Predicting the Wheat Flour Size Segregation Process From Particle Properties

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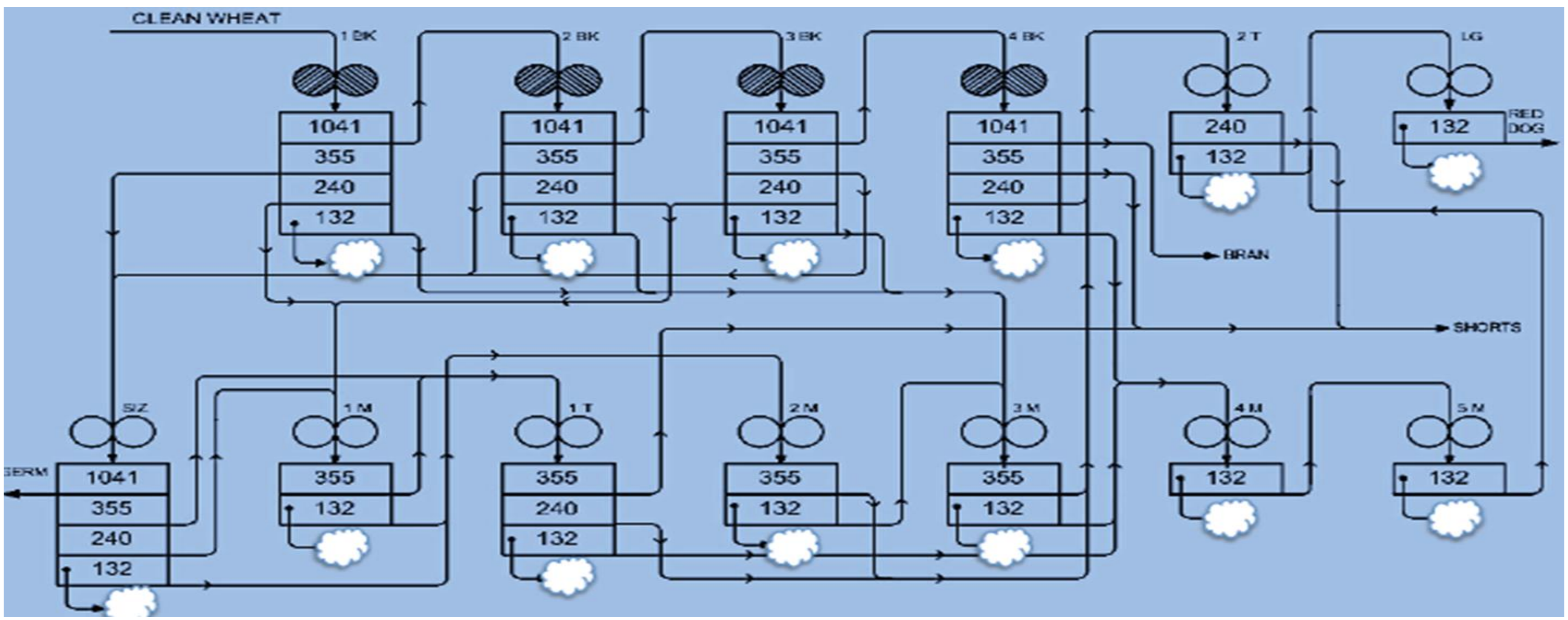
Introduction

- Majority of wheat is converted into flour
- Color, genetics, hardness, and growing season – 6 classes

Mill flow sheet



(Roller mill flow sheet, SH 101)

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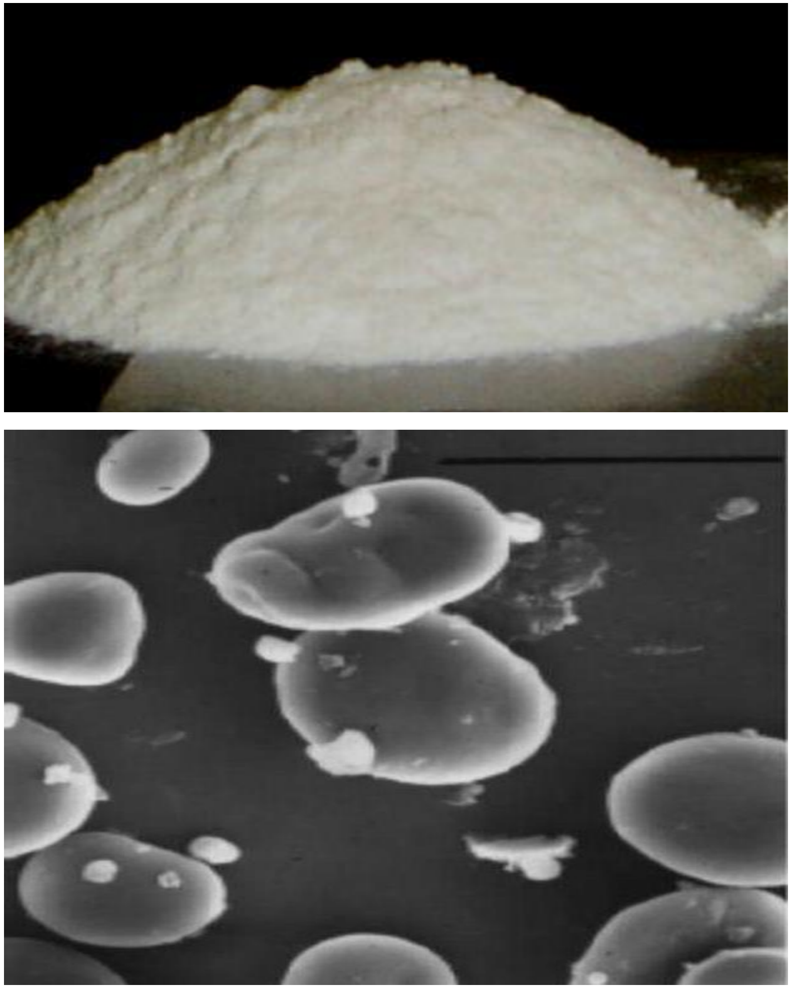
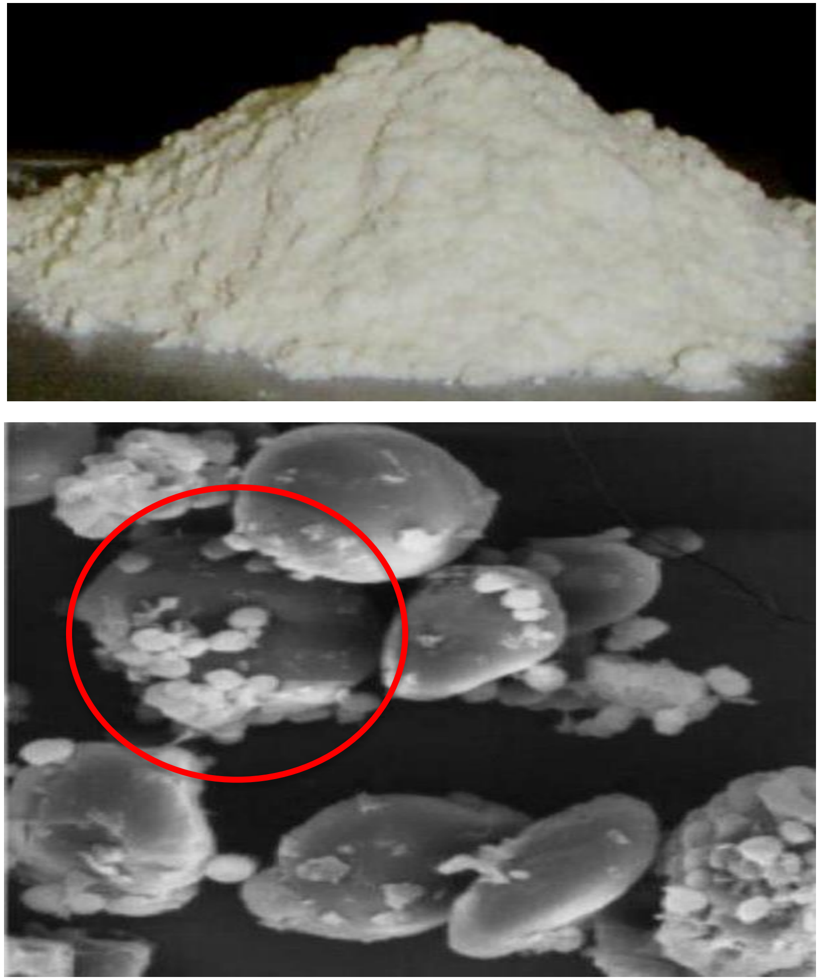
Sieving Process

- Three important particle motions (Nicholas et al., 1969):
  - Filtration of fines through the matrix of powder on the mesh
  - Free passage of particles through the mesh
  - Interrupted passage or blinding of particles in the mesh
- Loss in throughput is observed when sieving soft wheat flour compared to that of hard wheat flour (Neel and Hoseney, 1984).
- Particle size of wheat flour affects its physicochemical properties (Wang and Flores, 2000).



Hard wheat Flour



Soft wheat Flour

(Source: U. S. Wheat Associates, 2011)

Sieving Process

Sieving Process Design

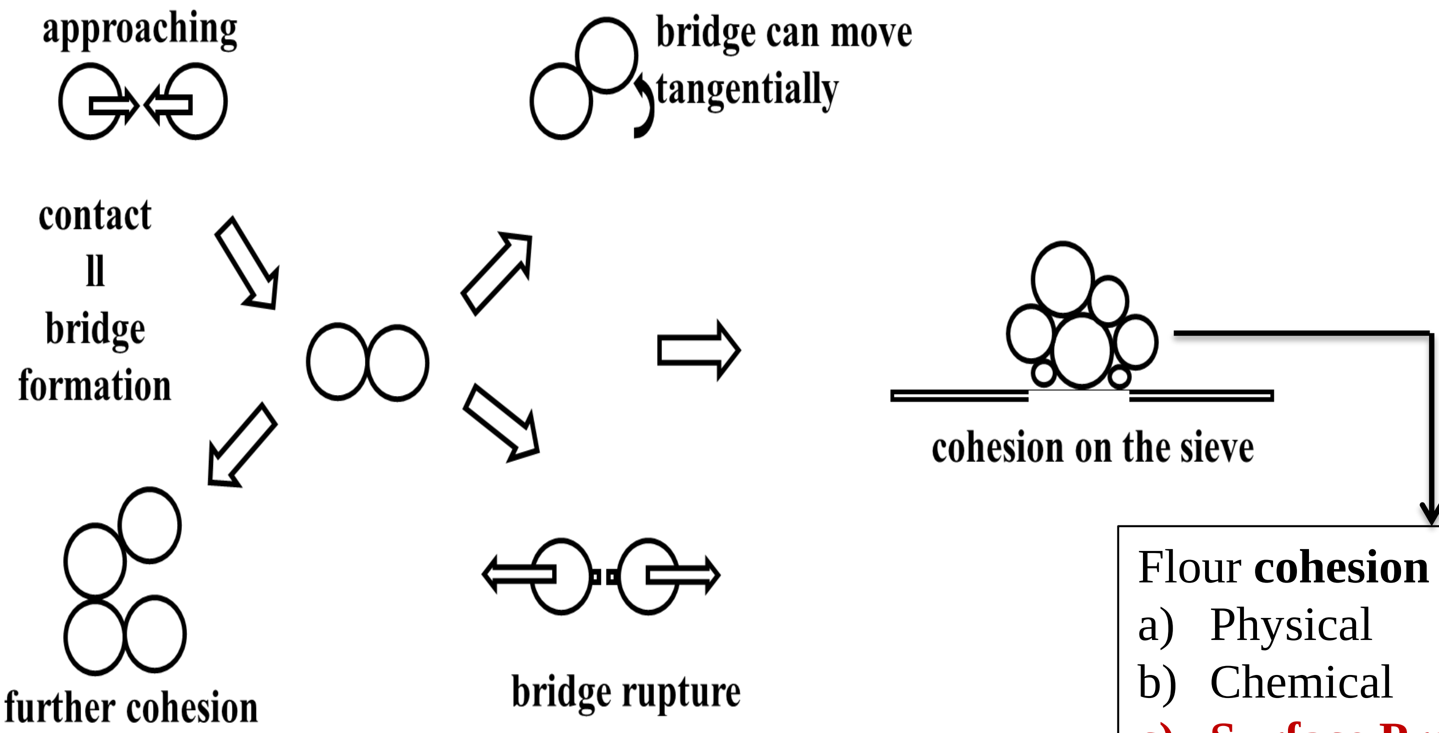
$$\left\{ \frac{\text{Driving force}}{\text{CONSTRAINTS}} \right\} \Longrightarrow$$ **Powder flow during sieving**

Sieve constraints:
a) Aperture opening
b) Rate and direction of movement of sieve
c) Sieve cloth

Flour (Intrinsic) constraints:
a) Size and shape of particle
b) Load on sifter
c) COHESION

(Source: Roberts and Beddow, 1968)

Flour Cohesion



Flour **cohesion** depends on:
a) Physical
b) Chemical
c) **Surface Properties**

Research hypothesis: Flour particle characteristics affects the sifting behavior of wheat flour.

Research Objectives

- Objective: **1 -** Determination of surface physical and chemical characteristics of hard and soft wheat flours.
- Objective: **2 -** Determination the significance of physical and chemical characteristics on the bulk cohesion of wheat flours.
- Objective: **3** – Develop a correlation to predict the flow behavior of wheat flours.
- Objective: **4** – Develop and validate of discrete element method (DEM) model to describe the wheat flour sieving process.

Surface Characteristics

- Determination of surface physical and chemical characteristics of hard and soft wheat flour particles.
  - Surface lipid content
  - Shape factor
  - Surface roughness

Materials

Flour from:

- Hard red winter wheat
- Soft red winter wheat

45, 75, and 90 µm particle size

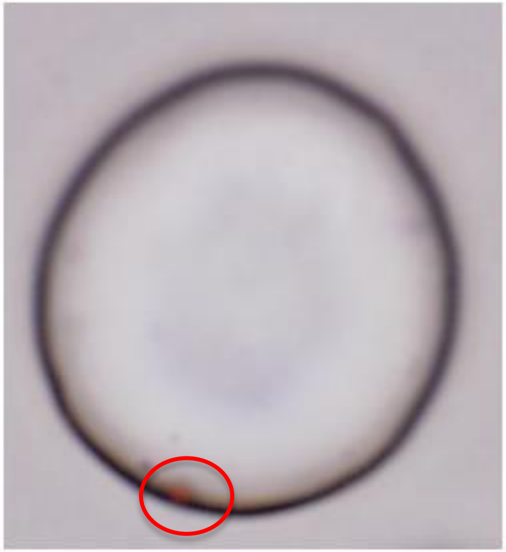
- Lab scale milling – AACC method (26-21.02; 26-31.01)

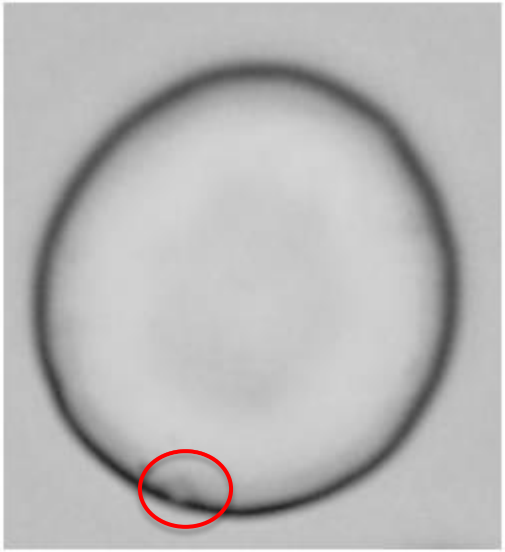
(Particle size selection : Neel and Hoseney, 1984)

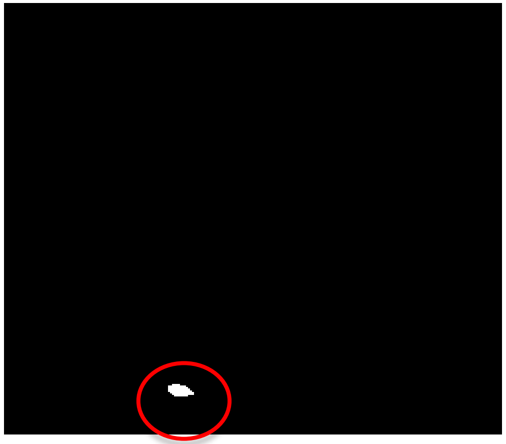
Methods

Property	*Test*
Surface lipid	Surface staining – Sudan IV dye, and Ethylene glycol (Chiffelle and Putt, 1951) ➢ 0.35 g dye/100 ml ethylene glycol ➢ Program written in MATLAB
Shape factors ➢ Form factor; Roundness ➢ Aspect ratio; Compactness	Scanning Electron Microscopy images ×500 magnification ➢ Shape descriptors plug in (V 1.48) in ImageJ
Surface roughness	Atomic force microscopy ➢ $R_q = \frac{1}{N}\sqrt{\sum_{i=1}^{N}(Z_i - Z_{ave})^2}$

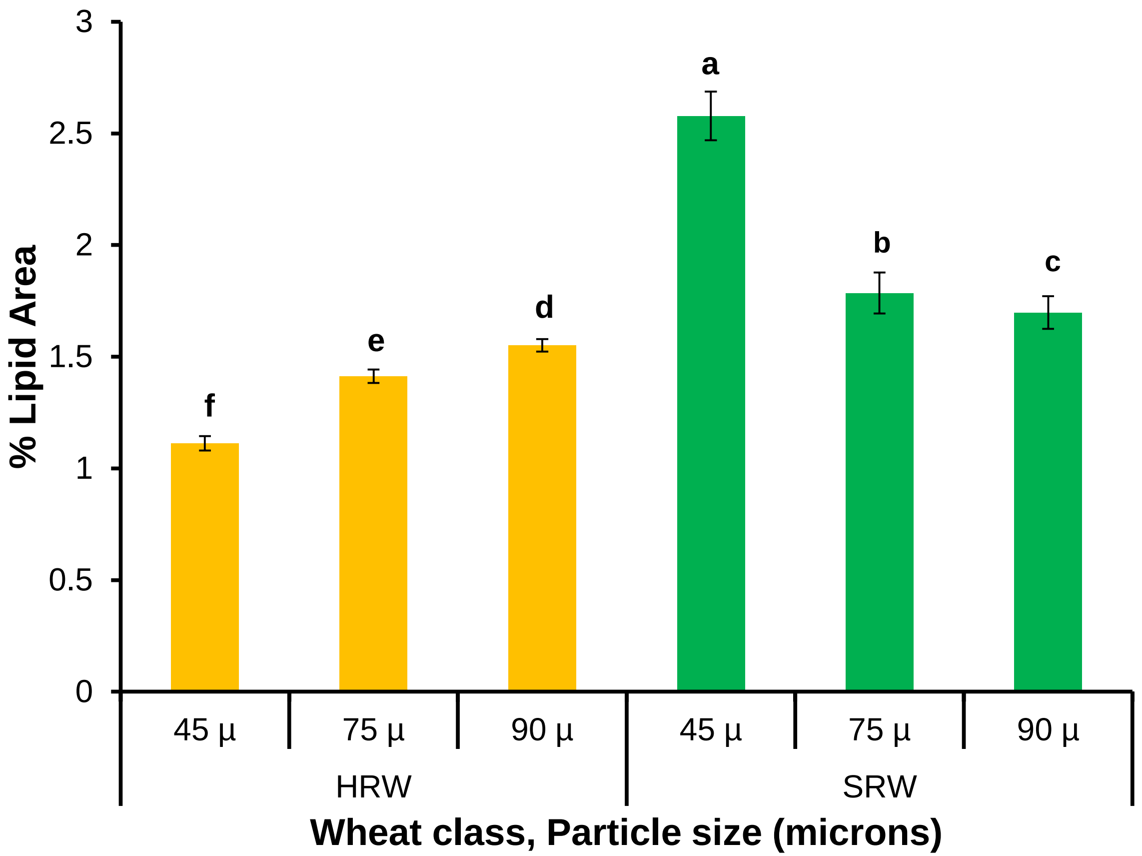
Surface Lipid Composition







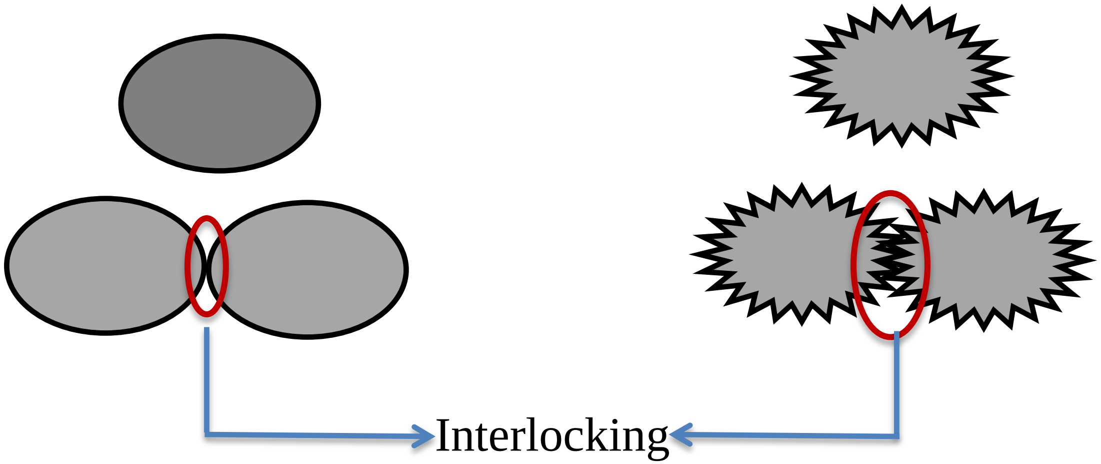
Surface lipid composition



** Values with same letters on a column are not significantly different for a particular size by least significant difference (LSD) comparison of means. ($\alpha = 0.05$)

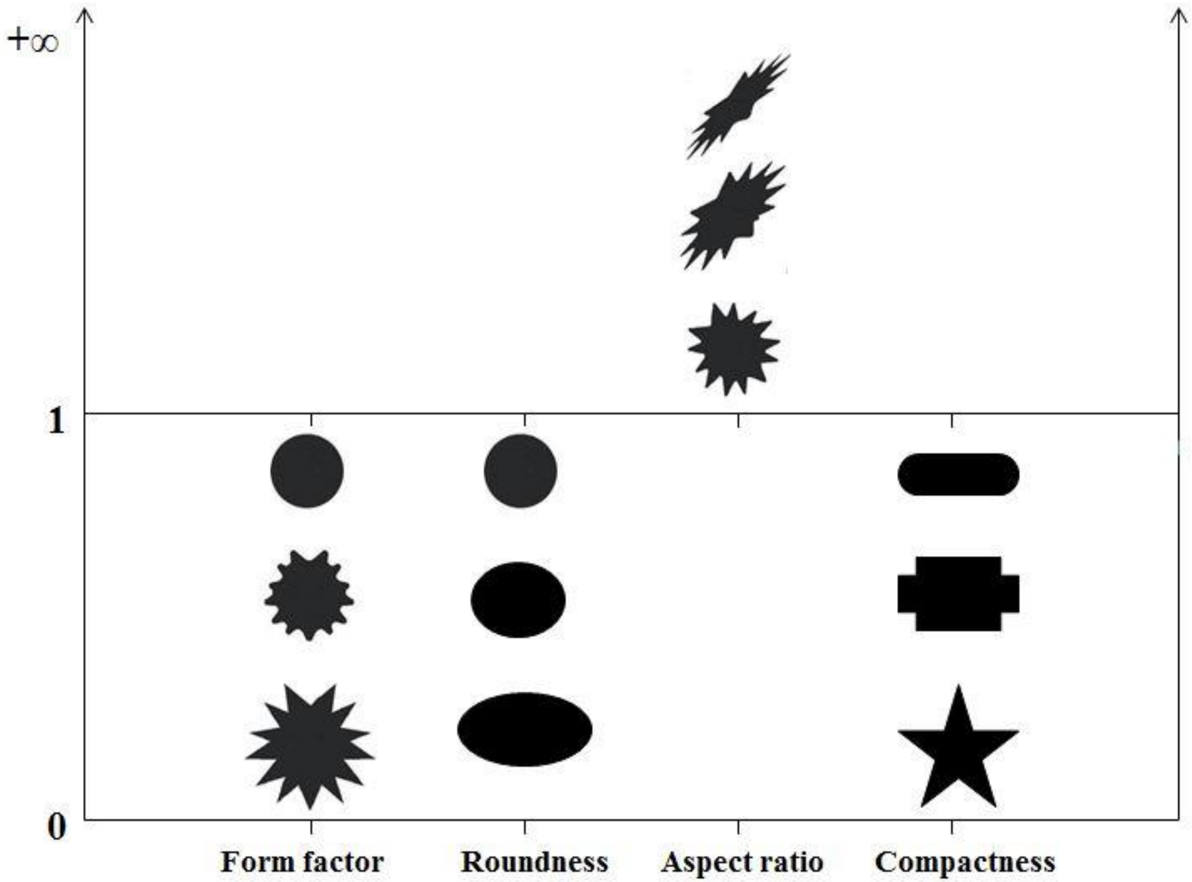
Shape Factor

- Shape factor – Shape descriptors plug in (V 1.48) in ImageJ
- Shape descriptors – form factor, roundness, aspect ratio, and compactness



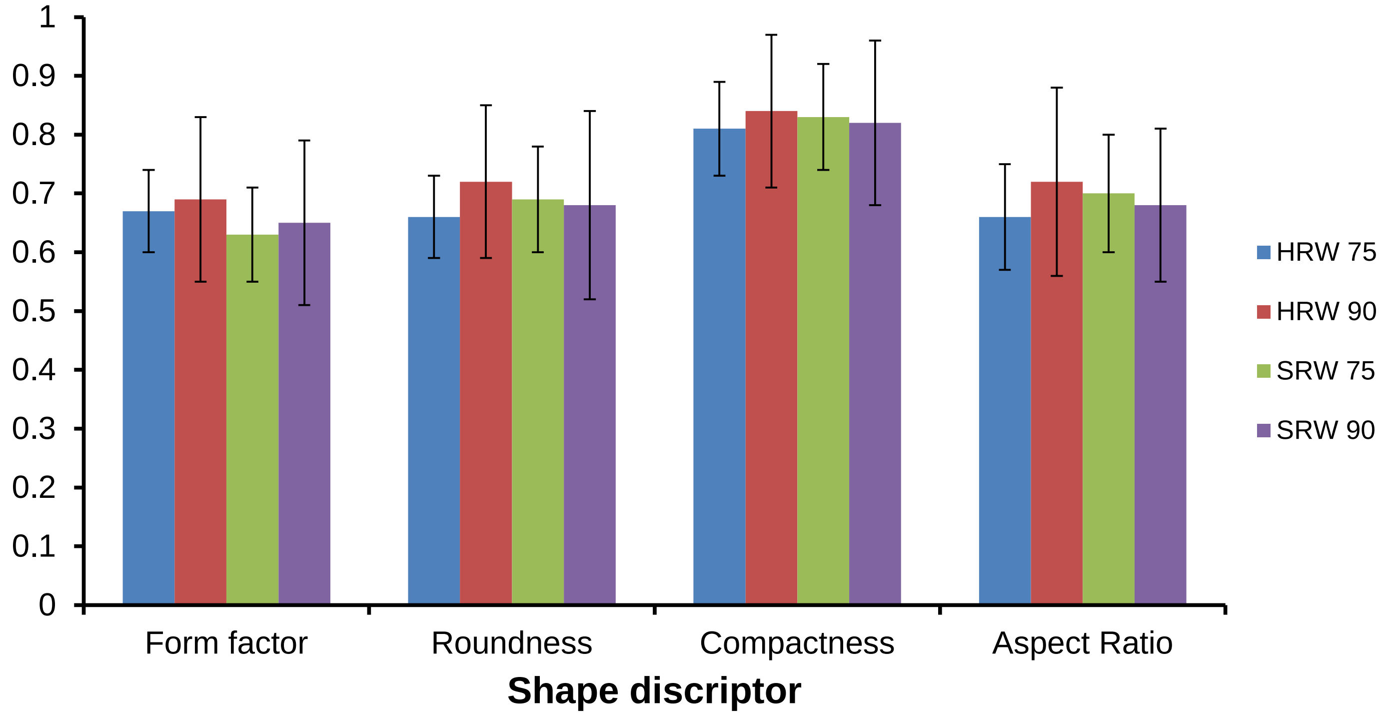
Interlocking in circular and irregular particles

Shape Factor



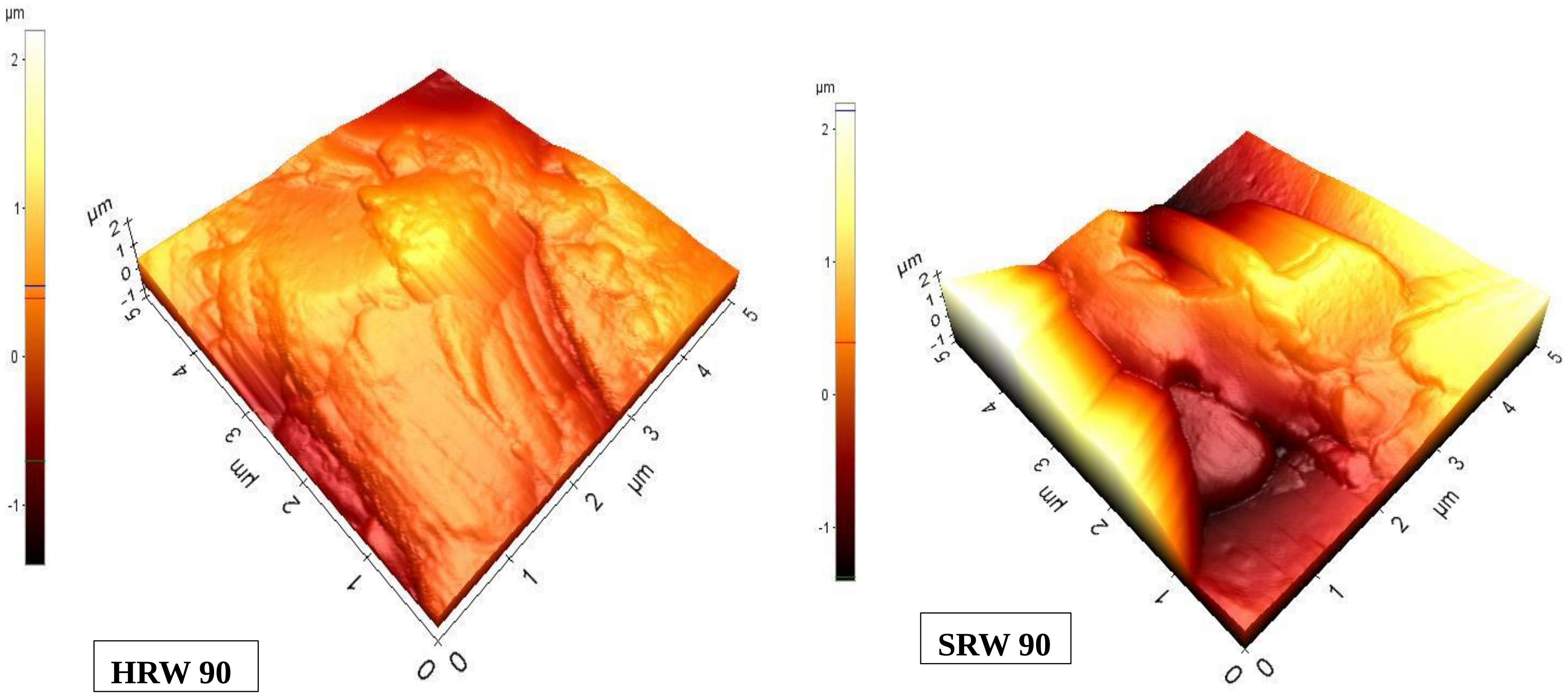
Range of values of shape factors from the regular shapes.

Shape Descriptors

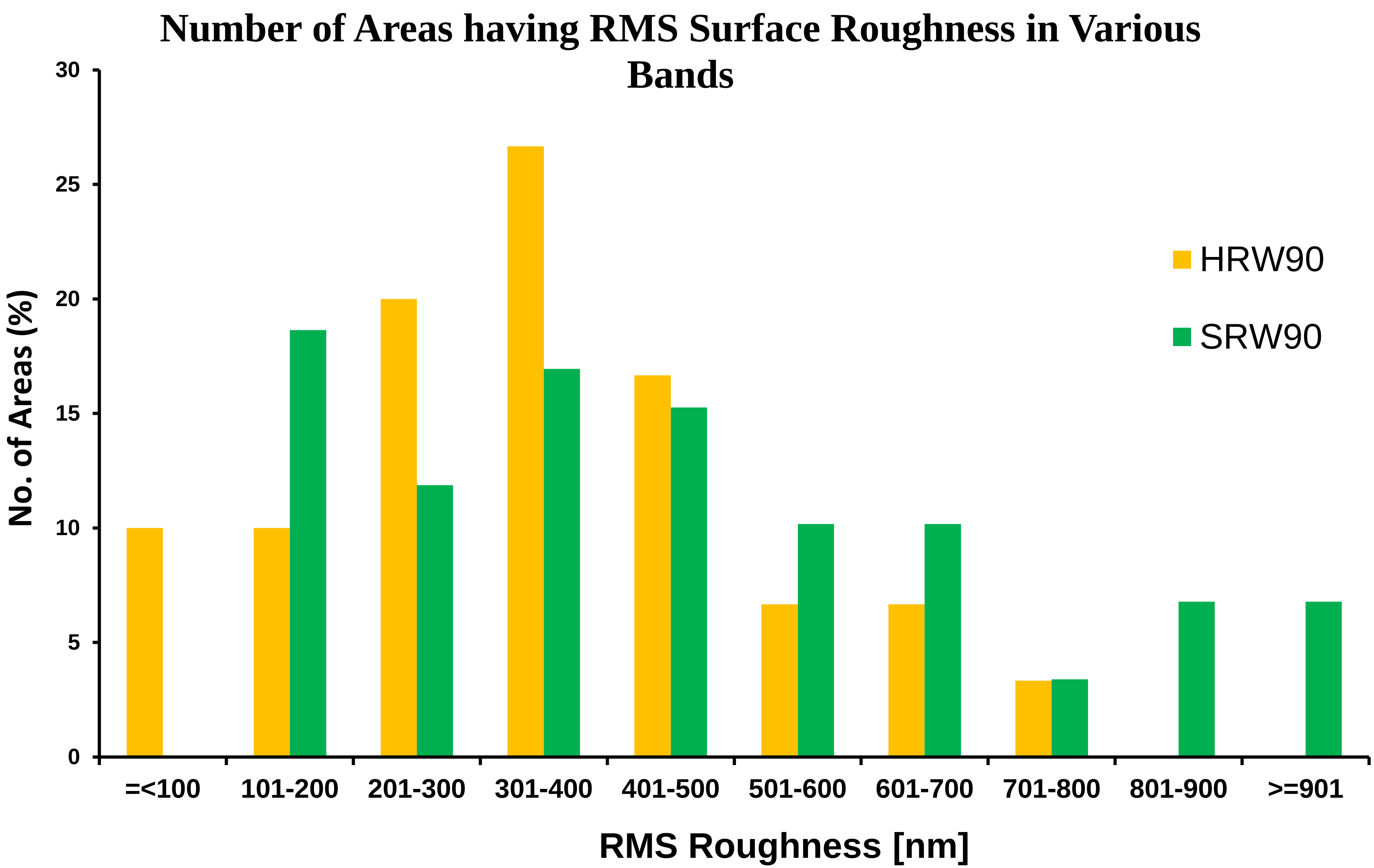


Measured **Shape Descriptors** values

Surface Roughness



3D topography of HRW 90 µm and SRW 90 µm particles. Scan size 5 × 5 µm and scan rate of 1-2 Hz.

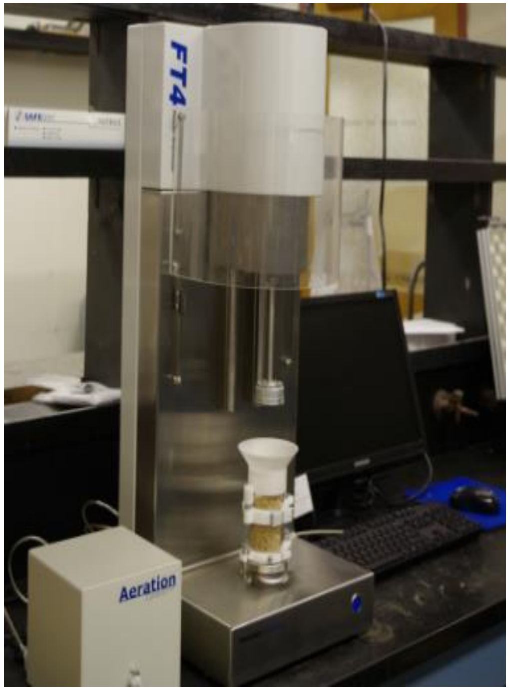

Number of Areas having RMS Surface Roughness in Various Bands
No. of Areas (%)
30
25
20
15
10
5
0
HRW90
SRW90
=<100
101-200
201-300
301-400
401-500
501-600
601-700
701-800
801-900
>=901
RMS Roughness [nm]

Surface characteristics: Conclusions

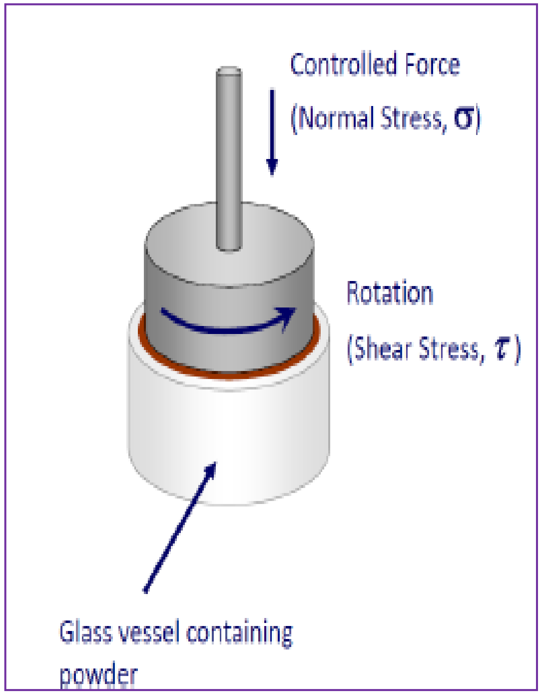
- The surface lipid composition and roughness were higher in soft wheat flours.
- The breakage behavior of flour components (protein and starch) influenced the overall shape and surface roughness of wheat flour.
- The irregular shape of the particle causes inter-locking behaviour between particles which could affect flour movement during sieving.
- The differences in surface characteristics could lead to agglomeration of flour particles that could affect the sieving process and also affects the product quality and uniformity.

Bulk Cohesion

Method



FT4-Powder rheometer



Shear cell measurement

Results

Sample	Cohesion, kPa		
	0.5 kPa	1.0 kPa	1.5 kPa
HRW (< 45 µm)	0.25 ± 0.01^{Bc}	0.39 ± 0.01^{Ab}	0.74 ± 0.02^{Aa}
H 45 - 75 µm	0.11 ± 0.01^{Cb}	0.12 ± 0.01^{Bb}	0.25 ± 0.01^{Ca}
H 75 - 106 µm	0.06 ± 0.01^{Ec}	0.16 ± 0.01^{Bb}	0.21 ± 0.02^{Ca}
SRW (< 45 µm)	0.32 ± 0.01^{Ac}	0.43 ± 0.02^{Ab}	0.73 ± 0.06^{Aa}
S 45 - 75 µm	0.08 ± 0.002^{Dc}	0.14 ± 0.03^{Bb}	0.29 ± 0.02^{Ba}
S 75 - 106 µm	0.06 ± 0.001^{Ec}	0.10 ± 0.002^{Cb}	0.18 ± 0.01^{Da}

** Values with same upper case letters in a column are not significantly different for different particle sizes; Values with same lower case letters in a row are not significantly different for a particular size by least significant difference (LSD) comparison of means. ($\alpha = 0.05$)

Sample	Flow Function (FF)		
	0.5 kPa	1.0 kPa	1.5 kPa
HRW (< 45 µm)	1.07 ± 0.01^{Eb}	1.13 ± 0.15^{Db}	1.11 ± 0.09^{Ca}
H 45 - 75 µm	2.47 ± 0.23^{Cc}	3.26 ± 0.10^{Cb}	4.18 ± 0.30^{Ba}
H 75 - 106 µm	4.45 ± 0.29^{Aa}	4.62 ± 0.24^{Aa}	5.14 ± 0.20^{Aa}
SRW (< 45 µm)	1.18 ± 0.02^{Da}	1.09 ± 0.04^{Da}	1.32 ± 0.04^{Da}
S 45 - 75 µm	2.93 ± 0.15^{Bb}	3.13 ± 0.04^{Cb}	3.73 ± 0.27^{Ba}
S 75 - 106 µm	3.03 ± 0.45^{Bb}	3.34 ± 0.04^{Bb}	3.74 ± 0.17^{Ba}

If **FF** is

<1: Hardened

1-2 : Very Cohesive

2-4: Cohesive

4-10: Easy flowing

>10: Free flowing

Ref: Fitzpatrick et al., 2004

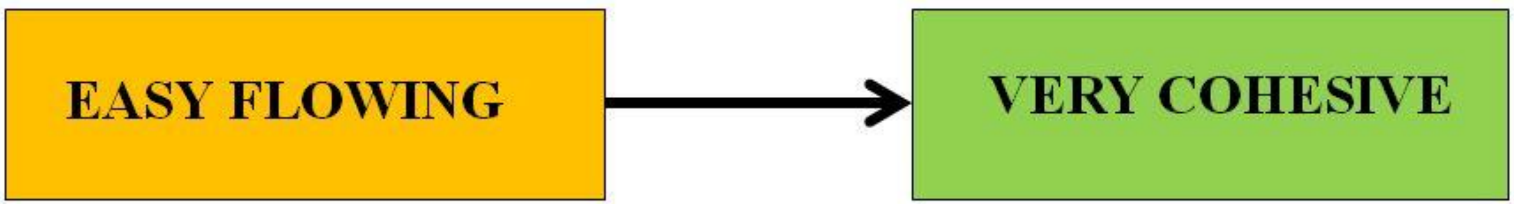
** Values with same upper case letters in a column are not significantly different for different particle sizes; Values with same lower case letters in a row are not significantly different for a particular size by least significant difference (LSD) comparison of means. ($\alpha = 0.05$)

	Cohesion	Flow Function	AIF
Moisture content	0.98**	-0.98**	ns
Particle size	-0.92**	0.96**	-0.94
Sifter load	0.99**	-0.95**	-0.83
Damaged starch	0.92**	-0.82**	ns
Protein	0.91* (Hard) -0.73* (Soft)	-0.84* (Hard) 0.91* (Soft)	ns
Crude fat	-0.64** (Hard) 0.92* (Soft)	0.74** (Hard) -0.86* (Soft)	ns

**, * Indicate significance at $P < 0.01$ and $P < 0.05$, respectively; ns, not significant.

Bulk cohesion: Conclusions

- High correlation between the physical independent variables (MC, PS, SL), chemical composition (damaged starch, protein, and fat) and the flow properties (cohesion, flow function, and AIF).



Moisture: **12% (w.b)**
Particle size: **<45 µm**
Sifter load: **1.0 kPa**

Predicting Flow Behavior

- **Development of granular bond number (GBN) model for predicting flow behavior of wheat flours.**

- Hard red winter flour
- Soft red winter flour

Size range

a. 75 – 106 μm
b. 45 – 75 μm
c. < 45 μm

Moisture content: 12 % (w.b)

Applied pressure: 1.0 kPa

Methods

Property	*Test*
Particle characteristics ➢ d_p - particle diameter ➢ d_{asp} - asperity diameter ➢ d_{32} - Sauter mean diameter	Morphologi G3-ID morphologically directed Raman system (Malvern Instruments, Worcestershire, UK) ➢ Dry dispersion 0.5 bar ➢ 125 images
Surface energy	Inverse gas chromatography (IGC-SEA, Surface Measurement Systems, London, U.K.) ➢ $A = 24\pi D_0^2 \gamma_d$ (Israelachvili, 1992)
Flour blend preparation	Lab scale rotary mixer ➢ 20 min; 60 rpm; 100 g of flour ➢ 33.3/33.3/33.3 ➢ 16.6/41.7/41.7 ➢ 41.7/16.6/41.7 ➢ 41.7/41.7/16.6

Model Development

- Cohesive force
  - $F_{cohesion} = \frac{A}{12z_0^2}\left(\frac{d_p}{2\left({H_0}/{z_0}\right)^2} + \frac{3d_{asp}d_p}{d_{asp}+d_p}\right)$
  - $A = 24\pi D_0^2 \gamma_d$
- Granular Bond number (Bo_g)
  - $Bo_g = \frac{F_{cohesion}}{W_g}$
  - $ff_c = \alpha\left(Bo_g\right)^{-\beta}$
  - $SEP = \sqrt{\frac{\sum(Y-Y')^2}{N}}$

Where, A – Hamaker constant
d_p - particle diameter
d_{asp} - asperity diameter
H_0 - separation distance
z_0 - equilibrium separation distance
γ_d - surface energy
D_0- cut-off distance
W_g- particle weight

α, β for Hard wheat flours – 53.68, 0.43
for Soft wheat flours – 63.38, 0.45

Results

	Bo_g	**FF (Predicted)**	**FF (Experimental)**	**SEP**
HRW (< 45 µm)	7.23×10^{-3}	1.21	1.26 (0.04)	0.04
H 45 - 75 µm	7.41×10^{-2}	2.94	2.98 (0.03)	0.08
H 75 - 106 µm	1.80×10^{-2}	6.01	5.96 (0.16)	0.10
SRW (< 45 µm)	7.18×10^{-3}	1.17	1.21 (0.02)	0.06
S 45 - 75 µm	7.95×10^{-2}	2.86	2.92 (0.07)	0.04
S 75 - 106 µm	2.18×10^{-2}	5.81	5.72 (0.09)	0.10

* Values in parenthesis indicate standard deviation.

If **FF** is

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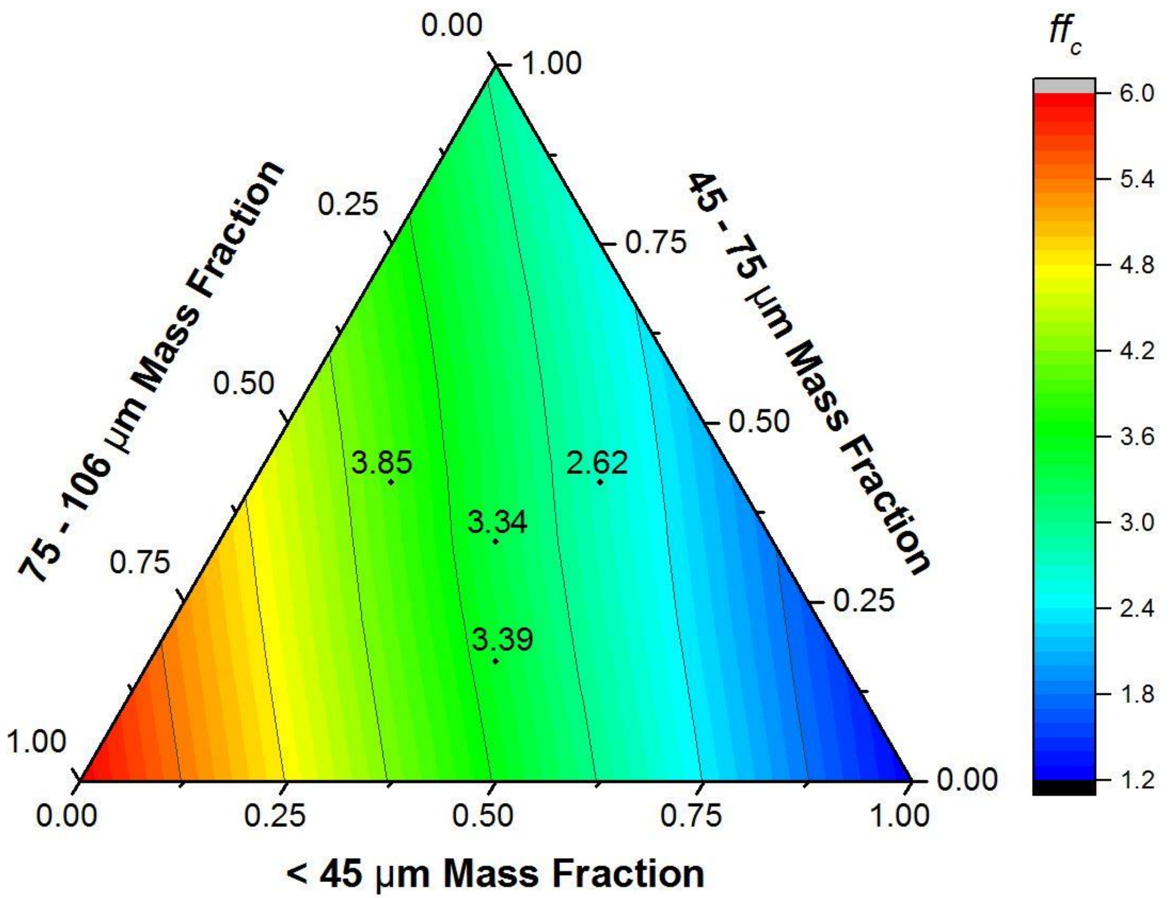
4-10: Easy flowing

>10: Free flowing

Ref: Fitzpatrick et al., 2004



Flow function coefficients predicted using developed model for ternary mixtures of HRW samples

If **FF** is

<1: Hardened

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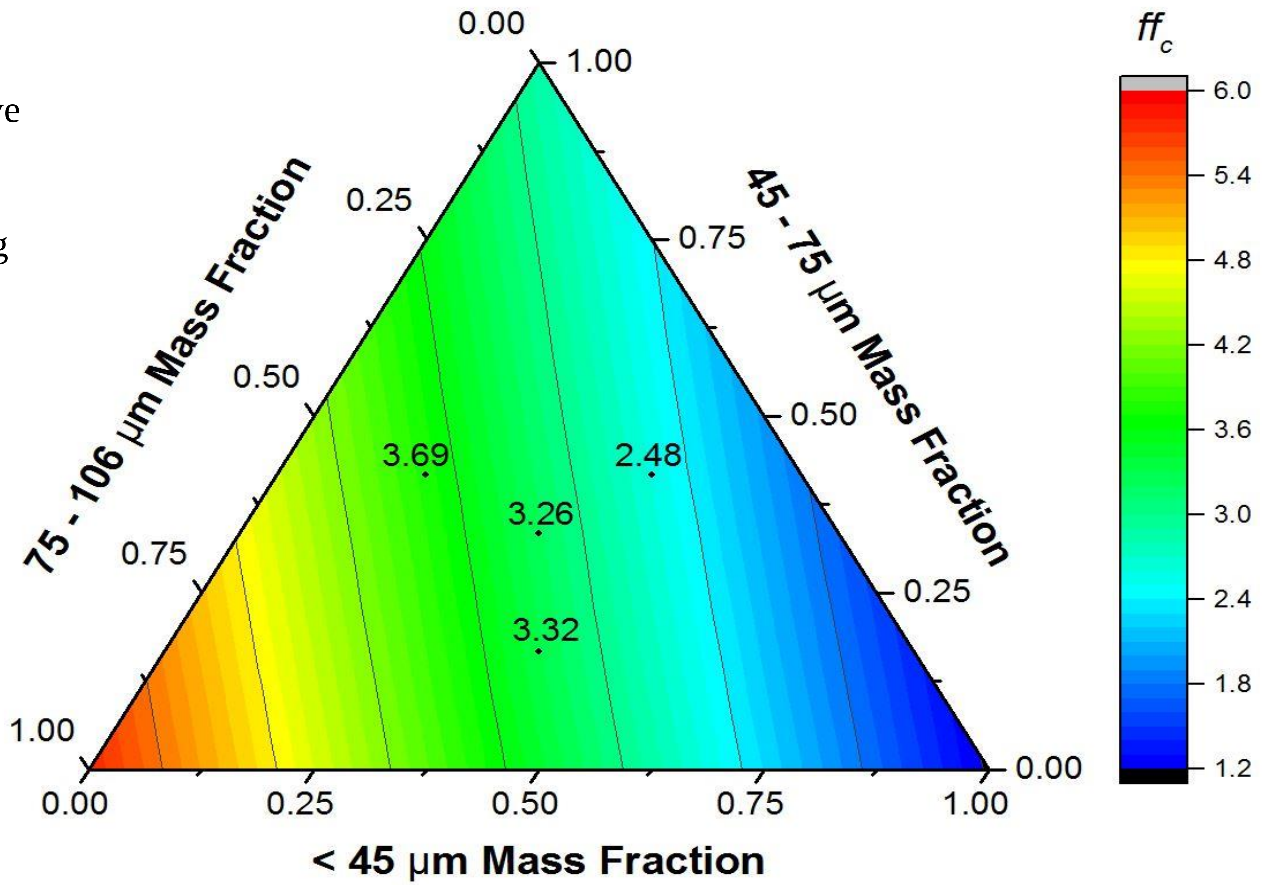
>10: Free flowing

Ref: Fitzpatrick et al., 2004



Flow function coefficients predicted using developed model for ternary mixtures of SRW samples

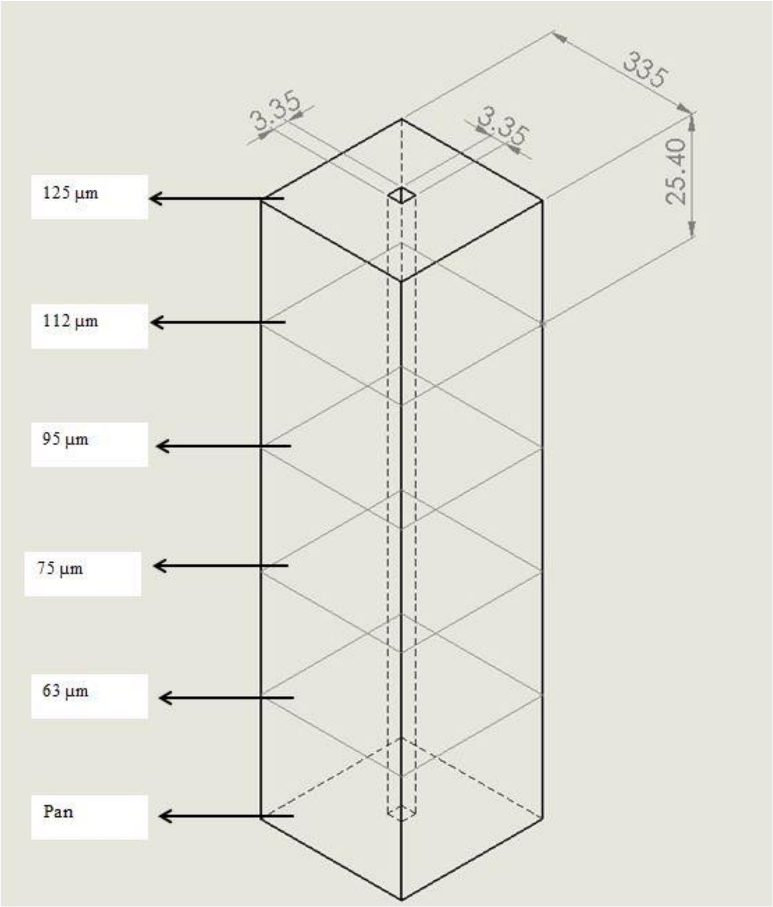
Predicting Flow: Conclusions

- The GBN model quantifies inter-particle cohesion and correlates well with the FF.
- The GBN model predicted the flow behavior of powders at particular particle size with SEP of 0.05 for HRW and SRW wheat powders.
- The GBN model was extended to multi-component mixtures (powder with different particle sizes) and was successfully predicted the FF.
- Anticipated applications include:
  - Corrective actions to increase or decrease sieving time
  - Change in sifter settings

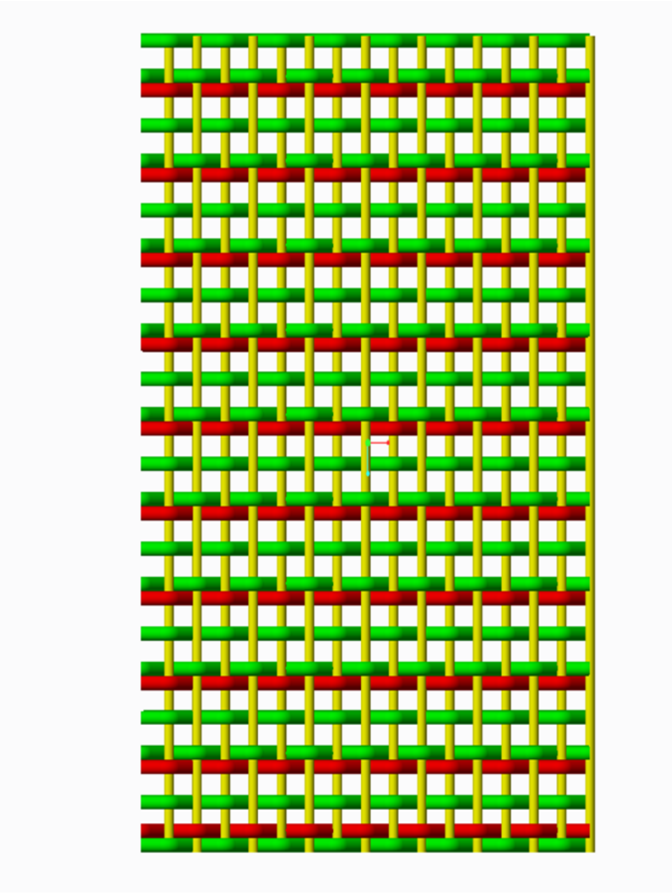
DEM Modeling of Sieving Process

- **Development of discrete element method (DEM) model for sifting flour**
  - Numerical modeling technique.
  - Based on principles of Newton's second law of motion and force-displacement laws.
  - Particles representing material in behavior and characteristics are created based on the physical and mechanical properties.
  - Model follows motion and interactions of each particle and predicts their motion.

Model Development



Sieve stack geometry



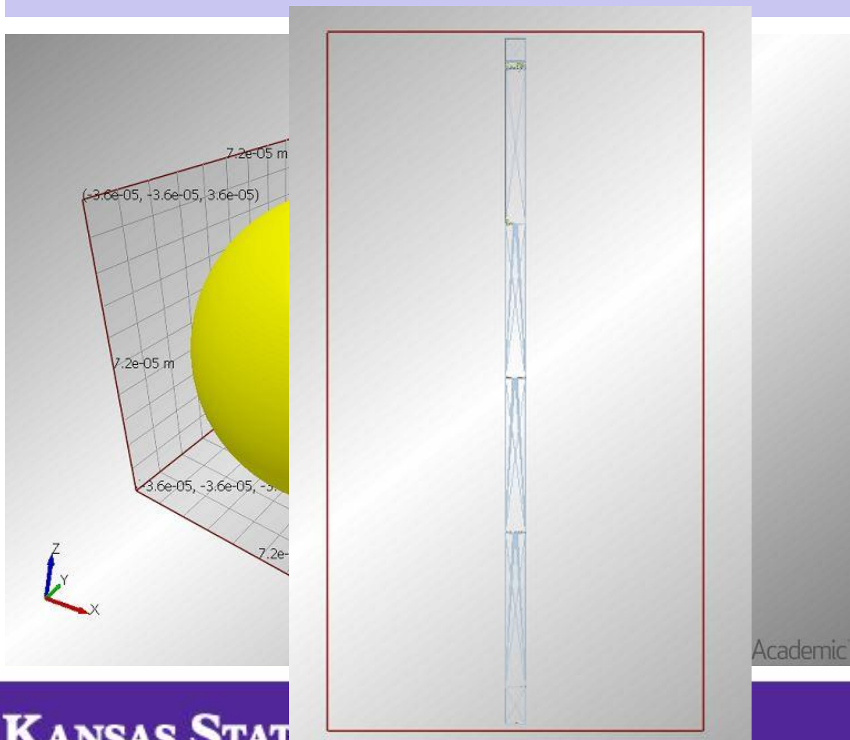
View of screen

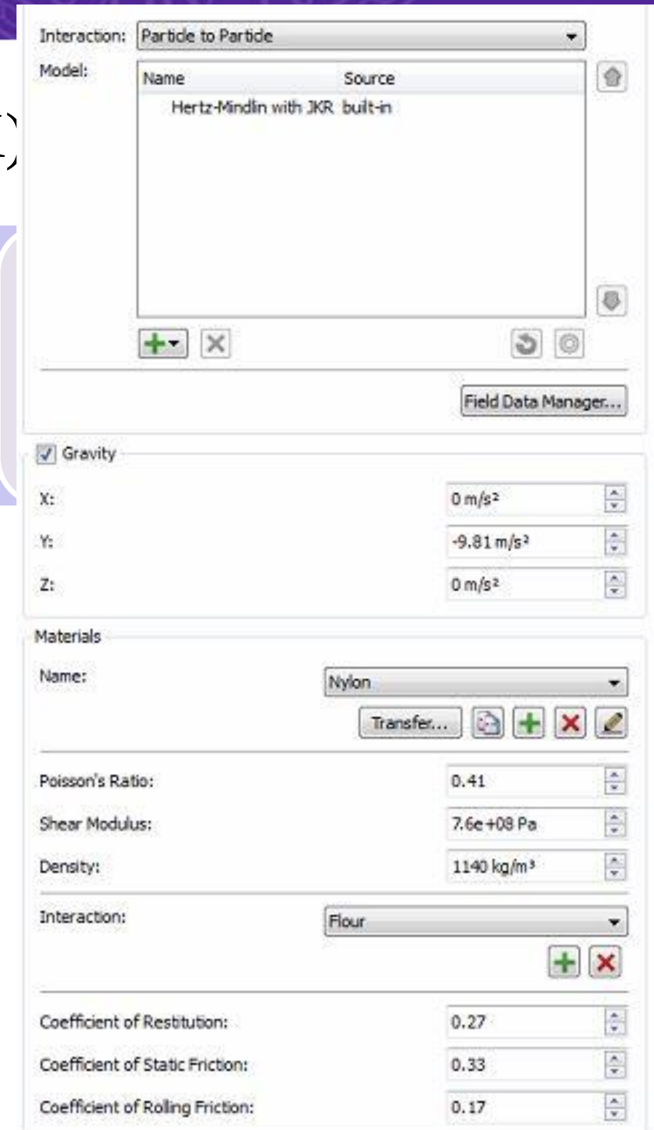
EDEM 2.6 (DEM Solutions, Edinburgh, UK)

Create Particles

Create & Import Geometry

Define Interactions





- Defining particle cohesion
  - Hertz-Mindlin with Johnson-Kendall-Roberts Model
  - $f_{JKR} = -4\sqrt{\pi\gamma E^*}\, a^{\frac{3}{2}} + \frac{4E^*}{3R^*}\, a^3$
  - $\delta = \frac{a^2}{R^*} - \sqrt{4\pi\gamma a / E^*}$
  - $P_{JKR} = -\frac{3}{2}\,\pi\gamma R^*$

Where, δ – normal overlap
γ – surface energy
f_{JKR}- cohesion force
E^*- equivalent Young's modulus
a – contact radius
P_{JKR}- pull-off force
R^*- equivalent radius

- Measure of accuracy of prediction

$$\text{SEP} = \sqrt{\frac{\sum(\text{Y}-\text{Y}')^2}{\text{N}}}$$

Where, SEP – standard error of prediction
Y – experimental value
Y′ - predicted value
N – number of observations

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Parameters used in model development and validation

Parameter	Model	Validation
Sieve cloth	Poly amide	√
Weaving pattern	XX	√
Sieve height, mm	25.4	√
Sieve area*, mm^2	11.22	11.22×10^4
Quantity of flour used , gm	0.01	100
Motion of the sieve stack	Circulatory, with diameter of 10.5 cm	√
Frequency of the sieve stack, rpm	180	√
Time interval for flour collection	5, 10, 15, and 20 sec	√

$Q \alpha A$

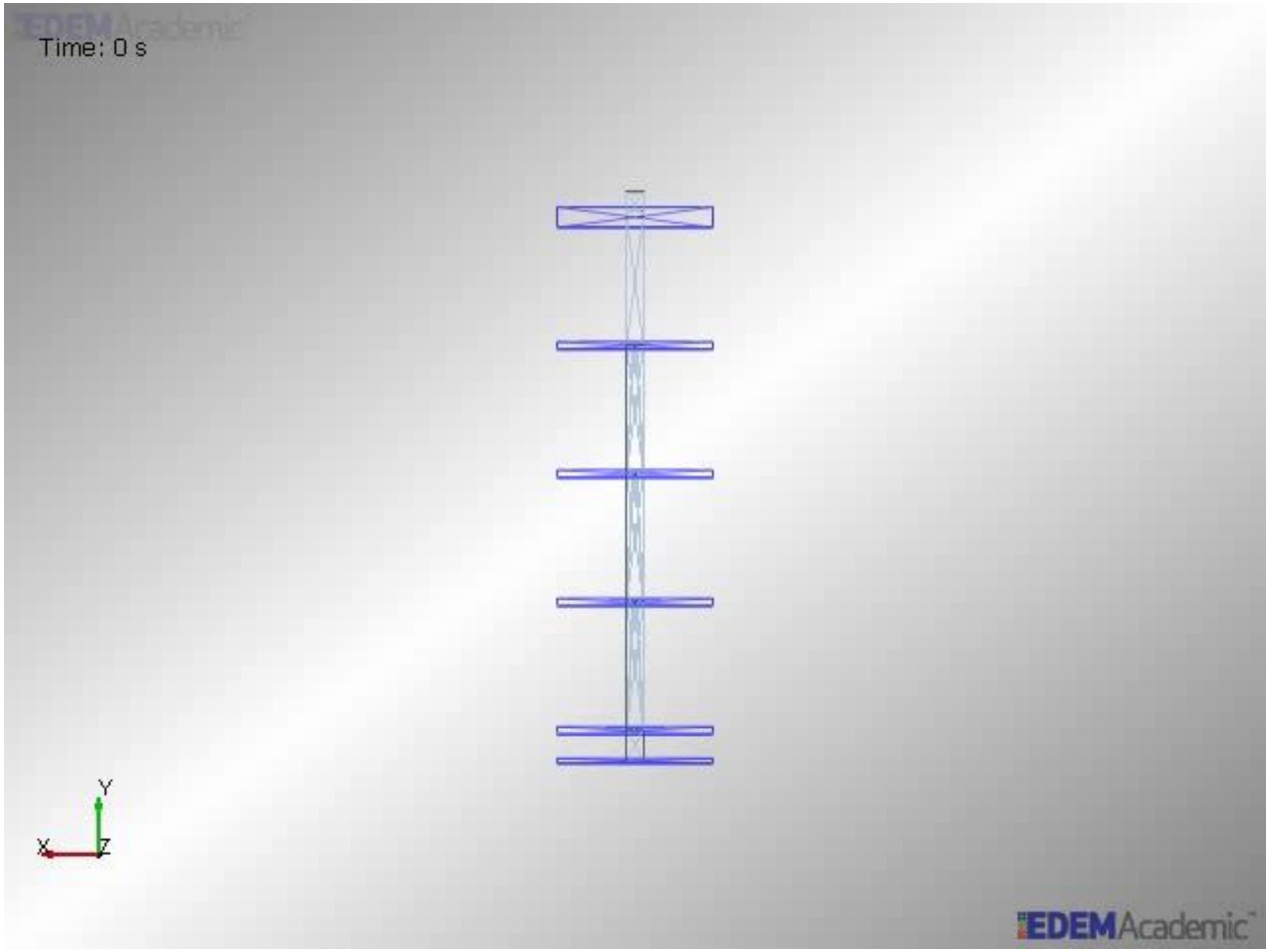
(Source: Prof Zworykin, Russian miller, 1911)

Model input parameters

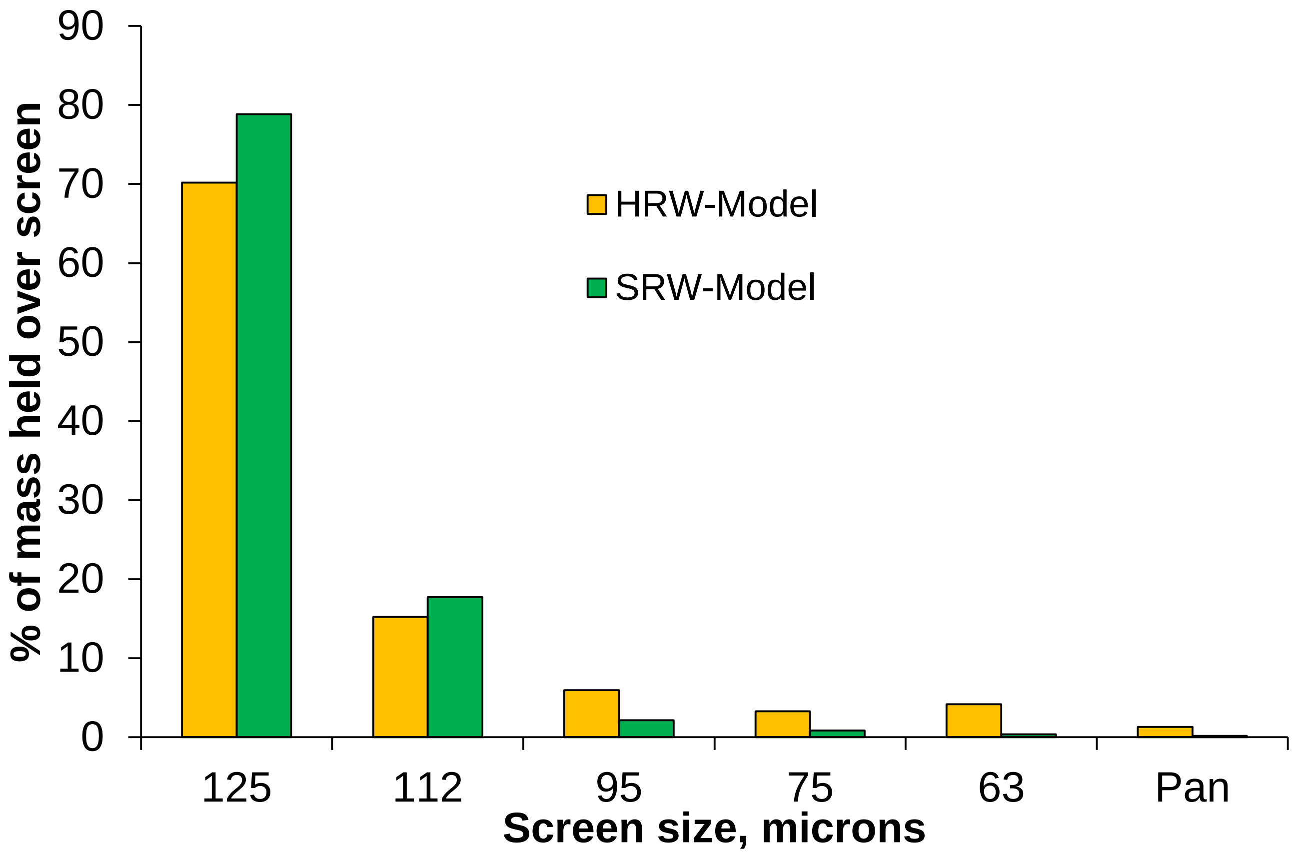
MC, (%wb)	*Mean Particle radius (µm)*	*Density (kg/m³)*	*Poisson's ratio**	*Shear modulus MPa*[×]	*Surface energy (mJ/m²)*	*Coefficient of static friction*[a]	*Coefficient of rolling friction*[a]
HRW							
10	72	1485	0.2	76.5	0.33	0.43	0.50
14	78	1473	0.2	76.5	0.32	0.43	0.55
SRW							
12	47	1491	0.2	76.5	0.27	0.44	0.39
Sieve cloth, PA							
		1140	0.41	760			

[a] Values from Patwa et al. (2015); *Weigler et al., (2012); [×]Markasaus et al., (2012)

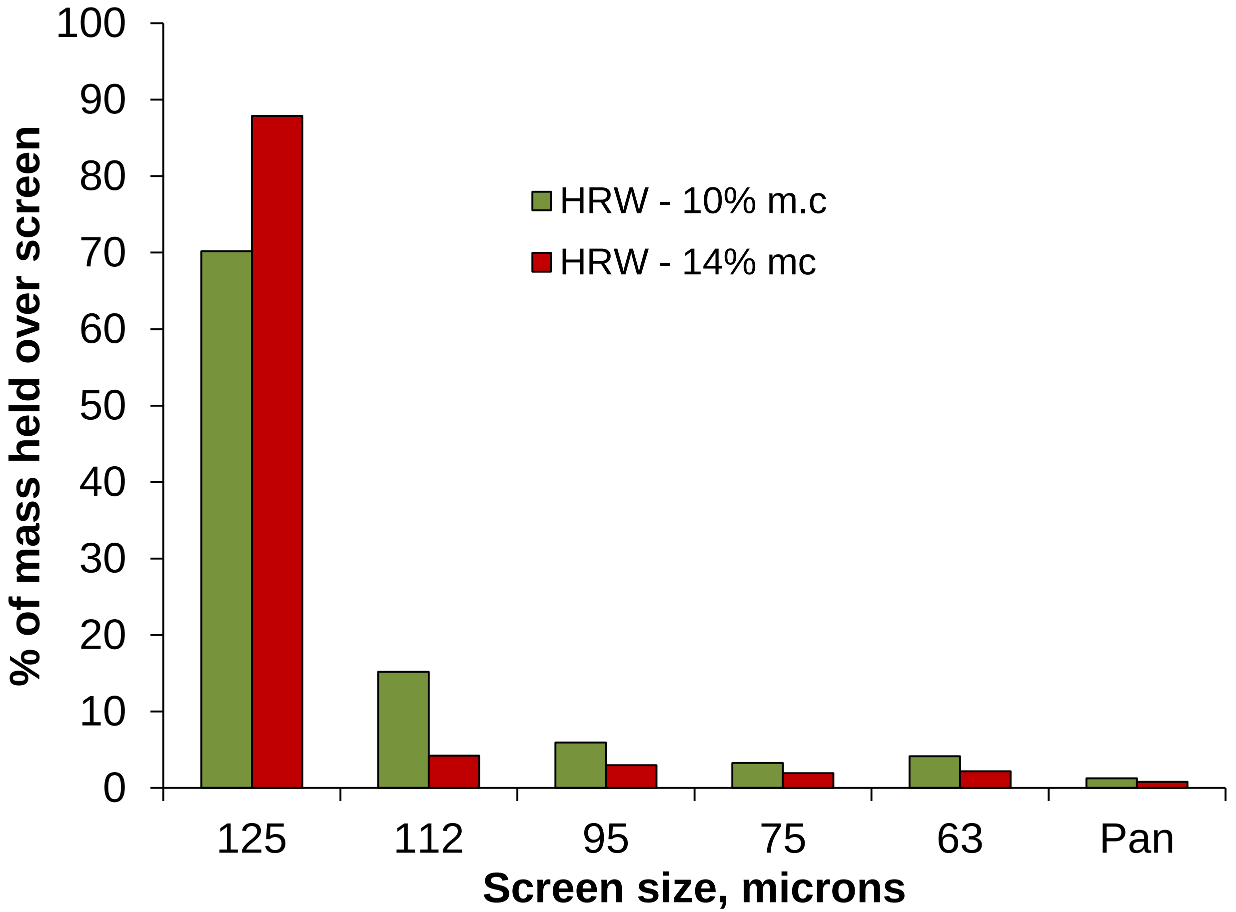

Time: 0 s
Y
X
Z
EDEM


Time: 0 s
Y
X
Z
EDEMAcademic

Results



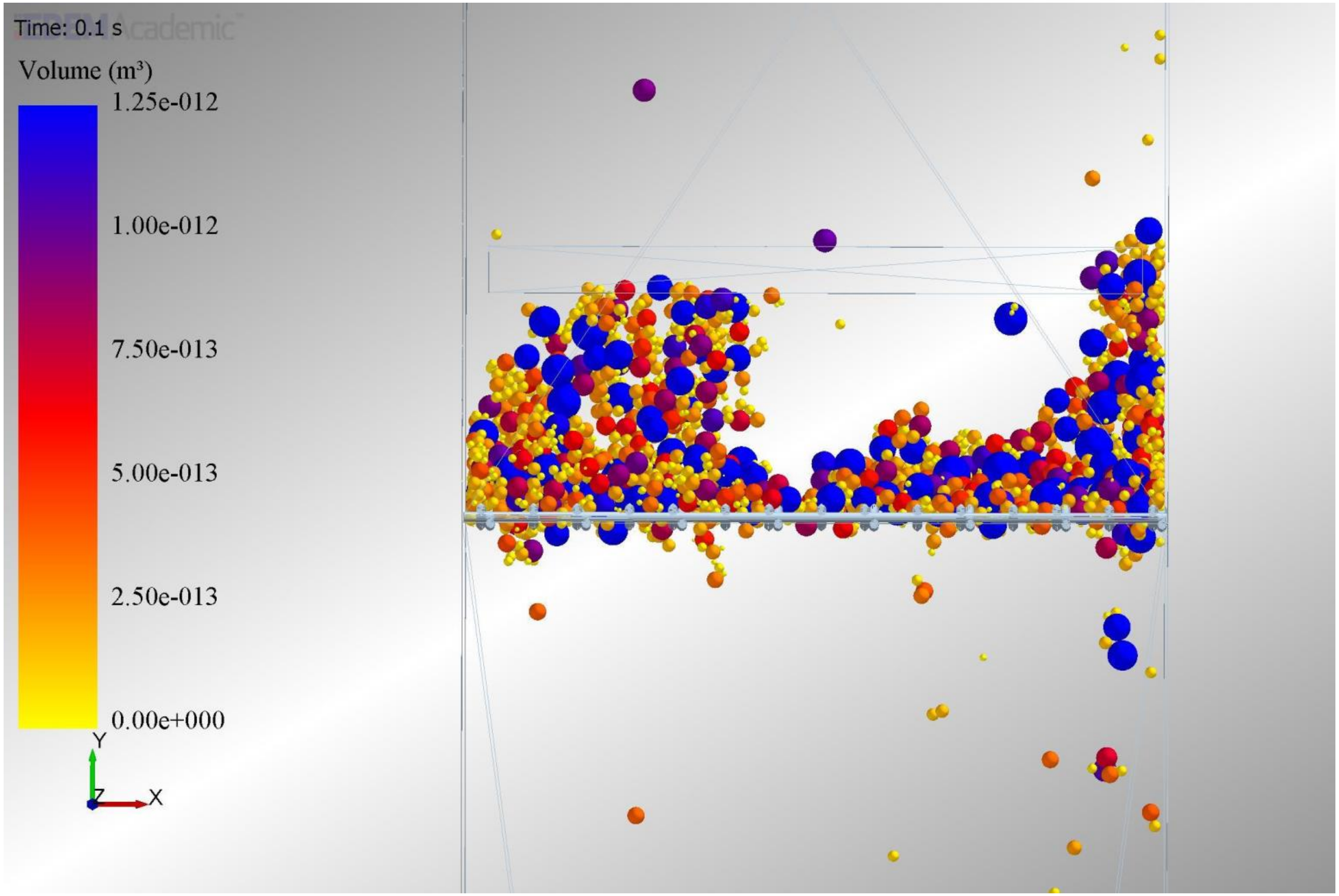
Simulation Results - HRW Vs SRW @ 10% m.c at 20 sec



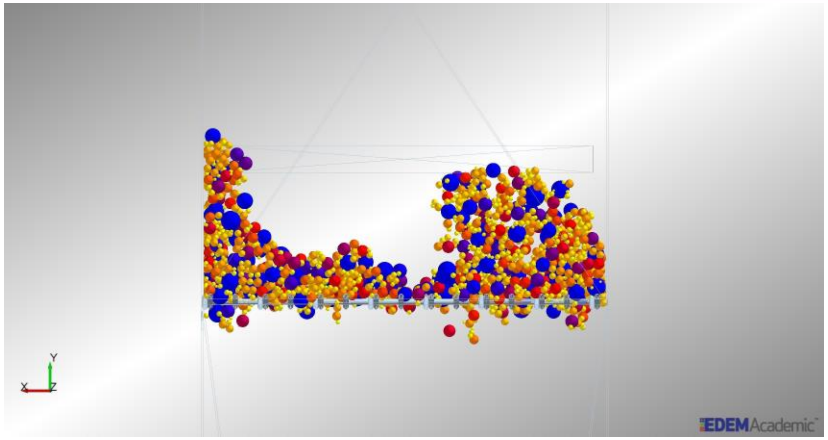
Simulation Results - HRW 10% m.c Vs 14% m.c at 20 sec

Particle size distribution of HRW at 10% m.c.

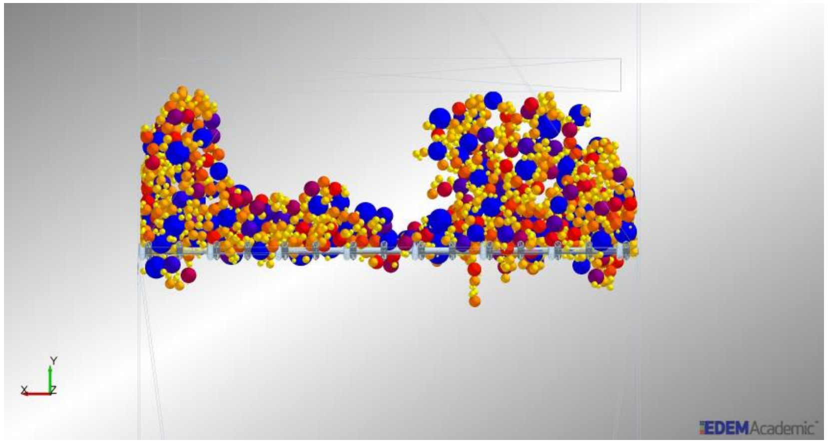
	Sieving Time								
Screen	At 5 S		At 10 S		At 15 S		At 20 S		SEP
microns	MOD	EXP	MOD	EXP	MOD	EXP	MOD	EXP	
125	78.38	84.70 (0.62)	74.21	78.45 (0.29)	70.19	76.37 (0.12)	70.19	75.88 (0.02)	9.27
112	7.49	10.59 (0.70)	11.26	13.08 (0.18)	15.21	12.77 (0.06)	15.19	10.93 ((0.24)	3.65
95	5.87	3.19 (0.06)	6.00	4.50 (0.45)	5.92	4.65 (0.01)	5.94	5.74 (0.13)	1.68
75	3.16	0.93 (0.02)	3.27	2.04 (0.13)	3.29	2.91 (0.04)	3.26	3.02 (0.08)	1.29
63	3.92	0.45 (0.07)	4.03	1.55 (0.36)	4.14	1.95 (0.08)	4.16	3.04 (0.16)	2.48
Pan	1.16	0.15 (0.07)	1.23	0.40 (0.12)	1.26	1.36 (0.18)	1.26	1.40 (0.11)	0.67



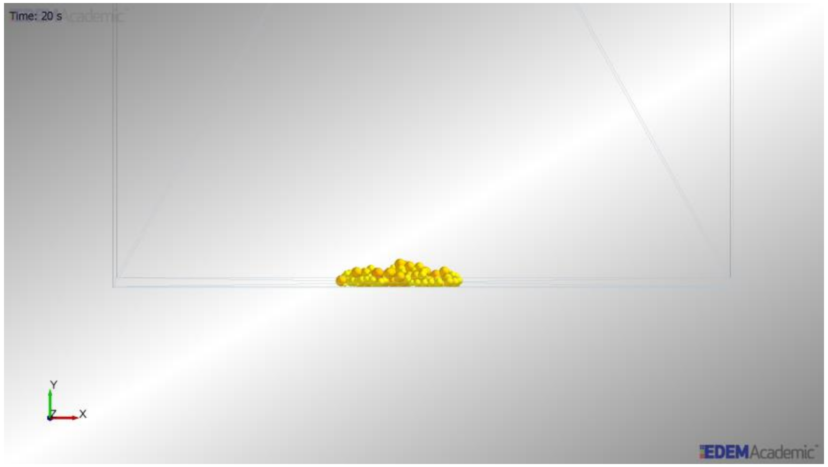
Segregation of HRW flour at 10% m.c at t = 0.1 sec



At time t = 0.2 sec



At time t = 5 sec

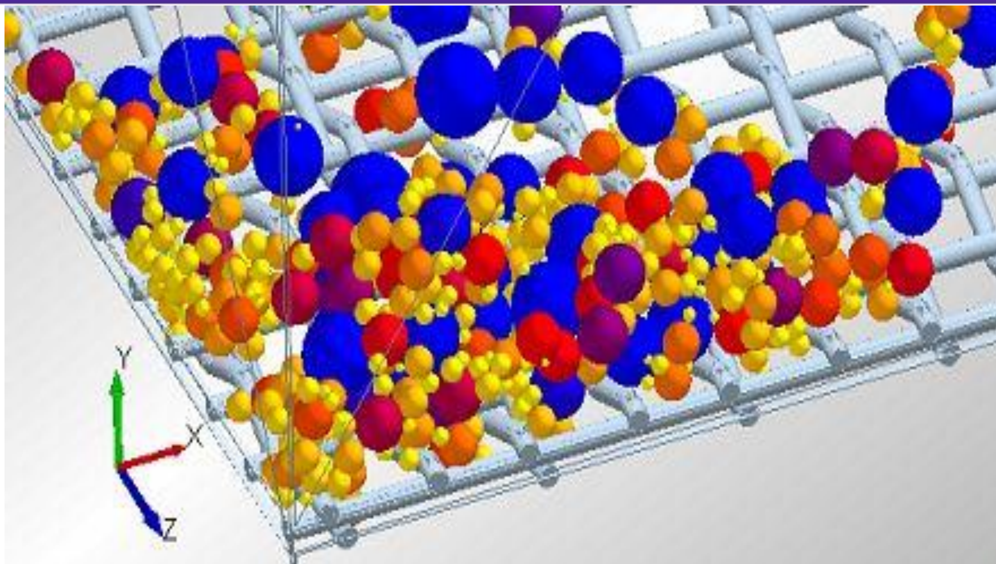


Collection pan

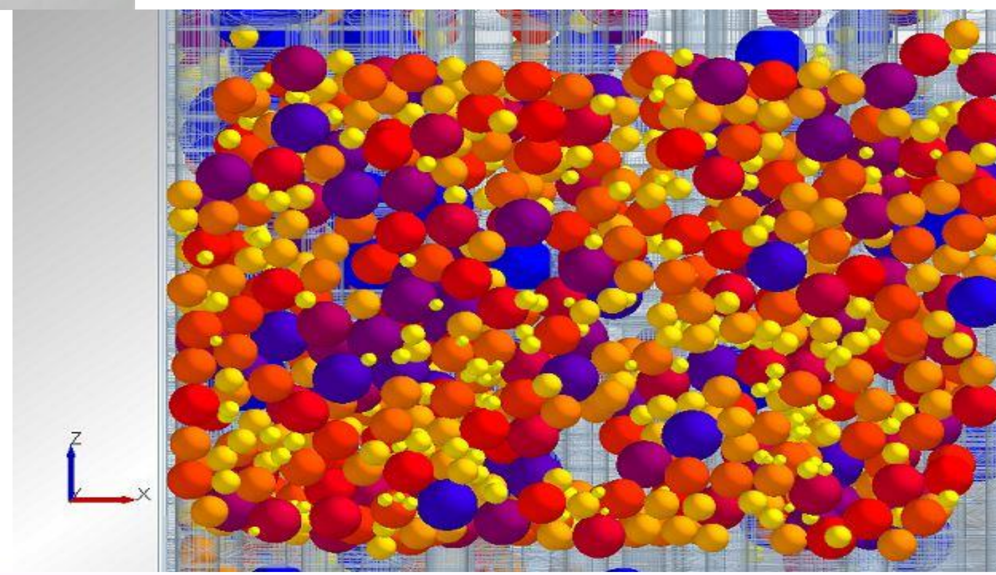
Measure of Accuracy Model (SEP)

Screen, microns	*HRW at 10% m.c*	*HRW at 14% m.c*	*SRW at 10% m.c*
125	9.27	3.55	4.61
112	3.65	5.75	5.28
95	1.68	2.22	0.59
75	1.29	1.85	0.37
63	2.48	1.97	0.34
Pan	0.67	0.75	0.13

Sieve Blinding or Agglomeration			
Time	15 sec to 20 sec	10 sec to 15 sec	10 sec to 15 sec
Mass retained		12% > HRW at 10% m.c	8% > HRW at 10% m.c



Sieve blinding over 125 µm screen



DEM Modeling: Conclusions

- The developed model is helpful in predicting the **particle size distribution** on each sieve.
- Prediction of sieve blinding time:
  - HRW @ 10% m.c – 15.25 s
  - HRW @ 14% m.c – 10.50 s
  - SRW @ 10% m.c – 10.25 s
- Mass retained over 125µm sieve
  - For HRW 14% mc is 12% > HRW at 10% m.c
  - For SRW 10% mc is 8% > HRW at 10% m.c
- Based on the predicted sieve blinding times **corrective actions** like:
  - Modification of sieving time can be done

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