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Discrete element model of particle transport and premixing action in modified screw conveyors

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ABSTRACT

In this paper, five types of horizontal single-pitch screw conveyors with modified geometry, with three different lengths (400, 600 and 800 mm) were investigated for transport and auxiliary mixing action of two materials: natural zeolite and quartz aggregate (sand) with particle sizes 3, 4 and 5 mm. The geometry of the screw transporter is changed by welding three additional helices oriented in the same or the opposite direction from screw cutting edges, enabling the premixing of materials, during the transport. The proper mixing of the observed materials provides an adequate disposition of zeolite particles within the composite and prevents agglomeration and interference with cement hydration. Zeolite application as a binder in a building material is a possible solution to environmental pollution problems caused by cement production. The influences of screw length, particle diameter, the studied geometry variations of screw design, on the mixing performances of the screw conveyor-mixer during material transport were explored. All investigations were performed experimentally and numerically, by using Discrete Element Method (DEM). The experimental results and the results of the DEM investigation were used for the development of mathematical models for the prediction of mixing quality, which are presented in the form of second order polynomial and artificial neural network model.

1. Introduction

Screw conveyors are used for transport of materials in the mining industry, process and chemical industry, building constructions, civil engineering, etc. These devices comprise of a helical screw rotating in a U-shaped trough the encased pipe. Screw conveyors have simple geometry, but a transport process in this device requires detailed and thorough analysis. Certain problems can occur during metering and dosing material which leads to deformation and crushing of the particles, which leads to the inhomogeneity of the mixture, segregation, increase of the energy consumption and degradation of the quality of the final product. Design and construction of the screw conveyors are nowadays developed and applied for specific demands, listed in the literature [1, 2]. Many researchers deal with explanations and descriptions of the theoretical behaviour of screw conveyors [3, 4]. The analyses of operating principals and basic parameters of the screw conveyors are listed in the literature [5].

Numerical models based on DEM approach appeared to be dependable and helpful in getting particle interactions and anticipating blending process for examination of solids mixing. Cundall and Strack [6] developed the soft-sphere method for granular dynamics simulations. DEM is a numerical technique used to predict and analysed the behaviour of the particles which can overlap and their positions, orientations, velocities, contact forces [6]. Theoretical development and applications of the DEM modelling and coupled DEM/CFD modelling of the non-spherical particles are presented in the study by Zhong, et al., [7].

The first report of the use of DEM in a screw conveyor was introduced by Shimizu and Cundal, [8], and the performance of horizontal and vertical screw conveyors were examined. Various authors [9–13] used periodic slice model for the research of long screw conveyors, studied the effect of the particle size and shape on the draw down flow from the hopper by a 25° inclined screw conveyor. The effect of the shape of the feed opening on the working parameters of the horizontal screw conveyor was the subject of the research in research by Zhong and O'Callaghan, [14]. DEM is used to predict the transportation process of the particles in the screw conveyor with variable parameters: screw pitch, screw flight outside diameters, core diameters, blade configuration, and conveyor's filling level and screw's rotating speed [15–17]. DEM was also used for modelling the transportation of the solids in the extruder [18,19]. Bracey et al., [20] used DEM for modelling

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multi shaft mill, and developed the novel comminution devices, and exploited its possibilities. Coupled DEM/CFD models can also be used for modelling particle behaviour as well as the working fluid, which has a significant effect on the solid parameters [21–27].

Screw conveyors are often used for dosing and metering small amounts of materials, like particles of granules [28–30]. The dosing process can be improved by the proper choice of geometry, changing the screw speed or prolonging the screw length [31]. Several additional elements welded to the screw can also contribute to a better dosing and metering. The diminished segregation in the continuous blender has been the subject in the research by Oka et al., [32].

The screw conveyors used for transporting, dosing and metering have been analysed widely in the literature. However, according to our best knowledge, the application of the screw conveyor as the premixer (during the transport of granular materials) have neither been studied experimentally nor numerically, except in our previous study [33]. The main leading idea for the investigation presented in this article was the application of DEM models developed for rotating drum mixers, which is widely available in the literature.

The behaviour of particles during mixing in a rotating drum mixer with filling level >50% has been analysed using Discrete Element Method (DEM), in the investigation performed by Sony et al., [34]. In this work, an attempt was made to understand and represent the mechanism of the dead zone formation in the mixer, and to evaluate the degree of mixing by varying the mixing parameters, such as the size of particles, and the shape of the mixer. In the investigation performed by Yamamoto, et al., [35], the mixing behaviour of particles in a rotating drum mixer was explored experimentally, and using DEM simulation, and the main goal was to discuss the effect of particle density. Two different materials were used for the mixing experiment (alumina and stainless steel particles), and the mixing degree was evaluated.

The mixing process of equal-sized acrylonitrile butadiene Styrene copolymers particles in a rotating drum were explored using the DEM method at different rotational speeds and filling degrees in study developed by Xiao et al., [36]. The experimental parameters which were necessary for the DEM model developing were determined by a series of experimental measurements, including high rebound test, friction and wear test, and stacking angle test.

The mixing capabilities of natural zeolite and the quartz aggregate, during transport in screw transporter, were investigated in this study. The possible application of natural zeolite in concrete formulation. Concrete is still the most common construction material, and two basic resources for concrete manufacturing are cement and quartz aggregate. The building sector aims towards replacing expensive and/or natural resources with either industrial bi-products or economic raw materials. Natural zeolite has the ability to immobilize heavy metals present in industrial byproducts uses as cement additives. Zeolite also acts as pozzolana which leads to acceleration of cement hydration, increase in early strengths, decrease in bulk density (lighter structures), evener surfaces, better drying mechanism, reduction in various processes (chloride penetration, sulfate attack, expansion due to alkali silica reaction), decrease in autogenous deformation and micro-cracking [37, 38].

In this paper, cluster analysis (CA) was applied to characterize the experimental and model data (used as descriptors) and differentiate among observed samples. Second order polynomial (SOP) models and artificial neural network (ANN) model were used for mathematical modelling.

The leading thought in this paper was to analyse the process in the screw conveyor and to assess the commitment of the adjusted geometry of screw blades on premixing process, before material enters the principle blender. The transporting path can be extraordinarily prolonged by embedding at least one extra helix or helical strips, in the same or the opposite direction of material flow, welded on the fringe of the helix. The velocity of particular particle is significantly increased, and the possibility of the mixing is increased due to the particle path being augmented. In this investigation, five horizontal single-pitch screw conveyors with modified geometry with three different lengths were investigated for mixing action of natural zeolite and sand with different particle sizes, during the transport.

The observed screw transporters could be considered as transporters, but yet in addition, they could be treated as the continuous premixer device.

DEM analysis was utilized to explore the influence of modifications in screw geometry on the transport path on premixing process [6, 34, 39]. The trajectories of the particles were explored and the effects of screw geometry and the dimensions of the particles on particle path, the mixing duration and the quality of the mixing process were investigated. All numerical simulations were confirmed by suitable experiments. The quality of the mixing process is investigated using relative standard deviation (RSD) criteria [39].

2. Materials and methods

2.1. Material

The applied zeolite is a natural hydrated aluminosilicate with the crystalline structure that comprises frameworks of dimensionally equate crystals. The frameworks are composed of SiO_4 and AlO_4 tetrahedra interlocked by oxygen atoms in the structural nodes [40, 41]. These molecular sieves are interconnected by pores and cavities [42]. The voids are resided by extra-framework exchangeable cations that are substantial for zeolites ion-exchange chemistry [43]. The ion exchange capacity and the hydrophilicity are the most appreciated characteristics regarding the zeolite application as a sorber in the construction composites. On the other side, zeolite pozzolanic behaviour guarantees that they can be applied as a cement substitute in the building materials.

The utilized natural zeolitic tuff originates from Vranjska Banja deposit in Serbia. The tuff occurs as a pale yellow pelitic rock covered with limonitic film. The rock mass was primarily composed of zeolitizated volcanic ash, and small amounts of quartz, plagioclase and biotite. The crude zeolite samples from the deposit were acquired following the standard sampling campaign. The sub-samples (10 kg) were obtained according to the cone and quartering principle subsequent to the initial crushing. Several zeolite samples (100 g) were pulverized in an agate stone mill (KHD Humboldt Wedag) prior to the chemical composition analysis. The pulverized sample had average specific surface of 75.9 m^2/kg. The grain-sizes of zeolite and quartz aggregate fractions used in the mixture were 3; 4 and 5 mm.

The quartz aggregate used in the mix design was obtained from Vlaško polje – Mladenovac, Serbia. The chemical composition of the quartz sand: SiO_2 (99.9%), it is a mineral composed of silicon and oxygen atoms in a continuous framework of SiO_4 silicon–oxygen tetrahedra, with each oxygen being shared between two tetrahedral. The bulk density of the quartz aggregate was 1810 kg/m^3 in loose condition and 1992 kg/m^3 in pressed condition. With SiO_2 content as high as 97.98%, aggregate primarily contained quartz, less abundant feldspar and small traces of mica. Moisture content in resource materials was assessed by measuring loss on ignition (LoI) parameter. LoI was determined after fringing zeolite and quartz sand samples at 1000 °C in laboratory furnace. LoI for quartz was <1%, while the LoI value foe zeolite was 14.52%.

2.2. Experimental method

The five types of modified screw transporters were tested for blending capacities during the transport of granular material. The studied types of altered screw conveyers were: single flight screw transporter (type I), screw conveyor-mixer with three additional helices oriented in the same direction as screw helix (type II), screw conveyor-mixer with three helices oriented in the opposite direction from screw blades (type III), screw conveyor-mixer with three truncated additional helices oriented in the opposite direction as screw blades (type IV), and screw