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Keywords

experimental, flow, conveyor, particle, rock, box, investigation, simulated

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An Experimental and Simulated Investigation of Particle Flow through a Conveyor Rock Box

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The use of rock boxes within conveyor transfers is not new, however, there is little published in the literature to aid in the design and implementation of rock boxes; instead mainly relying on prior knowledge and rules-of-thumb. A benefit of a rock box over other transfer types (e.g. soft loading chutes and impact plates) is their ability to capture material in such a way that it is only the initial feed of material which contacts chute walls or liners, with build-up of material creating a dominance of particle-particle interactions, thus reducing wear of the system and hence cost.

This paper presents the preliminary results from an experimental rock box test program using polyethylene pellets, conducted on the variable geometry conveyor transfer research facility at the University of Wollongong. The position of the rock box, along with the belt speed and feed rate of material were varied to obtain a range of visual as well as quantifiable data.

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Initial minor discrepancies between the experimental and simulated results were investigated via input parameter adjustment to determine the root cause of the variations. The final comparisons still show some variation, however, investigations are ongoing.

1. Introduction

In recent years an increased emphasis has been placed on the design verification of conveyor transfers, whether that be soft loading hood and spoon transfers, impact plates, rock boxes (single ledge or multiple ledge, e.g. WEBA chutes) or a combination of these. Two dimensional analytical models exist in the literature for the design of hood and spoons [1-3] and impact plates [4], but currently there is little information available in the literature to aid in the design of rock boxes for implementation in conveyor transfers. As a result, the general shape of a rock box is used (or manipulated) to fit within the constraints of a particular system and historically has been based on a rule-of-thumb approach and/or prior knowledge.

The main purpose of a rock box is to; capture the incoming product stream, partially fill with material to create particle/particle interactions rather than particle/wall interactions and direct material to the next stage of the conveying process. The benefit of reduced particle/wall interactions is to minimise the amount of wear occurring on the walls of the transfer.

The research presented in this paper investigates the experimental characteristics of the particle/bulk flow of polyethylene pellets through a conveyor transfer utilising a single ledge rock box to capture the product stream discharging from a belt conveyor and directing the stream onto an inclined chute for delivery onto a receiving conveyor. A range of belt speeds and product flow rates have been tested to provide comparisons and generate potential trends to aid in design. Further to this, discrete element simulations of the experimental test facility have been conducted to replicate the real behaviour of the flow stream through the conveyor rock box. Some variation between the methods was observed which will be explained in the following sections and conclusions drawn on the research presented.

2. Conveyor Test Facility

The conveyor transfer research facility, shown in Figure 1(a), was designed to incorporate a variable geometry conveyor transfer to allow testing of soft loading hood and spoons, impact plates and most recently rock boxes. The test rig comprises three 300 mm wide Aerobelt conveyors arranged in a recirculating layout to allow a maintained steady-state conveying condition using a finite quantity of material. The conveyor feeding the variable geometry transfer is inclined at 5º utilising a smooth belt while the other two conveyors are inclined at 23º and utilise a half-crescent cleated belt. The conveyors are individually controlled by VSDs and can obtain a maximum belt speed of 7 m/s, although 5 m/s is generally used as an upper limit due to vibrational effects. Other than the variable geometry transfer, several other chutes are utilised to direct product from one conveyor to the next, allowing continuous material recirculation. The current rock box transfer is shown in Figure 1(b) and allows movement of the upper frame along the receiving conveyor (to allow for ‘correct’ capture of the product stream at different belt speeds) and also allows 40 mm incremental vertical positioning of the rock box within the upper frame to allow investigation of varying impact angles as the product stream enters the rock box.

(a)

(b)

Figure 1 (a) Variable geometry conveyor transfer research facility and (b) conveyor transfer showing rock box and inclined chute

The product used for the comparisons was polyethylene pellets, chosen due to its relatively sphero-cylindrical granular shape, robustness and ease of simulation. The pertinent particle/bulk properties of the polyethylene pellets are listed below in Table 1.

Table 1 Particle and bulk properties of polyethylene pellets

Equivalent volume diameter (50 particle average)	4.65 mm
Particle density	919 kg/m^3
Loose-poured bulk density	515 kg/m^3

3. Experimental Rock Box Testing

To ensure a direct comparison between the experimental and DEM simulation results, a common coordinate system was used, where the centre of the head pulley of the feed conveyor was defined as the origin and the bottom left-most point of the rock box was used as the coordinate reference point. As previously stated, the product stream enters the rock box and builds up before discharging to the next stage of the conveying process. What is unclear is the best positioning of the rock box with respect to the incoming product stream. To investigate this aspect, three impact positions were trialled, impact with; the bottom corner, 100 mm up and 100 mm forward, as highlighted in Figure 2. This allowed the variation in the formation of the pile of stationary material within the rock box and the subsequent flow of material from the rock box to be observed and analysed. Belt speeds of 2 m/s and 3 m/s were used in the testing and the overall positioning of the rock box for the six varied positions are shown in Table 2.

A Phantom V611 high speed digital video camera was used to capture the steady-state product flow into and out of the rock box for each impact position and belt speed tested. The camera was positioned perpendicular to the side wall of the rock box to ensure accurate measurements could be taken. An analysis of the product flow was then performed using Image Pro Plus analysis software, where velocity measurements of individual particles within the flow stream were analysed to obtain velocity trends for the rock box. These velocity trends and comparisons are shown in Section 5. One important point to remember is that the product stream is three dimensional and the camera views from the size and as a result, there is no depth perception with respect to the position of the particles. It has been assumed that there is no change in velocity across the stream for the purposes of this analysis. Additionally, any particles which had obviously deviated away from the main flow stream were omitted from the analysis. It should also be noted that parallax error is an issue which needs to be carefully considered when performing this sort of analysis. As is evident in Figure 2, there is a degree of parallax present, identified by the fact the rock box side wall furthest from the camera is visibly smaller than the sidewall in the foreground. In the case of the velocity analysis this did not pose any issues, however, for the determination of the material profile, it does create inaccuracies. To overcome this problem, a separate set of still images were captured using a digital SLR camera which was set up approximately 5 m from the rock box, which dramatically minimised the level of parallax.

The still images were also used to determine several angular measurements for each of the experimental test positions. Figure 3 shows an arbitrary steady-state flow condition for a rock box test and the four angles used for comparative purposes. θ_1 is the angle of the incoming stream, θ_2 is the angle of the outgoing stream, θ_3 is the 'dynamic' angle of repose during the steady-state filling period and β_1 is the fan angle (angle of spread of the outgoing product stream). Image Pro Plus was again used to determine these angular values and subsequent graphs of the trends were produced, which are shown in Section 5.

4. Discrete Element Modelling of Flow through a Rock Box

4.1 DEM Calibration of the Test Product

To accurately simulate polyethylene pellets in the DEM software, a series of bench-scale tests were completed to determine; particle size, particle density, loose-poured bulk density, the coefficient of restitution and the coefficient of static friction. Additionally, the shear modulus, Poisson's ratio and the coefficient of rolling friction are required as DEM inputs, however, these values are difficult to determine experimentally. The first two of these parameters have previously been investigated in a sensitivity analysis [5, 6] and it was found that there was little difference in analysed simulation results for a range of values, however, a benefit of reducing the value of the shear modulus was that a reduction in simulation time could be achieved, as the parameter directly influences the Rayleigh time step [7].

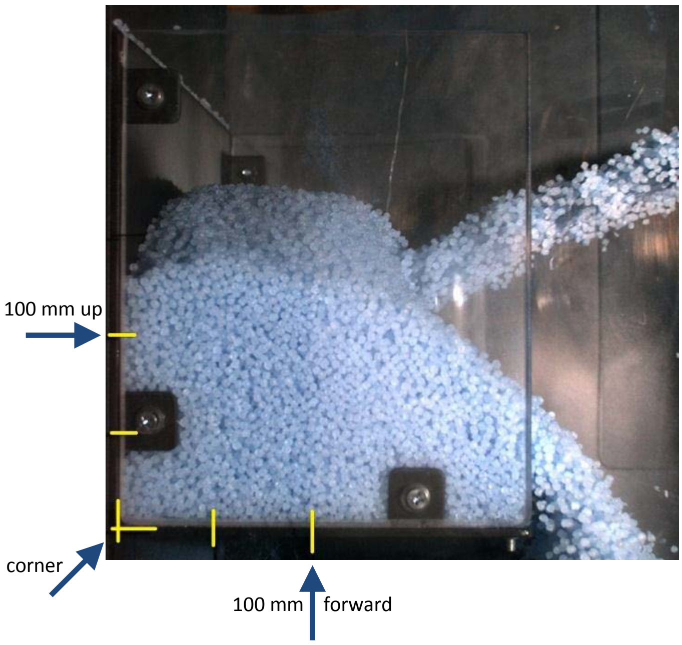


Figure 2 Impact locations investigated within the rock box

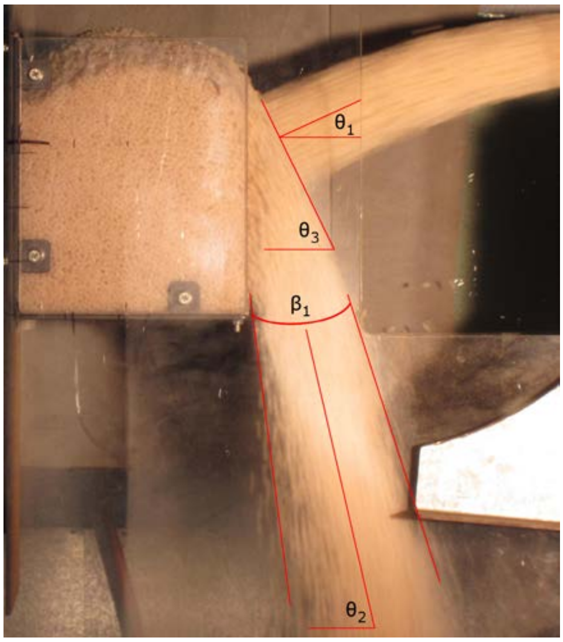


Figure 3 Identification of the angles used for analysis

Table 2 Position coordinates of the rock box

Position	x-coordinate (mm)*	y-coordinate (mm)*
2 m/s, corner	537	-190
2 m/s, 100 mm up	466	-221
2 m/s, 100 mm forward	605	-160
3 m/s, corner	718	-111
3 m/s, 100 mm up	636	-147
3 m/s, 100 mm forward	770	-88

* Positive x direction is to the left and positive y direction is up

The coefficient of rolling friction is difficult to measure because most bulk solids are not spherical and the question arises, should the coefficient of rolling friction be investigated for a single particle or the bulk as a whole? To obtain a representative value, a series of calibrated DEM simulations were performed by altering the coefficient of rolling friction in a series of simulations while leaving all other parameters constant. This produced a set of simulation results which could be compared to identical small scale experimental tests and the parameters for the DEM simulation which matched the experimental results were then used for the full-scale DEM simulations. A summary of the parameters used for the DEM simulations is provided in Table 3 along with those already presented in Table 1.

Table 3 Particle/bulk properties of polyethylene pellets

Coefficient of restitution, polyethylene / polyethylene	0.619
Coefficient of restitution, polyethylene / acrylic	0.649
Coefficient of restitution, polyethylene / mild steel	0.716
Coefficient of static friction, polyethylene / polyethylene	0.287
Coefficient of static friction, polyethylene / acrylic	0.277
Coefficient of static friction, polyethylene / mild steel	0.208
Shear modulus	1.17×10^{8} *
Poisson's ratio	0.45 *
Coefficient of rolling friction, polyethylene / polyethylene	0.123
Coefficient of rolling friction, polyethylene / acrylic	0.158
Coefficient of rolling friction, polyethylene / mild steel	0.158

* Hastie [5]

4.2 DEM Simulation

The polyethylene pellets are relatively mono-sized and have a sphero-cylindrical shape as a result of their manufacturing process. DEM modelling of particles should be as realistic as possible to ensure the accuracy of the result, which is achieved by clustering spheres. In the case of polyethylene pellets, two spheres have been used, as shown in Figure 4, with the dimensions defined based on the averaged measurement of the length and diameter of a 50 randomly sampled particles.

System geometries can either be created within the DEM package if they are simple designs, otherwise they can be created with a CAD package and imported. For this research the conveyor rig and rock box have been imported from a CAD model, as shown in Figure 5. The model has been accurately constructed from the experimental test rig to ensure accurate comparisons can be made with the experimental results obtained.

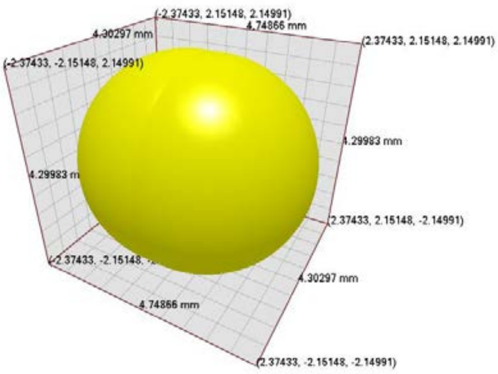


Figure 4 DEM 2-sphere cluster representing polyethylene pellets

Figure 5 CAD model of conveyor rig imported into EDEM

Simulations were set up to replicate the belt speeds of 2 m/s and 3 m/s and the six rock box positions tested experimentally. The simulated product feed rates are identical to those used in the experimental testing to provide direct comparison to the experimental test results.

The DEM simulations were performed until steady-state conveying had been achieved, ensuring no transient behaviour of the incoming or outgoing flow stream was observed in the rock box and thus no changes to the profile of the material building up within the rock box were detected. At this point, three-dimensional bins were created in the post-processing of the DEM simulation to allow for the specific extraction of data contained only in these bins. These bins were positioned to have a very narrow width (30 mm) and were located along the longitudinal axis to capture the particle velocities in the centre of the flow stream. The incoming and outgoing particle velocities were extracted in the x, y and z directions and the resultant velocity determined for each.

Still images of the simulation were captured for each simulated test and used to determine the same four angles as described for the experimental testing, θ_1, θ_2, θ_3 and β_1. These still images were also used to produce the profile of the material building up in the rock box.

5. Comparison of Experimental and DEM Simulated Particle Flow

The velocity analyses from both the experimental and DEM simulations have been compiled and are presented in Figure 6 for the 2 m/s belt speed tests. It should be noted that the outgoing velocity for the 2 m/s 100 mm up tests are missing due to obstruction by the conveyor frame. There are similarities between the two sets of data but it is also evident that there is more spread of velocity for the incoming experimental data than there is for the velocities from the DEM simulations. There are minor differences to the outgoing velocities also but both show the same increasing velocity as the product feed rate increases. The most likely cause of these variations is due to the particles analysed from the experimental results being at the lateral edges of the flow stream, whereas the velocities extracted from the DEM simulations are via the bins located on the longitudinal axis.

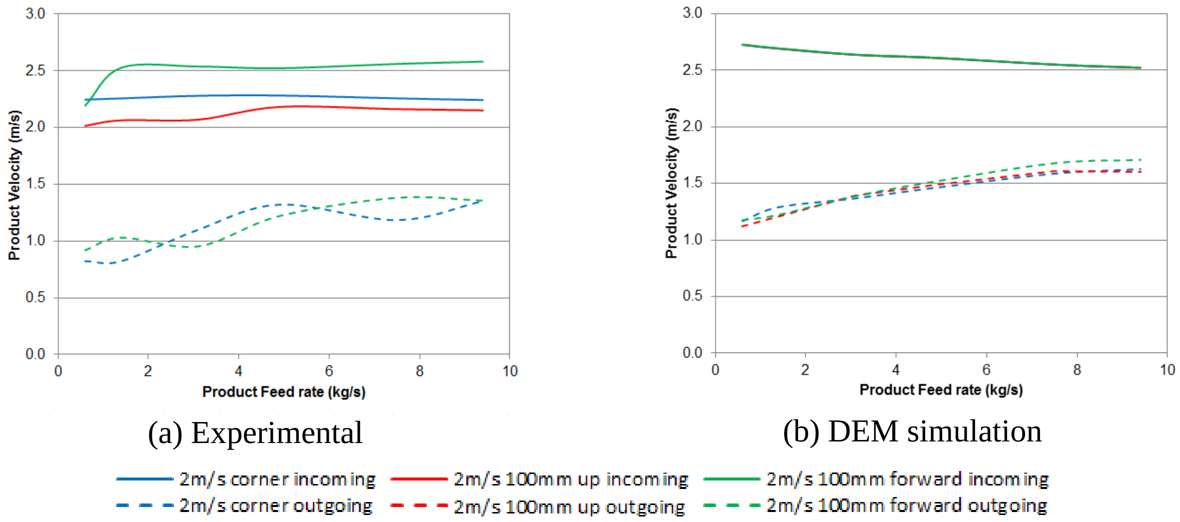


Figure 6 The analysed incoming and outgoing velocities from the rock box for a belt speed of 2 m/s

The experimental and simulated velocity results for the 3 m/s belt speed show a noticeable variation for the incoming flow stream, as seen in Figure 7. Extensive checks were made to ensure no experimental error was the cause, however, it was found that no obvious issues were causing the variation. In light of this, it is assumed that the variation is due to similar reasoning as that of the 2 m/s velocity variations. The outgoing velocity showed a very good comparison, although there is some fluctuation to the experimental results which is not evident in the DEM simulation results.

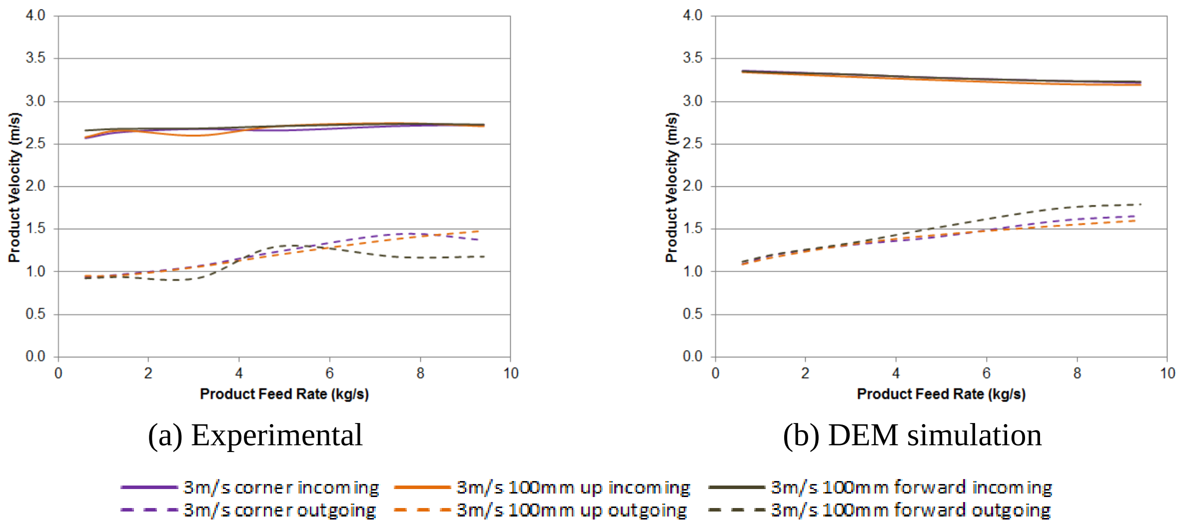


Figure 7 The analysed incoming and outgoing velocities from the rock box for a belt speed of 3 m/s

The angular measurement comparisons are presented in Figure 8 and Figure 9 and it can be seen in Figure 8 that there is very good agreement to the incoming and outgoing stream angles. The fan angles show a good agreement in Figure 9, however, there is slightly more scatter evident from the ‘dynamic’ angle of repose comparisons. The DEM simulation results generally show an overall good agreement to the trends observed experimentally, however, the dynamic angle of repose results for DEM are slightly lower than the experimental equivalents. There is one exception, the DEM simulation of the 2 m/s belt speed impacting 100 mm up the rock box wall, where the angle of repose remains relatively constant regardless of product feed rate. The variation of the incoming stream angles for the two belt speeds is due to the differing profile of the conveyor trajectory for both belt speeds. As a result the angle of the stream entering the rock box is different.

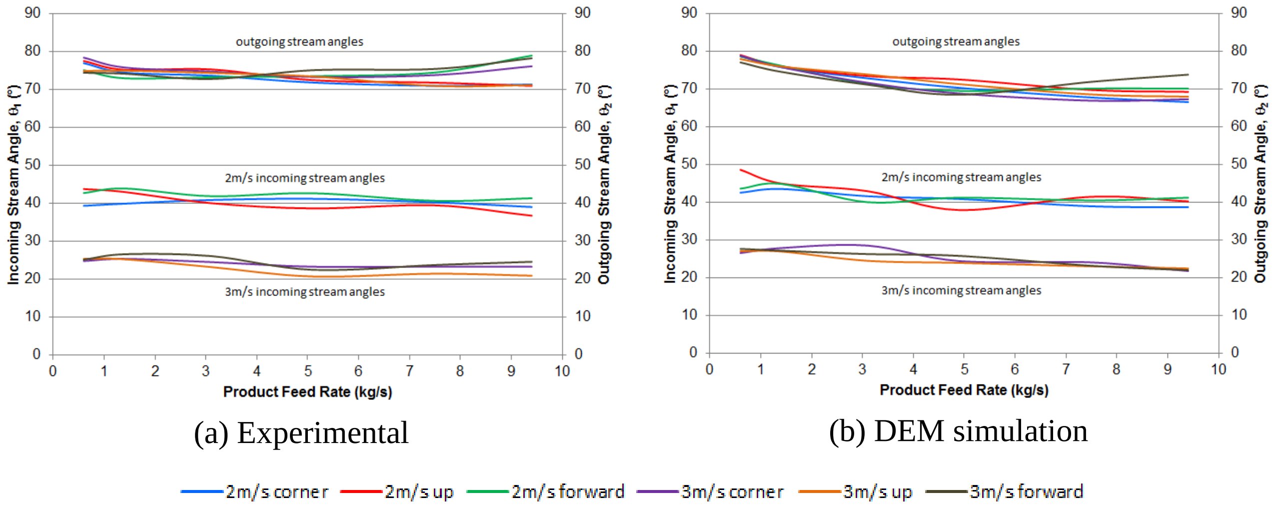


Figure 8 The incoming and outgoing material streams for the rock box

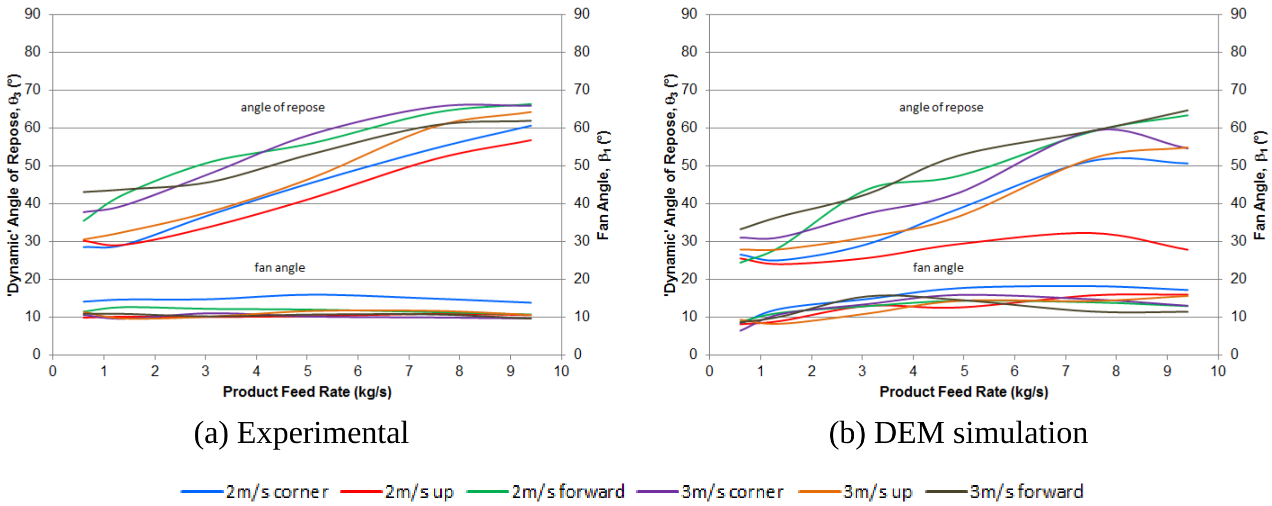
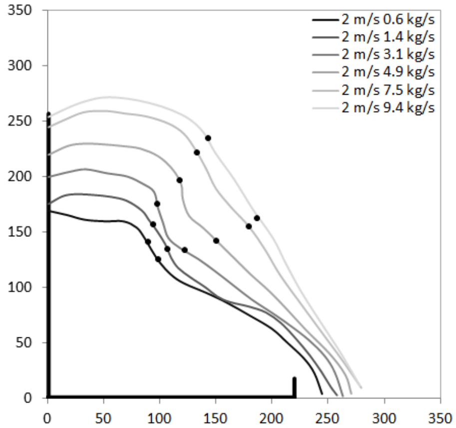


Figure 9 The 'dynamic' angle of repose and the fan angle measured in the rock box

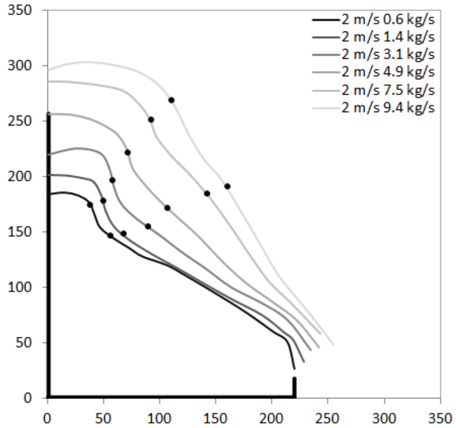
The still camera images from the experimental test work and the images taken from the DEM simulations were analysed to extract the profile of material build-up within the rock box for the full range of belt speeds and product flow rates tested. Particular care was taken to ensure the profiles represented the central longitudinal plane running through the belt conveyors and rock box. The results have been graphed in Figure 10 and Figure 11 and show the gradual build-up of material as the product feed rate increased. Also plotted are the locations of the upper and lower surfaces of the trajectory stream, which clearly show the thickening of the trajectory stream as the feed rate increased.

Comparing the experimental and DEM simulation profiles side by side shows some interesting results. For the 2 m/s belt speeds, there is a close agreement with the impact locations in the corner and 100 mm forward of the corner although the experimental results shown a slightly higher build-up in both cases. The 2 m/s impact 100 mm up from the corner shows a more noticeable difference, with a higher build-up of material for the experimental results and a different profile in the area where the angle of repose develops.

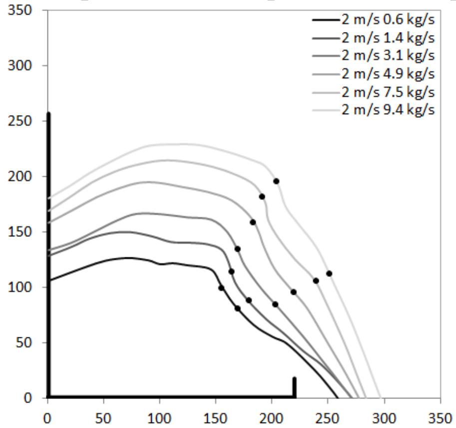
The results for the three impact zones for the 3 m/s belt speed cases all show a good agreement across the experimental and DEM simulation results, but like the 2 m/s belt speed cases, the build-up in the experimental tests is slightly higher than that predicted in the DEM simulations.



(a) Experimental, impact at corner

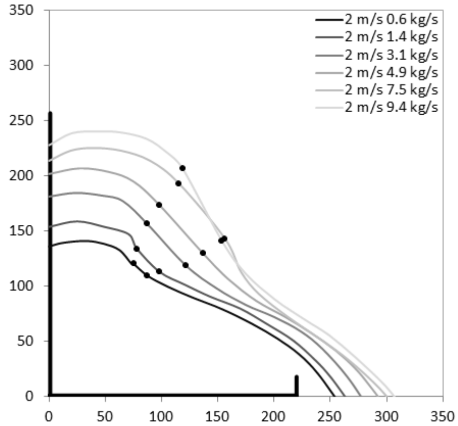


(b) Experimental, impact 100mm up

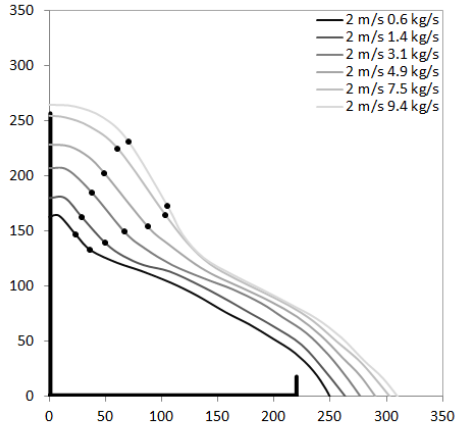


(c) Experimental, impact 100mm forward

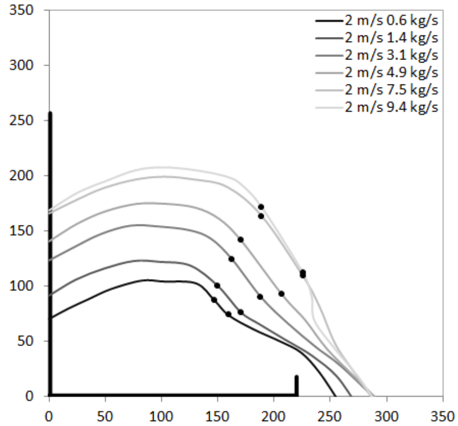
Figure 10 Experimental profiles of material filling the rock box for varying belt speeds and product flow rates (dimensions in millimetres)



(a) DEM, impact at corner



(b) DEM, impact 100mm up



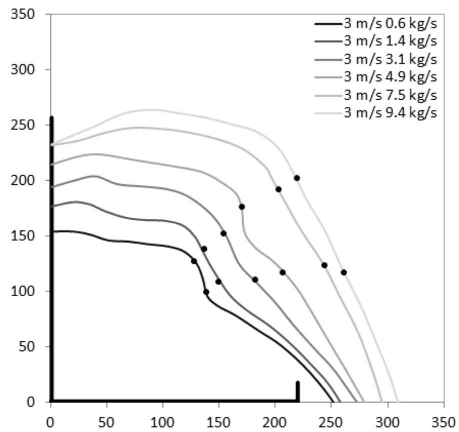
(c) DEM, impact 100mm forward

Figure 11 DEM simulated profiles of material filling the rock box for varying belt speeds and product flow rates (dimensions in millimetres)

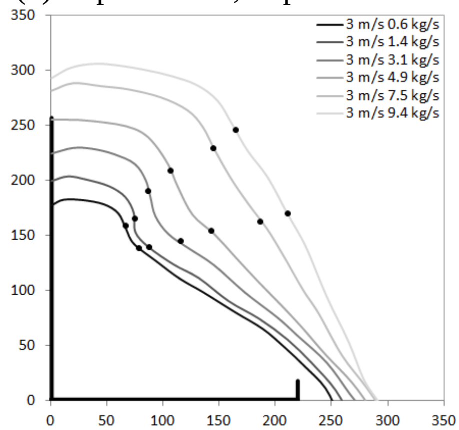
Another point of note is the location of the trajectory impact points for the DEM simulations. The results vary slightly to those observed from the experimental results, which could be due to a number of factors, such as;

(a) slight variations in the product feed from the experimental test rig, and

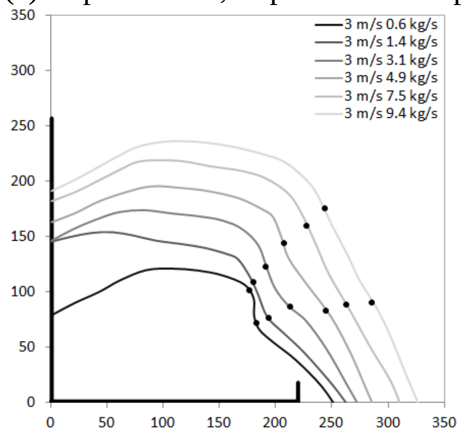
(b) the possible influence of the contact model used or the combination of static and rolling friction used not being completely applicable to every change to the flow mechanisms within the simulations.



(d) Experimental, impact at corner

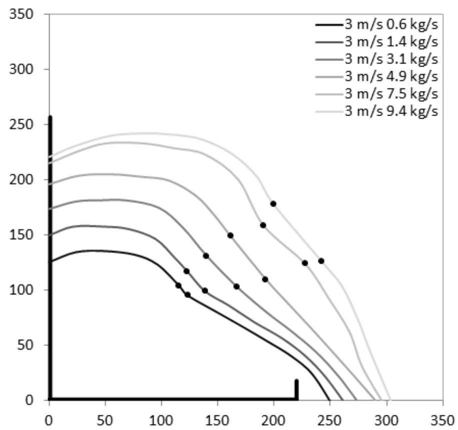


(e) Experimental, impact 100mm up

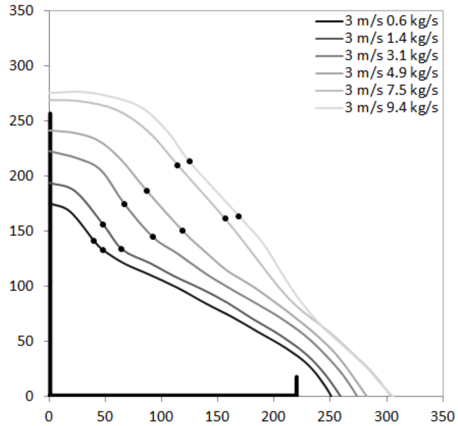


(f) Experimental, impact 100mm forward

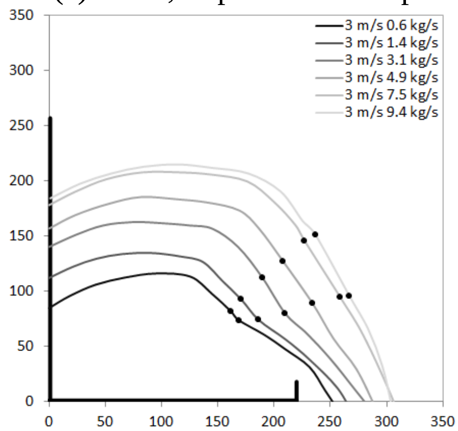
Figure 10 (continued) Experimental profiles of material filling the rock box for varying belt speeds and product flow rates (dimensions in millimetres)



(d) DEM, impact at corner



(e) DEM, impact 100mm up



(f) DEM, impact 100mm forward

Figure 11 (continued) DEM simulated profiles of material filling the rock box for varying belt speeds and product flow rates (dimensions in millimetres)

6. Conclusion

This paper has presented the results from a series of experimental tests and DEM simulations for the flow of polyethylene pellets through a conveyor transfer rock box, investigating the differences observed at two belt speeds and six product feed rates. Analysis has been conducted via high speed video footage, still images and DEM simulation outputs, which have been used to determine the velocity of the flow stream, key angular measurements and material profiles all under steady-state flow conditions.

The velocity trends for the 2 m/s and 3 m/s belt speeds are similar for both the experimental and DEM simulation results, however, one difference was identified for the incoming stream velocity for the 3 m/s belt speed case, where the experimental average velocities were noticeably lower. Further investigations are warranted to ascertain the cause of this variation as the most likely causes have been ruled out at this point (eg. incorrect belt speed, errors in analysis).

The comparisons of the incoming and outgoing stream angles, the ‘dynamic’ angle of repose and the fan angle showed an overall good agreement between the experimental and DEM simulation results. Minor variations were observed, but the overall result shows that the DEM simulations have been able to predict the experimental behaviour well.

The profile comparisons have shown that the DEM simulations have all slightly under-predicted the height of the material within the rock box, although the general trends match quite well. There are some likely reasons for this, such as slight variations in the experimental feed rate, the DEM material model not completely producing the correct particle/bulk behaviour throughout different sections of the simulation (vis. contact models and parameters used). These areas will be investigated further in the future to produce even better comparisons.

It is hoped that the findings from this research will start to fill the void which currently exists with respect to the design of conveyor transfer rock boxes. With little to no design criteria published in the literature a seemingly rule-of-thumb approach has been taken to date. It should also be highlighted that these initial findings are based on the collected data from one test material, polyethylene pellets, and for more conclusive results and trends to be formed, a wider range of test materials must be investigated and plans to do so are currently underway.

7. Acknowledgements

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