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The effect of temperature on the mechanical characteristics of individual particles

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ABSTRACT

The current work investigates the effect of temperature on the mechanical characteristics such as breakage force, breakage energy, yield force and effective modulus of elasticity of individual particles. This is important for modeling particle attrition at different temperature conditions. The results were obtained by employing uniaxial compression tests at different temperatures between 210 and 465 K. Besides giving results and analysis, this paper provides in detail unique particle's heating and cooling chambers specially designed for this topic and allows keeping particle temperature constant through the entire experiment process. Seven various particulate materials tested during this study: dead-sea salt and potash, GNP, silica gel, zeolite 4A, alumina and novolen 1040n particles, with different fraction sizes ranging 0.71 ÷ 5 mm. The results showed that the strengths of salt and silica gel particles increase with the temperature. Therefore, more energy is required in order to break these particles at high temperatures. Effective modulus of elasticity for most of the materials reduced at high temperatures confirming the particles become softer. Consequently, empirical models were proposed describing the distribution of the breakage force, breakage energy, yield force and effective modulus of elasticity versus the particle size and temperature.

1. Introduction

Mechanical properties of particles such as strength and elastic modulus are necessary material properties for modeling comminution processes and particle-particle, particle-wall interactions using DEM simulations [1–3]. These properties must be determined experimentally for accurate computational results. Since DEM deals with individual particles, these properties can be achieved only from experiments conducted on individual particles.

Investigation of an individual particle's mechanical properties at high and low temperatures is important for several reasons. Firstly, at low temperatures, many materials become brittle so that they can be grinded more effectively [4]. Therefore, cryogenic milling is used for Al and alloys [5–8] and polymers [9]. Secondly, during comminution processes, the dissipation phenomenon takes place due to particle impact and breakage leading eventually to rise in temperature of the mill and the particles. Therefore, numerical solutions and simulations of high impact systems taking into account the particles' strength properties at the determined elevated temperatures will increase the accuracy of calculations.

For any specific type of particle, it may have an optimum attrition temperature – at too low temperature the particles may become brittle and easy to break, whilst at too high temperature they may soften, agglomerate or melt and lose discrete particulate properties [10]. Hassanpour et al. [11] checked the effect of temperature on the breakage force of α-lactose monohydrate particles having size of 0.5 – 0.6 mm. The experiments were conducted at room temperature and 253 K. The samples were cooled down to 253 K in a freezer and then, compression tests were performed to measure the breakage force. The results showed an increase in the average single particle breakage force by a factor of 1.83 on decreasing temperature from room temperature to 253 K. In another work, Chen et al. [12] checked the temperature effect on cement clinker particles with mean diameter of 22 mm. The compression tests were conducted at five different temperatures between 185 K and 1273 K and only five particles were tested at each temperature. The samples were heated or cooled separately and outside the tester. The results showed that after cooling or heating, the clinker nodules were easier to be fractured than the untreated ones at room temperature. In both papers, the experiments created doubts regarding the real particle temperature at compression.

This paper investigates the effect of temperature on the breakage force, breakage energy, yield force and effective modulus of elasticity of individual particles by compression tests. A custom-built heating and cooling system is introduced to allow maintaining the particle temperature constant throughout the compression process. The results are analyzed by statistical distributions and eventually, empirical models

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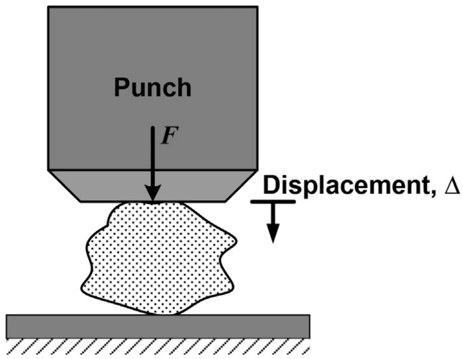


Fig. 1. The principle of a single particle compression test.

for the measured mechanical characteristics are proposed as function of particle size and temperature.

2. Materials and methods

2.1. Compression tester

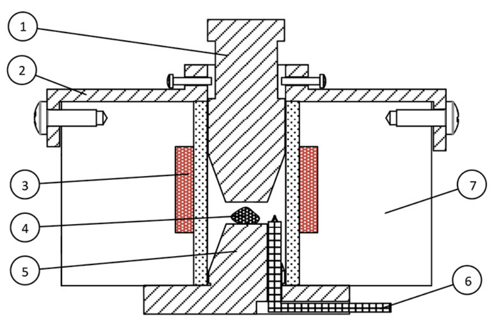
The mechanical characteristics of individual particles are measured using a custom-built compression tester [13]. According to the principle of the test (Fig. 1), the upper punch is operated by a hydro – pneumatic piston, loading the particle at a constant compression force rate until the detection of first breakage. The applied force is measured by a Load-Cell connected to the lower contact surface with an accuracy of ±0.01% from full scale. The punch and the lower contact surface are made from alumina 995. A linear variable differential transformer (LVDT) sensor measures the displacement simultaneously with an accuracy of ±5 μm. The tester is able to conduct experiments with individual particles in the size range of 100 μm – 6 mm. All the experiments were conducted with a constant compression force rate of 1 – 2 N/s.

2.2. The heating system

In order to investigate the effect of high temperature, a unique heating system is developed and installed. The purpose of the particle heating system is to maintain the particle temperature constant throughout the test. For this reason, the heating chamber is integrated to existing compression tester and the particle is heated by heating the surrounding air inside the chamber (Fig. 2). The shape of the heating chamber is cylindrical with an internal diameter of 20 mm, an outside diameter of 90 mm and a height of 50 mm. The coil heater with an output power of 50 W wound around the internal wall of the chamber. Due to the small dimensions of the chamber, this power is high enough to heat the air inside the chamber up to 473 K. The temperature inside the chamber is measured by a thermocouple of type – K and controlled through a solid-state relay (SSR) unit. In order to replace the broken particle at the end of each experiment with a new particle, the chamber is connected to the punch using an adapter (see Fig. 2), causing the chamber and the punch to move up and down along with a piston. In addition, this connection allows relative movement of the punch and the chamber while the chamber remains in contact with the lower contact plate.

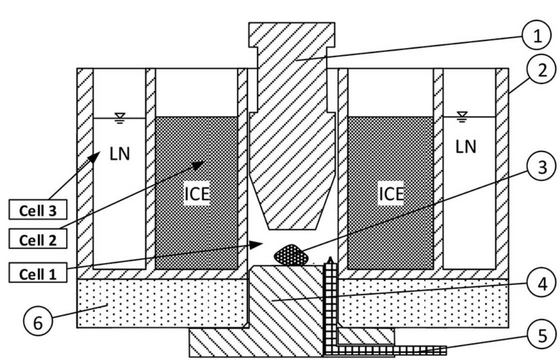
2.3. The cooling system

Particle cooling is performed using miniature cryogenic system. The system was also developed and integrated to existing compression tester. It consists of cryogenic chamber and uses liquid nitrogen and ice to cool the particles to the desired temperature (Fig. 3). The chamber is cylindrical with three internal cylindrical cells. The inner and outer dimensions are similar to the heating chamber. The particle is located at the center (cell 1) surrounded by air and cooled by liquid nitrogen (cell 3) and ice (cell 2). Since the liquid nitrogen evaporates quickly, this arrangement of the cells is effective to cool the particles to stable temperatures down to 200 K. The temperature inside the chamber is measured



#	Description
1	Punch
2	Piston-chamber adapter
3	Coil heater
4	Particle
5	Lower contact plate
6	Thermocouple
7	Isolation

Fig. 2. Schematic description of the heating chamber.



#	Description
1	Punch
2	Cryo-body
3	Particle
4	Lower contact plate
5	Thermocouple
6	Isolation

Fig. 3. Schematic description of the cryogenic chamber.