Application of simulation technologies in the analysis of granular material behaviour during transport and storage

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Abstract: Problems in the preservation of the quality of granular material products are complex and arise from a series of sources during transport and storage. In either designing a new plant or, more likely, analysing problems that give rise to product quality degradation in existing operations, practical measurement and simulation tools and technologies are required to support the process engineer. These technologies are required to help in both identifying the source of such problems and then designing them out. As part of a major research programme on quality in particulate manufacturing computational models have been developed for segregation in silos, degradation in pneumatic conveyors, and the development of caking during storage, which use where possible, micro-mechanical relationships to characterize the behaviour of granular materials. The objective of the work presented here is to demonstrate the use of these computational models of unit processes involved in the analysis of large-scale processes involving the handling of granular materials. This paper presents a set of simulations of a complete large-scale granular materials handling operation, involving the discharge of the materials from a silo, its transport through a dilute-phase pneumatic conveyor, and the material storage in a big bag under varying environmental temperature and humidity conditions. Conclusions are drawn on the capability of the computational models to represent key granular processes, including particle size segregation, degradation, and moisture migration caking.

Keywords: granular materials, continuum modelling, micro-mechanical parametrizations, segregation, degradation, caking

1 INTRODUCTION

One of the most common ways of transporting and storing materials is in granular form, especially in the mining, minerals, metallurgical, chemicals, food, and pharmaceutical industries. As such, a huge effort has been made over the last 40 years to understand the behaviour of granular materials. However, most of the research efforts have been targeted at the development of experimental procedures to characterize the behaviour of materials in a specific context, or to develop mathematical (and, less frequently, computational) models of aspects of the granular materials processing operations. Although there have been genuine advances in understanding and characterizing aspects of granular materials and their processing, such industrially based operations still frequently suffer from significant problems with respect to their operation involving both the consistency and control of the product.

Recently, the authors have worked for 5 years on a major academic–industry collaborative research programme, targeted at identifying and providing

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both experimental and modelling tools to support the challenge of optimising on quality in particulate based manufacturing. There are many outputs from the programme which have led to test equipment, software tools, structured design and test methodologies as well as a series of archival publications (see, for example, Christakis and co-workers [**1**–**6**] on the continuum modelling aspects that underwrite some of the software tools).

The research and development programme, quality in particulate manufacturing (QPM) was targeted at:

(1) characterizing the behaviour of granular materials during transport and storage, including the identification of the key industrial operational processes to focus upon in analysing industrial operations;
(2) the development of discriminating experimental techniques and procedures for the characterization of granular materials during storage and transport;
(3) the development of computational models to analyse both component processes and complete industrial granular material systems.

The objective of this programme was to build as much as possible on the progress that had already been achieved by the international research community and to develop a suite of laboratory tests and computational models within an integrated process analysis procedure to enable the rational design and optimization of granular materials-based operations. The audit of industrial operations available to the QPM team showed that there were three key processes which characterized the behaviour of most granular materials: segregation in hoppers and bins, degradation during pipeline transport, and caking during storage. In industrial practice, the traditional solution to these problems is largely based on empiricism and engineering experience. As the customer demands ever tighter controls over production levels, cost, and product quality the traditional empirical methods begin to run out of steam—a more fundamental approach is required where engineers can characterize and predict with confidence how materials will behave in a specific context, and then ensure that new designs can optimize on both product rate and quality.

The development of such an approach was the objective of the QPM project. In this paper we provide an overview of the computational models that embed the knowledge we have acquired and illustrate their application in the analysis of an industrial-level operation, as a prelude to their utility in process optimization and equipment design. We believe such a scientifically based approach could have a significant impact on the granular materials industry.

2 OVERVIEW OF AN APPROACH TO THE CONTINUUM MODELLING OF THE BEHAVIOUR OF GRANULAR MATERIALS

In an earlier publication [**1**], a general continuum framework was presented for the description of flow and transport processes in granular materials, with a particular emphasis on the description of particle segregation, degradation, and caking phenomena. In the present paper, these models are applied to simulate a complete large-scale process of handling of granular materials, involving consecutively segregation effects during the discharge of a hopper, degradation due to impact of particles on pipe bends during dilute-phase pneumatic conveying, and moisture migration caking phenomena in storage. This work actually builds upon substantial efforts at modelling the individual unit processes which are described in detail elsewhere [**1**–**6**]. These publications review the existing research literature and place these contributions in their appropriate context; the reader is referred to this body of work for a more considered description of the models utilized in the work reported here. The objective of this section is merely to provide an overview conceptual description of the computational modelling tools used in this work as an appropriate context for the simulations reported here.

2.1 Computational framework

In recent years, significant efforts have been put into the modelling of granular flows using a continuum mechanics approach [**7**, **8**]. Although these models are partially successful in capturing some characteristics of the flow, they do not generally incorporate information on particle interactions with other particles and with their environment, which are critical to a realistic simulation. Thus, they cannot be used to simulate some of the processes of great importance in the process engineering industry (i.e. hopper filling/emptying, pneumatic conveying, storage in containers, etc.), where these interactions might lead to phenomena such as particle size segregation, degradation, or caking.

Of course, an understanding of the behaviour of granular materials and their properties, such as segregation and caking, is very complex. The diversity and complexity of the behaviour of an assembly of particles, involves multiple length scales, and makes its theoretical description extremely challenging. Numerical simulations, based for example on discrete element methods (DEM), have become an increasingly popular tool to obtain important information for studying granular particle assemblies [**9**, **10**], as it is possible to represent parameters that are difficult if not impossible to observe in experiments. The study of granular material behaviour represents, therefore, a real challenge for both industry and academic researchers. DEM are able to describe successfully the behaviour of granular material assemblies by considering each particle separately and taking the interactions between particles and the external forces acting on each particle directly into account at the microscopic level [**9**]. However, the main limitation of this approach is associated with the high computational cost of the identification of contacts between contiguous particles and the subsequent calculation of the interaction forces. Furthermore, the number of particles in a typical bulk solids handling process is very large (10^{12} or more particles in a moderately size industrial silo). It is therefore unrealistic to perform direct DEM simulations of industrial processes at full scale.

However, as has been demonstrated as part of this research programme [**1**, **2**], DEM simulations can be effectively exploited as a tool to extract extremely useful information on the constitutive behaviour of groups of particles by using standard statistical techniques [**1**, **2**]. A continuum framework for the description of granular materials has been developed where the particle micro-mechanical behaviour is parametrized in the form of constitutive models [**1**]. The micro-mechanical parametrization involved performing experiments and/or DEM simulations on a limited number of particles for several representative sets of process conditions in order to characterize the macroscopic bulk behaviour. A variety of flow and important transport processes of granular materials were addressed, including particle size segregation, degradation, and moisture migration caking effects. The continuum framework employed was PHYSICA, a multi-physics three-dimensional unstructured-mesh, finite volume toolkit, which includes a computational fluid dynamics (CFD) module, and was developed at the University of Greenwich for the simulation of coupled physical phenomena [**11**]. Before presenting an application of this model to a series of consecutive processes of handling of granular materials, the key features of the continuum models of segregation during silo discharge, degradation during dilute-phase pneumatic conveying, and caking effects during storage are briefly outlined in the rest of this section.

2.2 Modelling of segregation during silo discharge

The details of the approach highlighted below to the modelling of segregation during silo discharge may be found in Baxter and co-workers [**2**, **3**]. In brief, the continuum framework is employed for the solution of the conservation of mass and bulk momentum in the computational domain. Equations for energy (i.e. granular temperature) are not solved in the present form of the model. Instead, energy-linked flow parameters are accounted for in the micro-physical constitutive models, which link the granular temperature of the flow to bulk velocity gradients through kinetic/theoretical considerations [**12**]. A viscoplastic constitutive law based on the Drucker–Prager yield criterion [**3**] has been adopted to simulate the behaviour of the bulk material.

The fraction of each individual material components f_i in a control volume is calculated through the solution of transport equations, which in the absence of source/sink terms may be written as

$$\frac{\delta f_i}{\delta t} + \nabla \cdot \left\{ f_i(\mathbf{u}_\mathrm{b} + \mathbf{u}_\mathrm{seg,i}) \right\} = 0 \tag{1}$$

where $\mathbf{u}_\mathrm{b}$ is the bulk velocity and $\mathbf{u}_\mathrm{seg,i}$ is a ‘drift’ velocity for species i relative to the bulk of material associated to segregation processes. The summation of all individual fractions in a cell gives the total amount of material present in that cell. This sum is only allowed to take values between 0 (cell empty of material) and the maximum allowed packing fraction (always less than unity). A special volume of fluid (VOF)-type algorithm with a donor–acceptor type of method is used for the prediction of the material interface [**2**, **3**].

The segregation ‘drift’ velocities were analysed in the micro-mechanical framework, by using principles of kinetic theory [**13**]. For each material component, three transport processes, which lead to segregation, were identified.

- Strain-induced segregation (kinetic sieving) arises due to the preferential motion of coarser particles in the mixture across gradients of bulk velocity, towards regions where the bulk strain-rate is highest, such as free surfaces in a heap of material.
- Segregation by ‘diffusive’ processes similar to classical molecular diffusion down a concentration gradient. Diffusion principally affects the finer particles in a multi-component mixture of granular material.
- Segregation may also occur through percolation, which is the gravity-driven motion of the finer particles through the interstices in the matrix of coarse.

Functional forms for all three ‘drift’ components were derived. Transport coefficients characterizing each segregation mechanism were then calculated for each species of the mixture in a DEM framework using linear response theory [**2**]. A full analysis of the functional forms of the derived constitutive equations for all three mechanisms and detailed validation results for mass-flow hopper discharge are given in Christakis *et al.* [**3**].

2.3 Modelling of particle degradation in dilute-phase pneumatic conveying

In dilute-phase pneumatic conveyors, the most extensive damage imparted to particles is caused by particle–bend wall collisions [**14**, **15**]. The modelling of particle degradation in dilute-phase pneumatic conveying combines a Eulerian flow model of the solids and gas phases along the pipeline and the calculation of particle impact degradation propensity from particle single impact experimental tests [**14**].

The solids flow in a straight pipe element is represented by a model consisting of two zones: a strand-type flow zone immediately downstream of a bend created due to the centrifugal force encountered by the particles while travelling around the bend, followed by a fully suspended flow region after dispersion of the strand. The model of the strand type flow is a one-dimensional model describing the flow of two layers (i.e. the dense strand and the suspended flow above it) with separate velocity and exchanging momentum between them due to shear forces at their interface. The model is based on a force balance on elements of the strand and of the suspended flow region. The friction force between the strand and the suspended flow τ_{str} is modelled in analogy to single-phase flow by using an equivalent Moody friction factor

$$\tau_{\mathrm{str}} = \frac{\rho_{\mathrm{air}} f_{\mathrm{str}}}{2} (\mathbf{v}_{\mathrm{air}} - \mathbf{v}_{\mathrm{str}})^2 \tag{2}$$

where ρ_{air} is the air density and $\mathbf{v}_{\mathrm{air}}$ and $\mathbf{v}_{\mathrm{str}}$ are the air strand velocities. The value of the friction factor f_{str} obtained from the Moody diagram is increased in order to account for the additional momentum transfer resulting from the interchange of particles between the strand and the suspended flow. In the fully suspended region, the pressure drop is represented by a Darcy-type relation. Particle deceleration in bends due to wall sliding friction and the rebound processes is also accounted for through a simple model where the particle–wall interactions are characterized by a coefficient of friction and a coefficient of restitution.

Bends are the most serious points of particle degradation [**14**, **15**], hence degradation is considered to occur only by impact at the bends. Particle degradation in a bend is represented by a single impact, since it has been observed that the first impact of the particles in the bend causes the major damage [**15**]. Moreover, it is assumed that a given value of the bend angle corresponds to a given value of the particle impact angle. As demonstrated in Chapelle *et al.* [**4**], this approach enables a reasonably accurate representation of degradation processes in 90° angle bends. The degradation model is based on particle single impact testing at a specified impact angle and velocity carried out in a new laboratory scale degradation tester [**16**]. Data from a limited number of particle single impact tests are utilized to build breakage matrices (based on the concepts of population balance models [**17**]) for a range of impact conditions, using regression analysis theory [**5**]. The constructed breakage matrices correlate the input particle size distribution at the bend inlet to the resulting distribution after impact and degradation at the bend outlet. The paper by Chapelle *et al.* [**5**] also contains details of the validation of this model.

2.4 Modelling of moisture migration caking

The mechanism that causes moisture migration caking of granular materials in storage under conditions of sharp variations of ambient air temperature/humidity (for example between day and night) can be described schematically as follows. When particle surfaces are hydrated or wetted by moisture, interparticle liquid bridges are formed by cohesion and adhesion. When drying occurs, the moisture evaporates from the particle surface, resulting in recrystallization and formation of a solid bridge between the particles. Repeated wetting/drying cycles cause a build-up of layers that strengthens the bridge to such an extent that a hardened cake is formed.

The continuum framework developed for the description of the caking process combines a model for the transport of moisture in porous media and a model of the solid bridge growth and the subsequent increase of the caking strength under wetting/drying cycles. Moisture migration is modelled through the solution of transient coupled heat and mass transfer equations with phase changes. The model includes appropriate source terms, which account for the moisture uptake/loss by the powder. These source terms, which have been derived on the basis of micro-physics [**6**], represent the increase or decrease in temperature due to the release or absorption of heat during condensation or evaporation, respectively, and the subsequent decrease or increase in the mass of vapour in the air around the solid particles. Moisture sorption isotherms are obtained via experimental analysis.

The model for the caking process is based on the growth of liquid bridges (during condensation) and the creation of solid bridges and their subsequent hardening (during evaporation). An equation for the radius of the solid bridge can be found in Tanaka [**18**]

$$b = 0.82R\left(\frac{\nu_{\mathrm{b}}}{R^3}\right)^{1/4} \tag{3}$$

where v_b is the volume of the bridge for a single particle around the contact area between two particles, R is the radius of the particle, and b is the radius at the narrowest part of the bridge. The volume v_b can be calculated by tracking changes in the moisture content of the solids during a wetting/drying cycle.

The tensile strength of the cake is related to the radius of the solid bridge formed around particles through Rumpf's equation [**18**]

$$\sigma_{\text{cake}} = \sigma_{\text{crystal}} \pi b^2 \frac{9}{8} \frac{(1-\varepsilon)}{\varepsilon} \left(\frac{1}{2R}\right)^2 \tag{4}$$

where σ_{crystal} is the crystalline strength of the material making up the bridge and ε is the granular material porosity. Hence, by tracking changes in b, the increase in the tensile strength of the formed cake can be determined. A more detailed description of the model and the numerical solution technique is presented in Christakis *et al.* [**6**].

3 SIMULATION OF A COMPLETE LARGE SCALE HANDLING PROCESS OF GRANULAR MATERIALS

This section presents the numerical simulation of a complete large scale process of handling of granular materials, commonly met in industry. It involves the discharge under mass flow conditions of a binary mixture from a cylindrical silo, then its transport through a pneumatic conveyor operating in the dilute-phase regime, and, finally, its storage in a polyethylene big bag in an environment where both ambient temperature and relative humidity vary significantly between day time and night time. The layout of the complete process is shown in Fig. 1. The granular material used for this study was granulated sugar with a solids density of 1660 kg/m^3, a bulk density of 700 kg/m^3, and an angle of internal friction of 37°. The material consisted of coarse and fines particles of 2 : 1 size ratio (average particle diameters of 362.5 and 725 μm). The initial composition by weight was 60 per cent fines and 40 per cent coarse particles. Initially, the silo was filled with an uniform distribution.

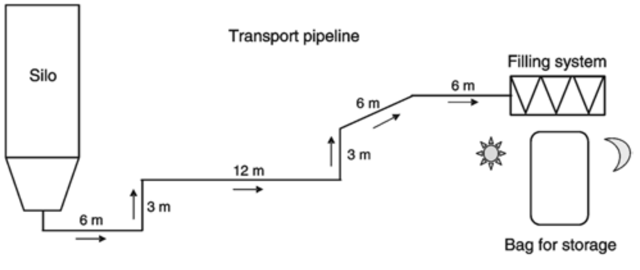

Fig. 1 Sketch of the simulated process of handling of granular materials. It includes a mass flow silo, a pneumatic conveying system, and a bag for storage

3.1 Segregation during silo discharge

The simulation was performed for a cylindrical silo, 1 m high and 0.55 m in diameter, having a discharge outlet of 0.05 m diameter. The silo half angle of the conical section was 45°. Initially the silo was uniformly filled with a binary mixture consisting of 60 per cent fines and 40 per cent coarse particles, with diameters of 362.5 and 725 μm respectively. A discharge rate of 0.714 kg/s (calculated from the Beverloo correlation) was prescribed at the silo outlet. The same set of values of the segregation transport coefficients as in other work [**2**, **3**] was used for this simulation.

The predicted flow pattern and temporal segregation profile during the discharge were qualitatively similar to those observed in [**3**] for the laboratory-scale silo. Snapshots of the position of the material–air interface at six different fractions of the total mass discharged are presented in Fig. 2. The flow behaviour corresponded to the well-known mass flow discharge mode. As the silo emptied, the material–air interface remained relatively flat until it reached the junction between the cylindrical and conical sections (fraction of total mass discharged equal to 92.1 per cent). Eventually, inside the conical section, the interface started progressively curving downwards towards the centre of the silo, reflecting the preferential motion of the particles localized in the central core above the silo outlet.

Figure 3 shows the temporal segregation profile at the silo outlet, plotted as the averaged content of fines across the silo outlet against the proportion of inventory discharged. The fines contents remained constant (equal to its initial value 60 per cent) as

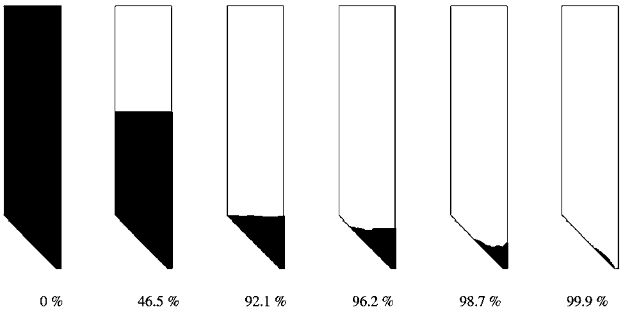

Fig. 2 Material–air interface at different fractions of the total mass discharged during the discharge of the large-scale silo

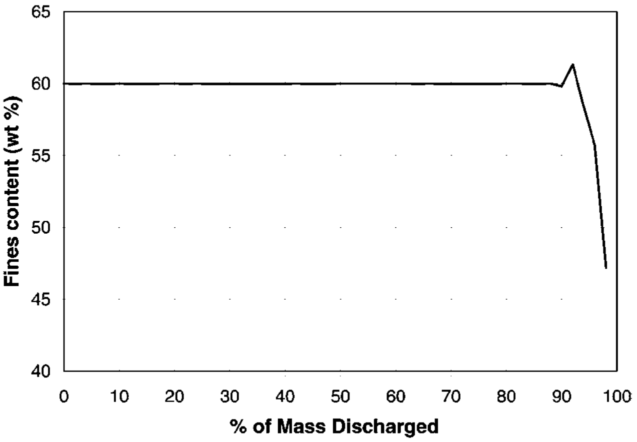

Fig. 3 Model predictions of the fines content averaged over the silo outlet during the discharge

the material–air interface moved through the cylindrical section (until about 90 per cnt of mass discharged), revealing that negligible segregation occured during this phase of the discharge. As the interface passed over the junction between the cylindrical and conical sections, significant segregation was observed, with the fines contents rapidly decreasing thereafter. The source of this segregation was the deformation of the material–air interface shown in Fig. 2. This produced high-flow-velocity gradients, leading to particle size separation by both the kinetic sieving and diffusion mechanisms.

3.2 Degradation during dilute-phase pneumatic conveying

The pneumatic conveying system considered in this study was a 36 m long pipeline with an internal diameter of 5.3 cm, consisting of six straight pipes and five 90° bends. The simulation was performed for typical industrial operating conditions. The inlet air velocity was equal to 11.6 m/s. The suspension density (computed from the silo discharge rate and the inlet air velocity) was set equal to 28 kg/m^3. In order to study the degradation of the conveyed material, five discrete size classes were defined with sizes uniformly distributed between, respectively, 850 and 600 μm, 600 and 425 μm, 425 and 300 μm, 300 and 212 μm and 212, and 0 μm. As seen from Fig. 3, the silo outlet mixture composition varied during the latter stages of the discharge. For the purpose of this simulation, a mixture of 60 per cent fines and 40 per cent coarse particles was considered at the inlet of the pipeline (with the fine particles placed in the 300–425 μm size range and the coarse particles placed in the 600–850 μm size range). Fully suspended flow conditions were assumed at the inlet, i.e. the air and particle velocities were equal.

The calculated profiles of the pressure of the air and of the air and particle velocities along the pipeline are shown in Figs 4 and 5. The air expanded along the pipe, with greater pressure gradients in the flow region immediately downstream of each bend. This pattern of the pressure profile was in accordance with the experimental work reported by Bradley *et al.* [**19**]. Expansion of the air caused an increase in the air velocity and thus in the particle velocity as a result of the momentum transfer between the gas and solid phases. Particles were considerably slowed down through the bends due to the interactions of the particles with the bend walls. Downstream of a bend, particles, which were conveyed in the form of a dense strand, were progressively re-accelerated towards the air velocity. The model predicted that only the third straight pipe in the system was long enough for the transition between strand type flow and fully suspended flow to occur. The transition was observed at a conveying distance of 7.6 m from the outlet of the second bend. This result is in good agreement with the value of the dispersion length of the order of 8 m reported in the literature [**20**].

The full particle size distribution after each bend is shown in Figure 6. Particles underwent significant degradation during the conveying process. Both fractions of the initial binary mixture [i.e. the coarse particles (600–850 μm) and the fine particles (300–425 μm)] decreased continuously through each bend, with a smaller decrease rate for the fine particles. Indeed, decreasing the particle size increased the material strength [**21**]. Moreover, the size class of fine particles in contrast to that of the coarse particles was re-populated by the fragments resulting from the breakage of larger particles.

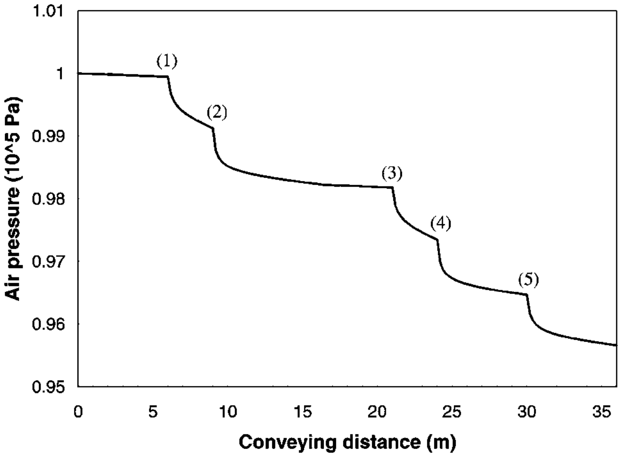

Fig. 4 Predictions of the model for the air pressure profile along the pipeline. The indexes ($i = 1, \ldots, 5$) refers to the location of the bend along the pipeline

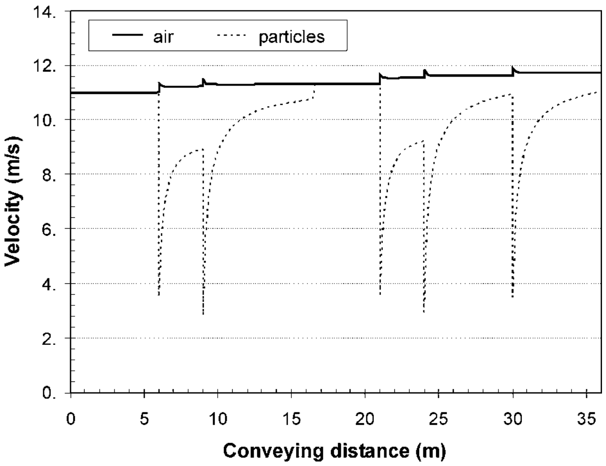

Fig. 5 Predictions of the model for the air and particle velocities profiles along the pipeline. The indexes ($i = 1, \ldots, 5$) refers to the location of the bend along the pipeline

At the end of the conveying line, the fraction of coarse particles had dropped to about 60 per cent of its initial value and more than 15 per cent of the material was made up of 'fine dust' (defined as particle of size below 300 μm). Hence, it can be concluded that granulated sugar is very prone to degradation under the pneumatic conveying conditions considered in the present study.

3.3 Moisture migration caking during storage

Downstream of the pneumatic conveyor, the granular material was packed in a polyethylene big bag of 0.6 m diameter and stored for one month in an environment where both temperature and humidity conditions varied between day and night. The bag lining was assumed to be permeable to environmental humidity (hence, humidity was allowed to enter/leave the system). Since the height of the bag was much larger than its diameter, only a one-dimensional strip across the bag (from polyethylene lining to bag centre) of 0.3 m was simulated. The day-time environmental temperature and relative humidity were taken as 27°C and 38 per cent, respectively. Night-time environmental conditions were taken as 16°C and 76 per cent, respectively. These conditions were imposed at the exposed boundary of the bag and are varied periodically every 12 h. The granulated sugar was assumed initially at equilibrium at 20°C and its moisture content was 0.033 per cent. The average particle diameter was taken to be 435 μm, as a result of material degradation during pneumatic conveying.

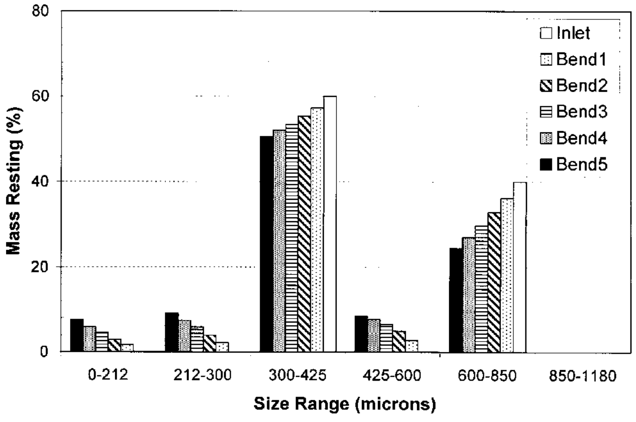

Fig. 6 Particle size distribution after each bend

Figure 7 shows the changes along the simulated strip of temperature, solids moisture content, and caking strength at different times during the first 24 h cycle, with night-time conditions for the first half-cycle followed by day-time conditions for the second half-cycle. Owing to the high thermal conductivity of the polyethylene bag, the temperature inside the bag layer responded quickly to the external temperature fluctuations and almost instantaneously tools the value of the environmental temperature. The variations in temperature and humidity caused the moisture to migrate between the bag–material interface and the bag centre, with the sharpest changes occurring as expected in the vicinity of the exposed surface of the material. The region affected by gradients of temperature and relative humidity was confined within a distance of approximately 0.15 m from the bag–environment boundary. Beyond that point, the system remained almost unaffected.

During the first half-cycle (i.e. 6 and 12 h), as the environmental relative humidity was at its peak (i.e. when the boundary temperature decreased), the moisture migrated into the system due to diffusion. The granulated sugar took up moisture in its attempt to bring the system back into equilibrium. This wetting process caused the formation of liquid bridges between solid particles but no caking occured, as can be observed in Fig. 7(c). During the second half-cycle (i.e. 18 and 24 h), when the relative humidity dropped (i.e. when the boundary temperature increased), the process of moisture migration was driven by two mechanisms. Near the bag–material interface, the moisture tended to migrate out of the system due to the decrease in the relative humidity. Further inside the bag, the gradient of relative humidity produced in the system tended to drive the moisture from the bag–material interface towards the core of the bag, thus slowly increasing the moisture content further away from the bag–material interface. The decrease in the moisture content in the bag–material interface region caused the evaporation of moisture from the surface of the

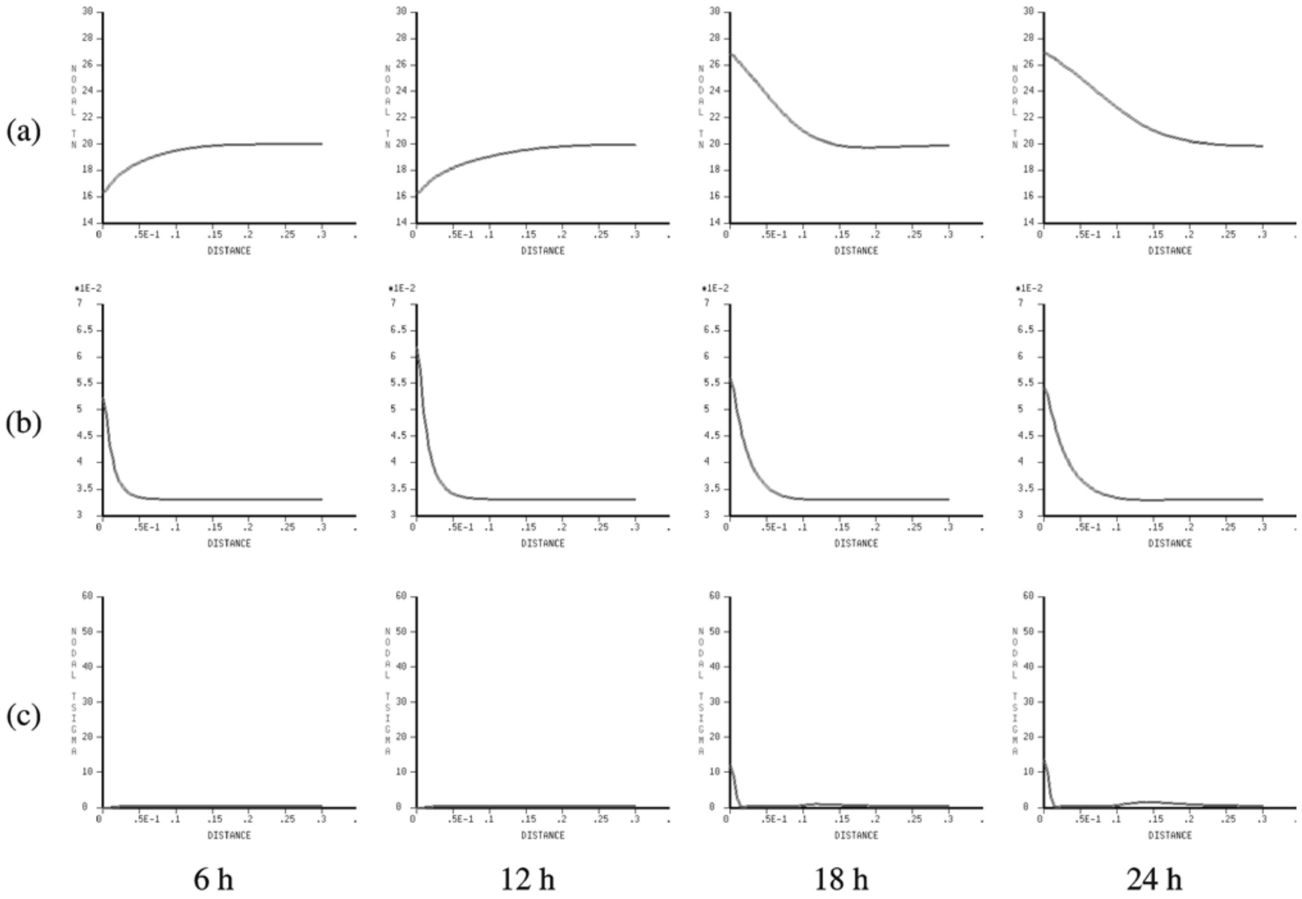

Fig. 7 Variations along the simulated strip (bag–material interface at 0 m, bag centre at 0.5 m) of (a) temperature (in °C), (b) solids moisture content (in per cent), and (c) caking strength (in Pa) at various times during the first 24 h cycle

solid particles, in order for the system to return to equilibrium. During this drying process, liquid bridges hardened. This led to the formation of solid bridges, hence the increase of the tensile strength of the material causing the sugar to cake near the bag–material interface [see Fig. 7(c)]. Similarly to the first half-cycle, the increase in moisture content further inside the bag resulted in condensation on the grain surface, with subsequent formation of liquid bridges, for the system to be driven back to equilibrium. A comprehensive discussion of the dynamic processes of moisture migration and caking process is presented in Christakis *et al.* [**6**].

The repetition of this wetting/drying cyclic process and the subsequent moisture migration caused a build-up of layers that strengthen the bridge to such an extent that a hardened caked formed. Figure 8 presents the increase in the tensile strength of the caked sugar at different penetration depths along the simulated strip at the end of each cycle during one month storage. It can be seen that the highest tensile strength of the caked sugar occured close to the bag–material interface, while the tensile strength was negligible at 0.15 m (middle) and 0.3 m (centre) from the bag–material interface. This result is in agreement with the simulated behaviour of granulated sugar during the first 24 h cycle presented in Fig. 7, where the sharpest interaction between environment and material was predicted to occur

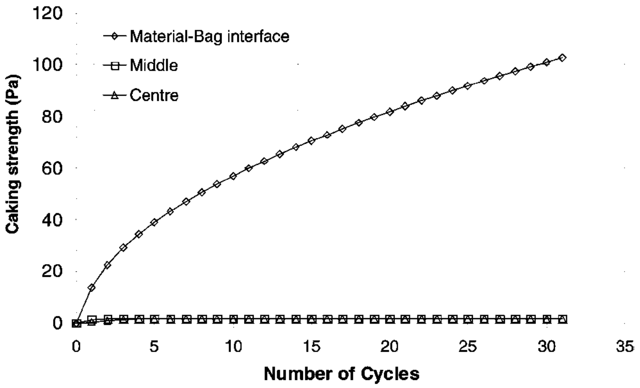

Fig. 8 Variation of the caking strength at different locations along the simulated strip after each cycle

within the first 0.15 m penetration depth. Figure 8 shows that the increase in the tensile strength of the caked sugar at the bag–material interface was greater during the first five cycles. Then an approximate linear increase of the tensile strength was observed.

A key reason for showing the results of the simulation of this cascade of processes is to demonstrate the possibility of using the simulation tools (coupled with the measurement technology) to provide a comprehensive description of the complete transport and storage system. Given this simulation technology, the next steps here are to utilize it in the optimization of industrial plants with respect to product quality. This effort is now underway.

4 CONCLUSIONS

In order to address the enduring problems of product quality degradation that arise in the transport and storage of granular materials, new measurement technologies and simulation tools are required. These technologies and tools need to enable a consistent and comprehensive approach to the characterization of granular materials throughout the whole industrial process. A large collaborative project, QPM (see www.qpm.org.uk) involving eight industrial and three academic partners and funded by EPSRC for 5 years has targeted the development of both experimental measurement technologies and simulation tools to enable a coherent and integrated approach to the analysis of the problems of the degradation in quality of granular materials that arise during transport and storage from a variety of sources. This paper describes simulation of a complete large-scale process of handling of granular materials, involving silo discharge, pneumatic conveying, and storage in a big bag, performed using a continuum model, where the interactions between particles at the microscopic level are parametrized and employed in the form of constitutive models. It is believed that this description of a cascade of granular material handling operations under a continuum framework with the aid of micro-mechanical/experimental parametrisations is unique. Ultimately, this suite of computational models should constitute a powerful computational tool for engineers, which will aid them in the optimization of existing process and the design of new equipment.

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