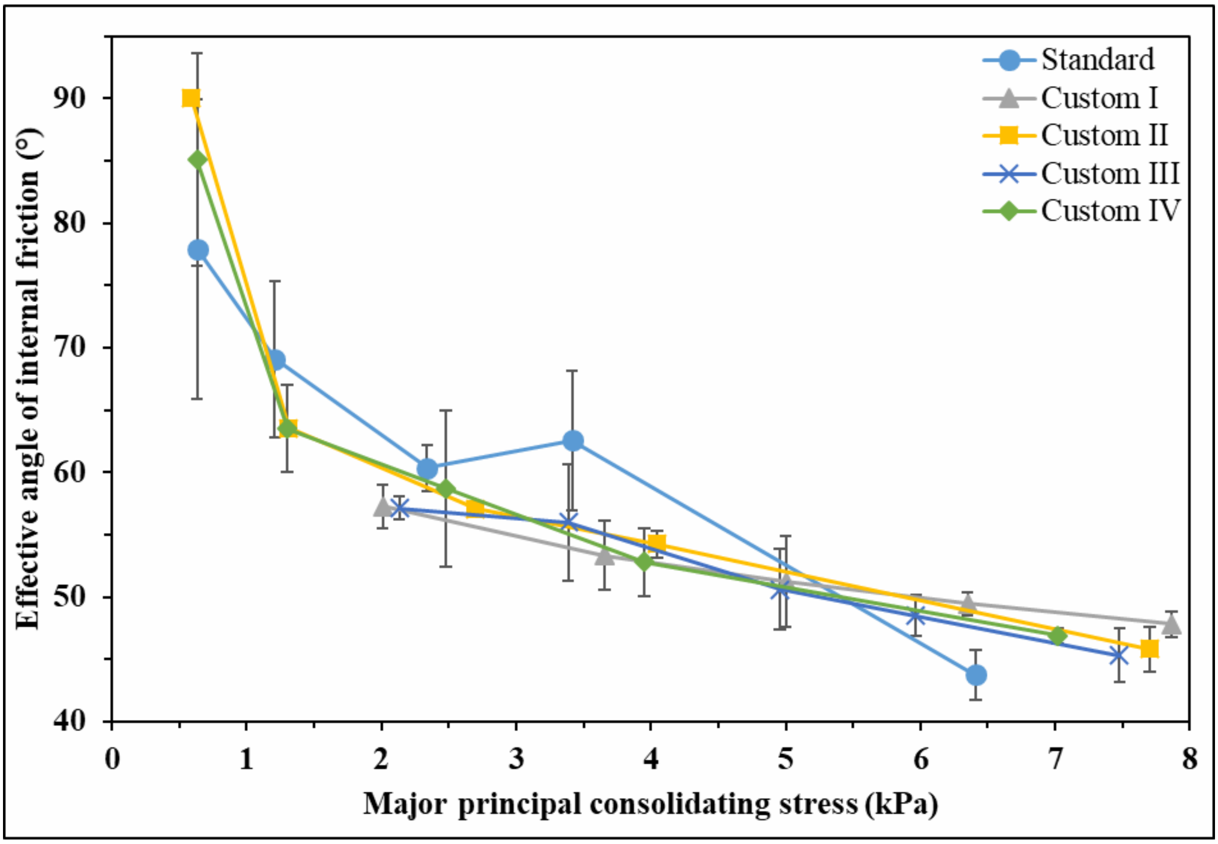


Figure 7. Effective angle of internal friction versus major principal consolidating stress for chickpea flour

Wall Friction

The following test configurations were undertaken:

Standard I: Standard Wall Friction test

Custom V: Custom Wall Friction test using Separate Samples with Even Spacing

Custom VI: Custom Wall Friction test using Separate Samples with Doubling Progression

Figures 8 and 9 show that the wall friction angle is higher at lower normal stress, which decreases as the normal stress increases and becomes almost constant. Two custom tests with separate samples using different options of even spacing and doubling progression, referred as “Custom V” and “Custom VI”, respectively have been conducted which explains that higher the displacement between the powder and wall, the lower will be the wall friction angle in case of wheat flour, which is having larger particle size than chickpea flour. In case of chickpea flour, the wall friction angle using standard test is the largest at lower normal stress and smallest at higher normal stress. The wall friction angles using “Custom VI” is larger than the wall friction angles using “Custom V”. The chickpea flour has larger wall friction angle when compared to wheat flour because of its smaller particle size and larger specific surface area, which results in more particle to surface contact friction. (For detailed data see Table 4)

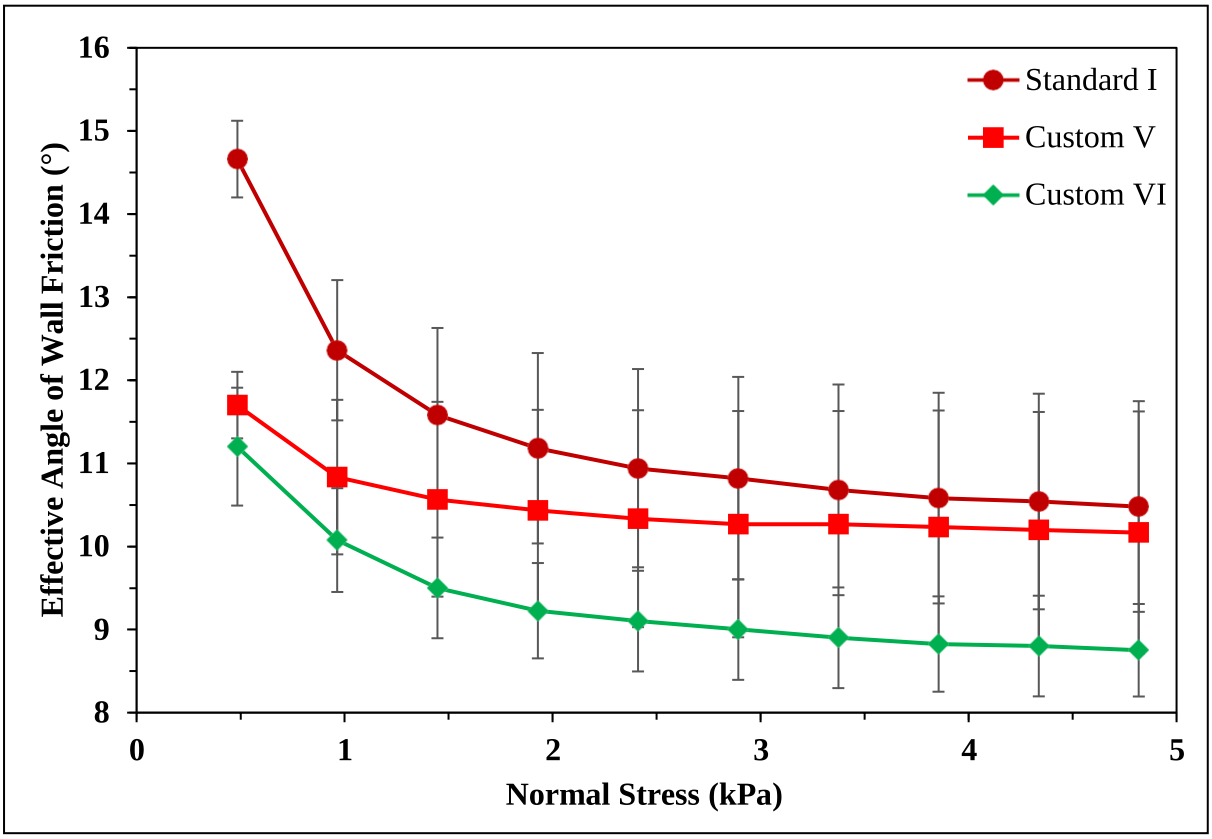


Figure 8. Effective angle of wall friction versus major principal consolidating stress for wheat flour

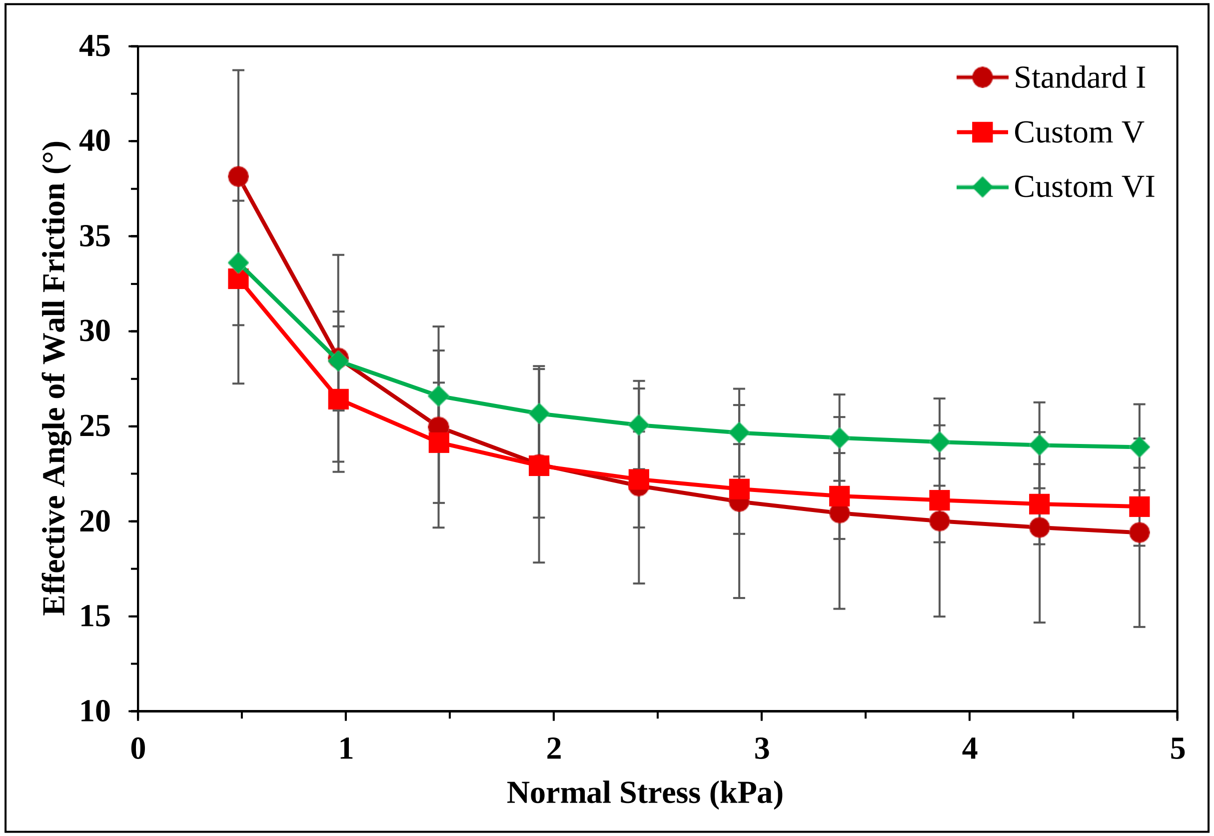


Figure 9. Effective angle of wall friction versus major principal consolidating stress for chickpea flour

Table 4. Wall friction test results for wheat and chickpea flour

Wheat flour		Chickpea flour	
Normal Stress (kPa)	**Effective angle of wall friction (°)**	**Normal Stress (kPa)**	**Effective angle of wall friction (°)**
Standard I			
0.483	14.66	0.483	38.14
0.9644	12.36	0.963	28.58
1.446	11.58	1.445	24.96
1.9282	11.18	1.928	23
2.4102	10.94	2.410	21.86
2.892	10.82	2.892	21.04
3.374	10.68	3.373	20.44
3.8554	10.58	3.855	20.02
4.337	10.54	4.337	19.68
4.818	10.48	4.817	19.4
Custom V			
0.483	11.700	0.483	32.77
0.9644	10.833	0.965	26.43
1.446	10.567	1.447	24.13
1.9282	10.433	1.929	22.93
2.4102	10.333	2.41	22.2
2.892	10.267	2.892	21.7
3.3738	10.267	3.374	21.33

3.8554	10.233	3.855	21.1
4.3374	10.200	4.336	20.9
4.8178	10.167	4.817	20.77
Custom VI			
0.483	11.2	0.483	33.6
0.964	10.075	0.965	28.43
1.446	9.5	1.447	26.6
1.9285	9.225	1.929	25.67
2.41	9.1	2.41	25.07
2.89175	9	2.892	24.67
3.37325	8.9	3.374	24.4
3.855	8.825	3.856	24.17
4.337	8.8	4.337	24
4.818	8.75	4.817	23.9

Bulk Density

Figure 10 shows the bulk density results of wheat flour and chickpea flour using standard and custom test. The following configurations were carried out:

Standard II: Standard Bulk Density test for wheat flour
Standard III: Standard Bulk Density test for chickpea flour
Custom VII: Custom Bulk Density Test for wheat flour
Custom VIII: Custom Bulk Density Test for chickpea flour

No significant difference was observed when the powder samples were tested using different methods. The wheat flour has higher bulk density as compared to the chickpea flour under the applied normal stress. The variation in bulk density with increasing normal stress tends to get constant at higher normal stress values. (For detailed data see Table 5)

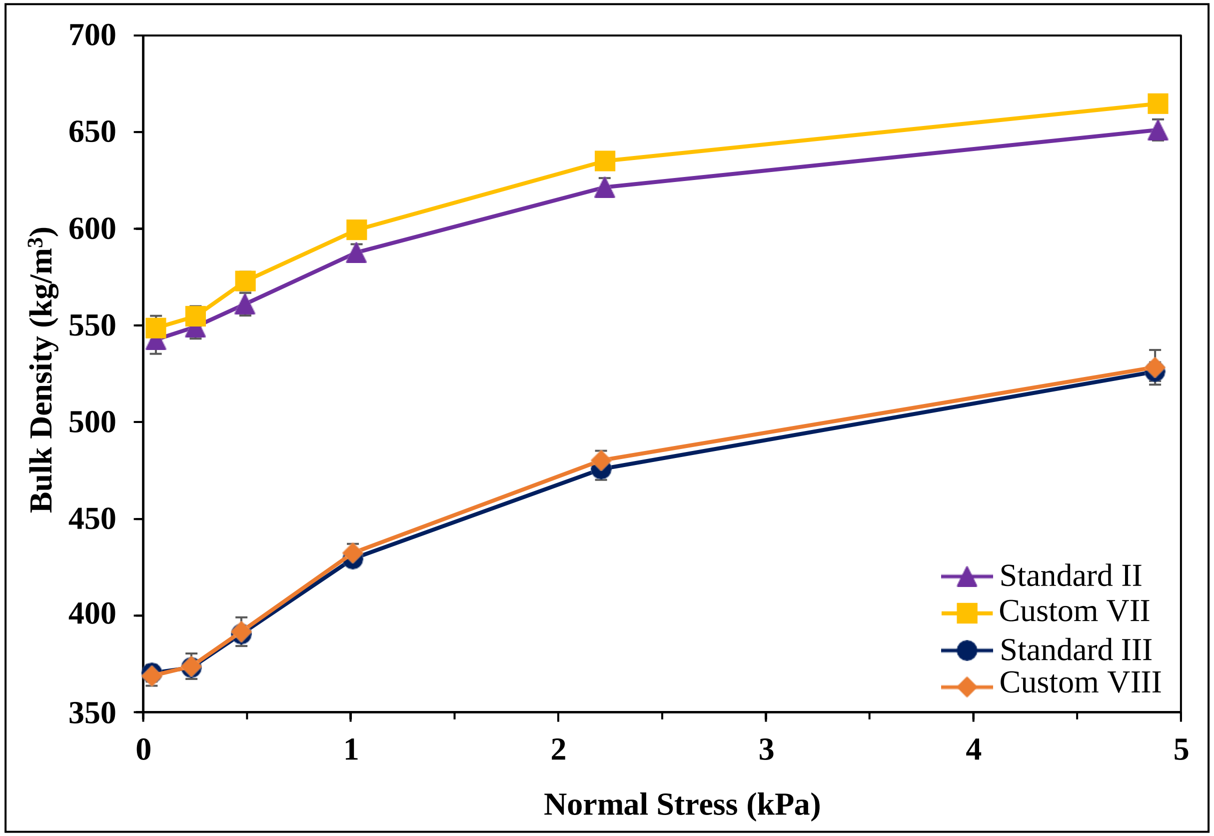


Figure 10. Bulk density versus normal stress for wheat flour and chickpea flour

Table 5. Bulk density test results for wheat and chickpea flour

Wheat flour		**Chickpea flour**	
σ_1 (kPa)	**ρ_b (kg/m^3)**	**σ_1 (kPa)**	**ρ_b (kg/m^3)**
Standard II		Standard III	
0.0602	542.72	0.041	370.2
0.252	549.44	0.232	373.2
0.491	561.1	0.473	390.5
1.027	587.76	1.010	429.3
2.223	621.54	2.206	475.7
4.888	651.22	4.875	526.2
Custom VII		Custom VII	
0.061	548.8	0.0403	368.8
0.252	554.9	0.232	373.9
0.492	573	0.473	391.7
1.029	599.6	1.01	432.4
2.224	635.1	2.206	480.2
4.890	664.8	4.875	528.5

Time consolidated flow function

Figure 11 represents the instantaneous and time consolidated flow function results for wheat flour and chickpea flour. After an overnight time consolidation test, non-significant changes in the flow behaviour of wheat flour was observed; on the other hand the flow behaviour of chickpea flour got shifted from very cohesive region to non-flowing region. This might be due to the effect of higher amount of agglomeration during time consolidation test for chickpea flour compared to wheat flour, which can be clearly seen in the SEM images (See Figure 2 and 3).

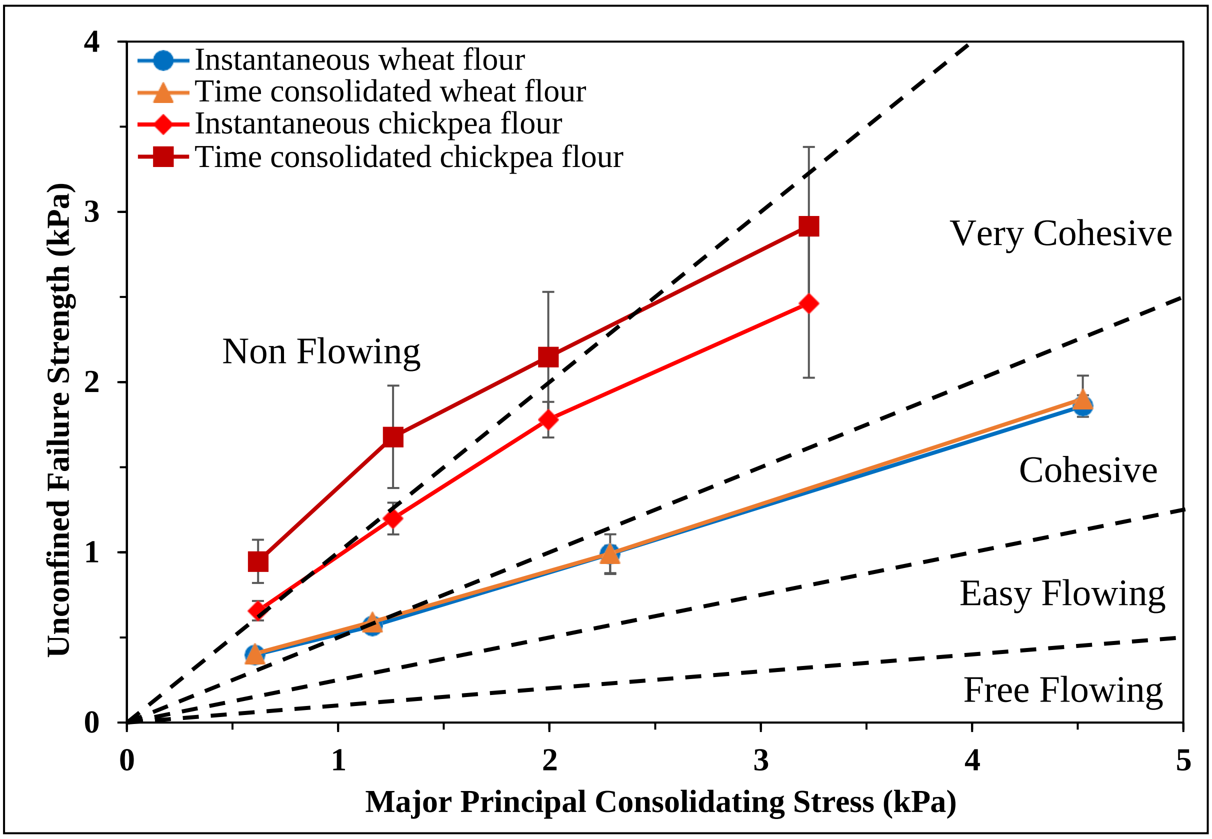


Figure 11. Time consolidated flow function curves for wheat and chickpea flour

Table 6. Time consolidated flow function test results for wheat and chickpea flour

σ_1 (kPa)	**Instantaneous**	**Time Consolidated**
	σ_c (kPa)	**σ_c (kPa)**
Wheat flour		
0.606	0.3984	0.4056
1.161	0.5664	0.5912
2.288	0.9896	0.9942
4.525	1.8598	1.902
Chickpea flour		
0.6204	0.657	0.9468
1.2608	1.1982	1.6782
1.9942	1.779	2.1486
3.2278	2.4642	2.917

4.3. Hopper design for mass flow

The parameters required for hopper construction is the hopper outlet dimension or diameter (D) and hopper half angle (θ). These are calculated from the flow property results of wall friction test, flow function test and bulk density test, which provide the values of unconfined failure strength (σ_c), critical bulk density (ρ_b), effective angle of internal friction (δ_i) and effective angle of wall friction (ϕ_w) [3]. The hopper design values for mass flow hopper can be calculated using the following equations:

$$\square_{\square\square\square h\square \square\square} = \frac{2\times\square_{\square}\times 1000}{\square_{\square}\times\square} \tag{6}$$

$$\square = [90 - \frac{1}{2}\cos^{-1}\left(\frac{1-\sin\square_{\square}}{2\sin\square_{\square}}\right)] - \frac{1}{2}[\square_{\square} + \sin^{-1}\left(\frac{\sin\square_{\square}}{\sin\square_{\square}}\right)] \tag{7}$$

The arching flow factor for wheat flour and gram flour is 1.36 and 1.3, respectively, which is used in “powder flow pro” during hopper design calculation for mass flow hopper for conical and plane shaped hoppers (see Figure 12). It can be seen from Figure 12 that the hopper outlet required for chickpea flour is wider than that of wheat flour in both conical and plane shape hoppers because of higher cohesion values of chickpea flour (see Table 3), the critical hopper angle for wheat flour for plane or wedge shaped hopper is 41° (which is rather shallow) and for conical shape, it is 32°. Hence, the conical shape mass flow hopper is more suitable for wheat flour. The critical hopper angle for chickpea flour for conical shaped hopper is 9°, which is rather steep [9, 30]. For the plane or wedge shaped mass flow hopper, the angle is 20°.

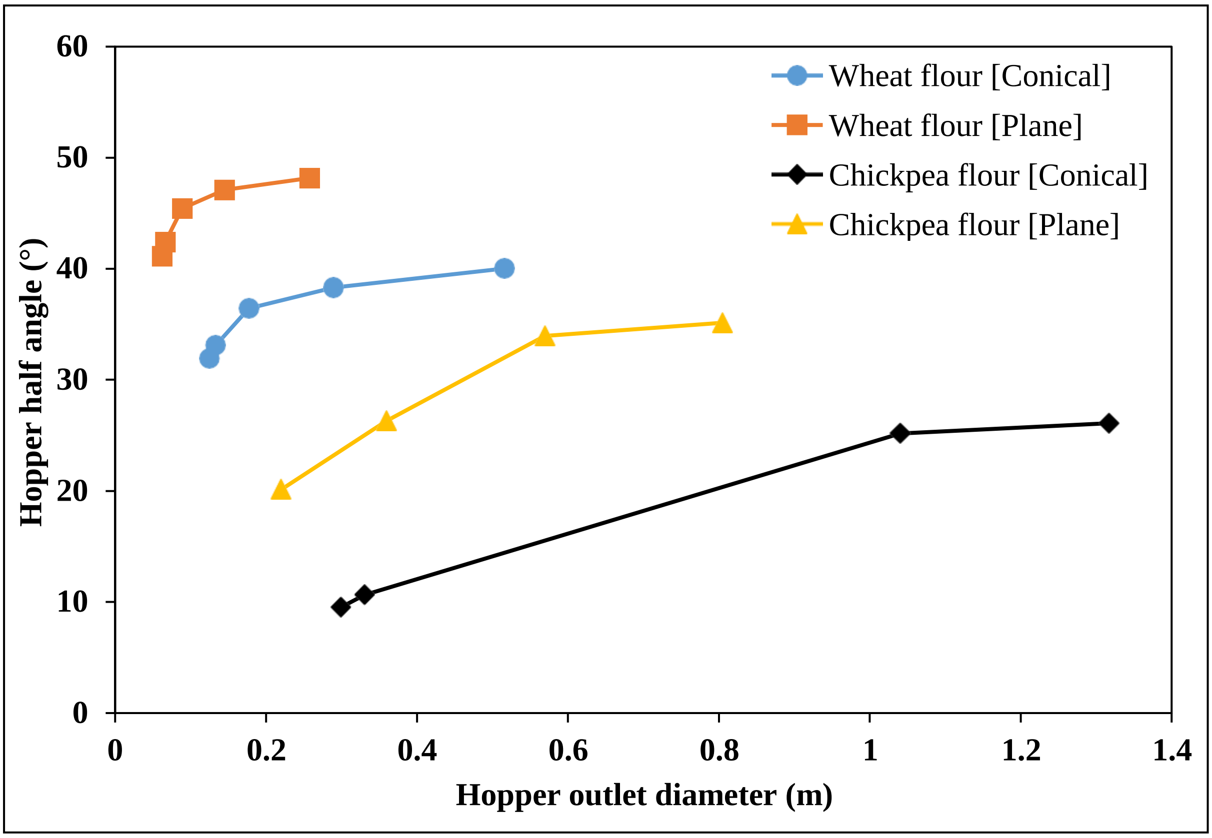


Figure 12. Hopper half angle versus hopper outlet diameter for wheat flour and chickpea flour (conical and plane shape hoppers) with time consolidation effects

A comparison between hopper design values for plane and conical shape hopper has been done to examine the effect of different wall friction results on hopper design (see Figures 13 and 14). Different wall friction test results (Standard I, Custom V and Custom VI)) were used with "Standard" flow function test results for wheat flour and "Custom IV" flow function test result for chickpea flour. It has been observed that as the displacement increases from 0.06 m to 0.399m (standard wall friction test to custom wall friction using separate samples with even spacing to custom wall friction using separate samples with doubling progression) the critical value of hopper half angle increases. The critical hopper angles obtained using custom methods are almost same for both the flours when calculated for also both the shapes (conical and wedge shaped hoppers).

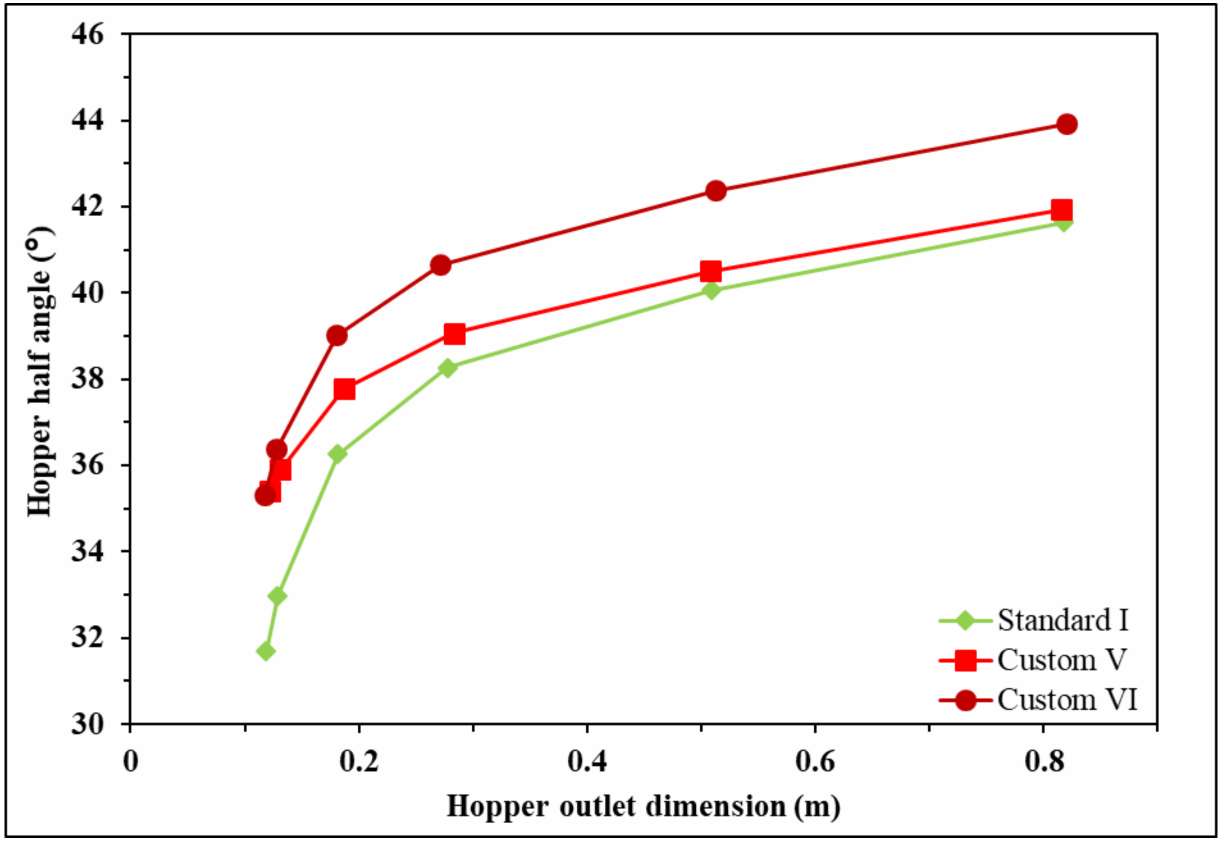


Figure 13. Hopper half angle versus hopper outlet diameter for wheat flour using instantaneous standard flow function and different wall friction (for conical hopper)

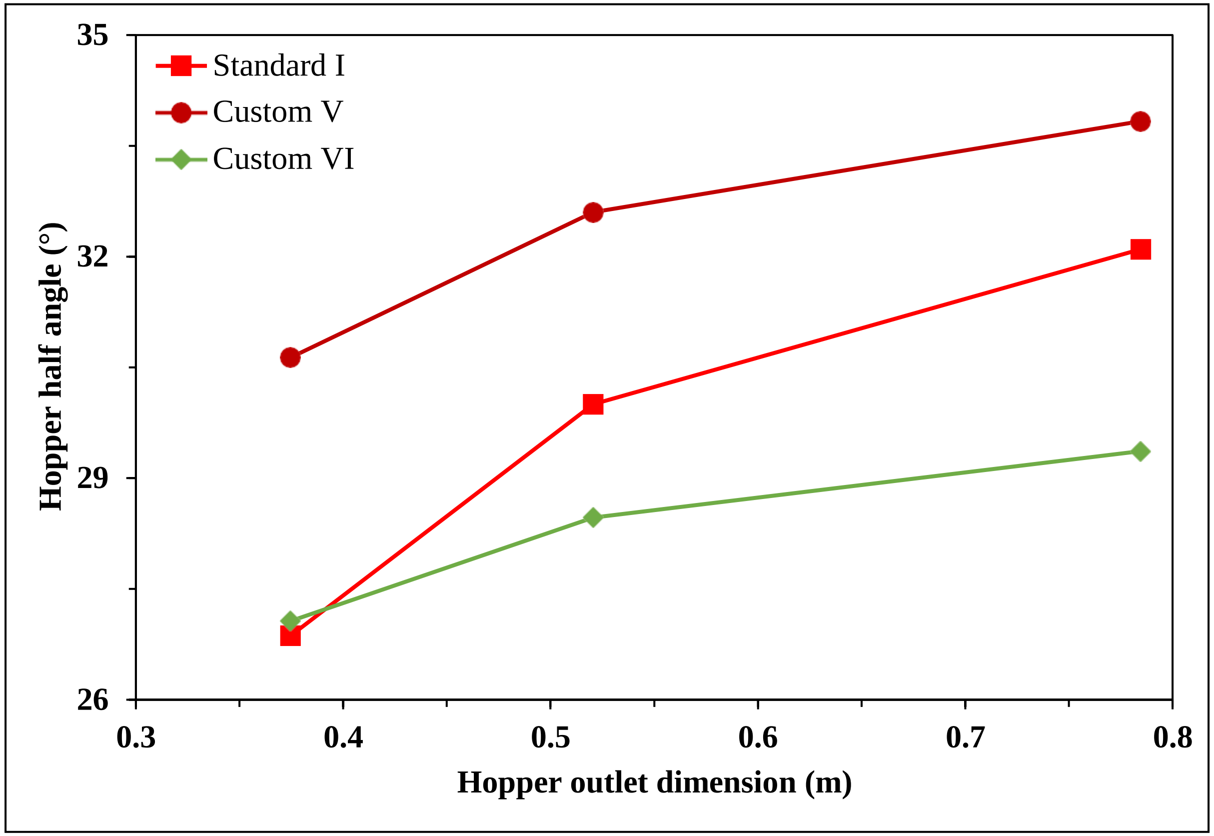


Figure 14. Hopper half angle versus hopper outlet diameter for chickpea flour using instantaneous custom flow function with separate samples geometric spacing and tangent to unconfined Mohr circle flow function and different wall friction (for plane shaped hopper)

Chapter-5

Conclusion & Future Scope

5.1 Conclusion

Instantaneous flow function tests of wheat and chickpea flour were conducted using standard and custom (with separate samples, geometric spacing, even spacing and tangent to unconfined Mohr circle and their different combinations) test methods. Results indicate that wheat flour falls in cohesive region and chickpea flour in very cohesive region based on instantaneous test results. It was found that there was no considerable effect of time consolidation on the flowability of wheat flour, but the flowability of chickpea flour decreases considerably and it changes to non-flowing nature from the original very cohesive state. A significant difference was observed between the "Standard" and "Custom" (with separate samples, geometric spacing and tangent to unconfined Mohr circle) instantaneous flow function test results at higher stresses for chickpea flour. The "custom" test method provided better flow function results than that of "standard" methods. It was found that the conical shape hopper is more suitable for wheat flour with a hopper half angle of 32° and wedge shape hopper for chickpea flour with a hopper half angle of 20°. It was observed that critical hopper half angle increases with the displacement used in wall friction tests.

5.2. Future Scope

This study was done to describe the flow behaviour of the flours which is eaten by almost everybody on a daily basis, using physical characteristics and flow properties. A noteworthy attempt was made to determine the suitable shape and dimensions of hopper for these powders, as process industries are facing problems in handling of these powders. Further work on powder flow can be done in the following areas

- More fundamental studies are required to be carried out in future addressing the moisture content and shape of agricultural powders on their flowability.
- CFD-DEM modelling and analysis of the mass flow of bulk solid.

References

[1] Alrayyes, W.H., 2018. Nutritional and Health Benefits Enhancement of Wheat-Based Food Products Using Chickpea and Distiller's Dried Grain.

[2] Annual Report on Agriculture 2016-17, Ministry of Agriculture and Farmers Welfare.

[3] Schulze, D., 2008. Powders and bulk solids. *Behaviour, Characterization, Storage and Flow*. *Springer*, pp.35-74.

[4] Peleg, M., 1977. Flowability of food powders and methods for its evaluation—a review. *Journal of Food Process Engineering*, *1*(4), pp.303-328

[5] Bian, Q., Sittipod, S., Garg, A. and Ambrose, R.K., 2015. Bulk flow properties of hard and soft wheat flours. *Journal of Cereal Science*, *63*, pp.88-94.

[6] Schubert, H., 1987. Food particle technology. Part I: Properties of particles and particulate food systems. *Journal of food engineering*, *6*(1), pp.1-32.

[7] Schubert, H., 1987. Food particle technology. Part II: Some specific cases. *Journal of food engineering*, *6*(2), pp.83-102.

[8] Teunou, E., Fitzpatrick, J.J. and Synnott, E.C., 1999. Characterisation of food powder flowability. *Journal of Food Engineering*, *39*(1), pp.31-37.

[9] Fitzpatrick, J.J., Barringer, S.A. and Iqbal, T., 2004. Flow property measurement of food powders and sensitivity of Jenike's hopper design methodology to the measured values. *Journal of Food Engineering*, *61*(3), pp.399-405.

[10] Teunou, E. and Fitzpatrick, J.J., 2000. Effect of storage time and consolidation on food powder flowability. *Journal of Food Engineering*, *43*(2), pp.97-101.

[11] Koynov, S., Glasser, B. and Muzzio, F., 2015. Comparison of three rotational shear cell testers: Powder flowability and bulk density. *Powder Technology*, *283*, pp.103-112.

[12] Ripp, M., Debele, Z.A. and Ripperger, S., 2015. Determination of Bulk Flow Property of tef Flour and Seed and Design of a Silo. *Particulate Science and Technology*, *33*(5), pp.494-502.

[13] Amagliani, L., O'Regan, J., Kelly, A.L. and O'Mahony, J.A., 2016. Physical and flow properties of rice protein powders. *Journal of Food Engineering*, *190*, pp.1-9.

[14] Crowley, S.V., Gazi, I., Kelly, A.L., Huppertz, T. and O'Mahony, J.A., 2014. Influence of protein concentration on the physical characteristics and flow properties of milk protein concentrate powders. *Journal of Food Engineering*, *135*, pp.31-38.

[15] Juarez-Enriquez, E., Olivas, G.I., Zamudio-Flores, P.B., Ortega-Rivas, E., Perez-Vega, S. and Sepulveda, D.R., 2017. Effect of water content on the flowability of hygroscopic powders. *Journal of Food Engineering*, *205*, pp.12-17.

[16] Domian, E. and Poszytek, K., 2005. Wheat flour flowability as affected by water activity, storage time and consolidation. *Int. Agrophysics*, *19*, pp.119-124

[17] Kamath, S., Puri, V.M. and Manbeck, H.B., 1994. Flow property measurement using the Jenike cell for wheat flour at various moisture contents and consolidation times. *Powder technology*, *81*(3), pp.293-297.

[18] Berry, R.J., Bradley, M.S.A. and McGregor, R.G., 2015. Brookfield powder flow tester–Results of round robin tests with CRM-116 limestone powder. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*, *229*(3), pp.215-230.

[19] Jenike, A.W., 1964. Storage and flow of solids, bulletin no. 123. *Bulletin of the University of Utah*, *53*(26).

[20] Saw, H.Y., Davies, C.E., Paterson, A.H. and Jones, J.R., 2015. Correlation between Powder Flow Properties Measured by Shear Testing and Hausner Ratio. *Procedia Engineering*, *102*, pp.218-225.

[21] Lee, Y.J. and Yoon, W.B., 2015. Flow behavior and hopper design for black soybean powders by particle size. *Journal of Food Engineering*, *144*, pp.10-19.

[22] Mallick, S.S., Rohilla, L., Garg, V. and Setia, G., 2018. Modeling flow properties of fine dry powders using particle morphological properties and its effects on geometry of fly ash evacuation hoppers. *Particulate Science and Technology*, *36*(4), pp.464-472.

[23] Rohilla, L., Garg, V., Mallick, S.S. and Setia, G., 2018. An experimental investigation on the effect of particle size into the flowability of fly ash. *Powder Technology*, *330*, pp.164-173.

[24] Garg, V., Mallick, S.S., Trinanes, P.G. and Berry, R.J., 2018. An investigation into the flowability of fine powders used in pharmaceutical industries. *Powder Technology*.

[25] Hausner, H.H., 1967. Friction conditions in a mass of metal powder. Polytechnic Inst. of Brooklyn. Univ. of California, Los Angeles.

[26] Carr Jr, R.L., 1965. Classifying flow properties of solids. *Chem. Eng.(Feb.)*, *1*, pp.69-72.

[27] Saravacos, G.D. and Kostaropoulos, A.E., 2002. *Handbook of food processing equipment*. Kluwer Academic/Plenum

[28] Horn, E., 2008. Development of a composite index for pharmaceutical powders (Doctoral dissertation, North-West University).

[29] Ambrose, R.P., Jan, S. and Siliveru, K., 2016. A review on flow characterization methods for cereal grain-based powders. *Journal of the science of food and agriculture*, *96*(2), pp.359-364.

[30] Chen, P., Yuan, Z., Shen, X. and Zhang, Y., 2012. Flow properties of three fuel powders. *Particuology*, *10*(4), pp.438-443.

[31] Iqbal, T. and Fitzpatrick, J.J., 2006. Effect of storage conditions on the wall friction characteristics of three food powders. *Journal of Food Engineering*, *72*(3), pp.273-280.

[32] Xanthakis, E., van Ommen, J.R. and Ahrné, L., 2015. Flowability characterization of nanopowders. *Powder Technology*, *286*, pp.156-163.

[33] Zafar, U., Hare, C., Calvert, G., Ghadiri, M., Girimonte, R., Formisani, B., Quintanilla, M.A.S. and Valverde, J.M., 2015. Comparison of cohesive powder flowability measured by Schulze Shear Cell, Raining Bed Method, Sevilla Powder Tester and new Ball Indentation Method. *Powder Technology*, *286*, pp.807-816.

[34] Saw, H.Y., Davies, C.E., Paterson, A.H. and Jones, J.R., 2015. Correlation between Powder Flow Properties Measured by Shear Testing and Hausner Ratio. *Procedia Engineering*, *102*, pp.218-225.

[35] Ji, J., Fitzpatrick, J., Cronin, K., Fenelon, M.A. and Miao, S., 2017. The effects of fluidised bed and high shear mixer granulation processes on water adsorption and flow properties of milk protein isolate powder. *Journal of Food Engineering*, *192*, pp.19-27.

Communications

Saluja, G., Mallick, S.S. An Investigation into the Flowability of Flours and Evaluation of Testing Methods of Powder Flow Tester. **Powder Technology, Elsevier.** (Under Communication)