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Characterization modelling and validation of a two-point loaded iron ore pellet

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A B S T R A C T

Iron ore pellets are sintered, centimetre-sized spheres of ore with high iron content. Together with carbonized coal, iron ore pellets are used in the production of steel. In the transportation from the pelletizing plants to the customers, the iron ore pellets are exposed to different stresses, resulting in degradation of strength and in some cases fragmentation. For future reliable numerical simulations of the handling and transportation of iron ore pellets, knowledge about their mechanical properties is needed. This paper describes the experimental and numerical work to investigate the mechanical properties of blast furnace iron ore pellets. To study the load deformation behavior and the fracture of iron ore pellets, a number of point load tests are carried out and analyzed. Material parameters for an elastic–plastic constitutive model with linear hardening for iron ore pellets are derived and expressed in terms of statistical means and standard deviations. Two finite element models are developed for different purposes. For the material parameter determination, a perfectly spherical model is used. The constitutive model is validated with a finite element model based on a representative optically scanned iron ore pellet. The proposed constitutive model is capturing the force displacement relation for iron ore pellets in a two-point load test. A stress based fracture criterion which takes the triaxiality into account is suggested and calculated as the maximum equivalent effective stress dependent on the three principal stresses at fracture. The results of this study show that the equivalent effective stress in the vicinity of the centre of an irregular model of an iron ore pellet is very close to the results of a model of a perfectly spherical iron ore pellet. The proposed fracture criterion indicates fracture in the representative iron ore pellet model coincident with the location of the crack developed during the test of the optically scanned iron ore pellet.

1. Introduction

Handling of iron ore pellets is an important part in the production chain for many producers of iron ore pellets. Knowledge about this sub process is very important for further improved efficiency and increased product quality. After production in the pelletizing plants, the iron ore pellets pass through a number of transportation and handling systems like conveyor belts, silo filling, silo discharging and transport by rail and ship. During these treatments, the pellets are exposed to different stresses, resulting in degradation of their strength and generation of fines. To study and optimize processes of transportation and handling of bulk material, traditionally half- or full-scale experiments have been used [1,2]. The focus of these studies is often the pressures on the surrounding structures and not the stresses in the bulk material. A reason for this is that it is difficult to measure the actual stresses inside the bulk material and analyze the mechanism behind the degradation. Another drawback with full-scale experiments is that they are very time consuming and costly to perform. Numerical simulations of these processes give a possibility to study the processes in more detail. Most of the work so far in simulation and constitutive modelling of granular materials like soils [3] and metal powders [4,5] is carried out with continuum based methods like the finite element (FE) method. For iron ore pellets flow particle based methods like the smoothed particle hydrodynamics (SPH) method [6] is used. Such models give the flow, stresses and strains on a continuum length scale but not the stress state inside the individual granules. To study the local contact behavior of compressed granular material, detailed models of the individual particles are necessary. Such models are available for some granular materials in 2D, see for example [7,8]. For future trustworthy numerical simulations of the local contact behavior in flow problems with iron ore pellets, physically realistic constitutive models need to be developed. To develop such models further, the mechanical properties have to be investigated. This paper describes the experimental and numerical work to investigate the mechanical properties for blast furnace iron ore pellets. Material parameters for an elastic–plastic constitutive model for iron ore pellets are also determined in terms of statistical means and standard deviations. This is an important input to model assemblies of iron ore pellets for studying interaction phenomena. The model and material data for single iron ore pellets worked out in this paper could be used to model the individual particles in an assembly.

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2. Theoretical considerations

Iron ore pellets are a hard and brittle porous material and can be compared with materials like rocks and ceramics. Theories developed for these materials have been used in this study.

2.1. Contact between a sphere and a plate

The elastic and elastic–plastic contact of a solid sphere and a plate, see Fig. 1, is a fundamental problem in contact mechanics. In the 19th century Hertz studied the contacts of elastic bodies [9]. The elastic contact of a sphere and a plate can be solved analytically according to the Hertz theory [10]. The elastic–plastic contact of a sphere and a plate is a more complex problem and can be studied analytically, see for example [11] or numerically with the FE method, see for example [12].

According to [13], the contact area A_p for a fully plastic contact is equal to the geometric intersection of the plate with the original non-deformed profile of the sphere

$$A_p = 2\pi R\omega \tag{1}$$

where R is the radius of the sphere. The contact mean pressure P and contact load F can be expressed in terms of the contact interference ω (see Fig. 1) as

$$P = \frac{4E^{Hz}}{3\pi}\left(\frac{\omega}{R}\right)^{1/2} \tag{2}$$

and

$$F = PA_p = \frac{8E^{Hz}R^{1/2}}{3}\omega^{3/2} \tag{3}$$

where E^{Hz} is the Hertz elastic modulus defined as

$$\frac{1}{E^{Hz}} = \frac{1-\upsilon^2}{E} + \frac{1-\upsilon'^2}{E'} \tag{4}$$

and E, E', υ, υ' are the Young's modulus and Poisson's ratio for the two materials, respectively. Combining Eqs. (3) and (4), substituting ω gives a relation for the elastic unloading interference $\omega^{e\text{-}unload}$ of a sphere and a plate from a fully plastic contact

$$\omega^{e-unload} = \sqrt[3]{\frac{9F^2}{64R}\left(\left(\frac{1-\upsilon^2}{E}\right) + \left(\frac{1-\upsilon'^2}{E'}\right)\right)^2} \tag{5}$$

The total interference ω^{tot} is the sum of the persistent interference after unloading ω^p and the elastic unloading interference according to

$$\omega^{tot} = \omega^p + \omega^{e-unload} \tag{6}$$

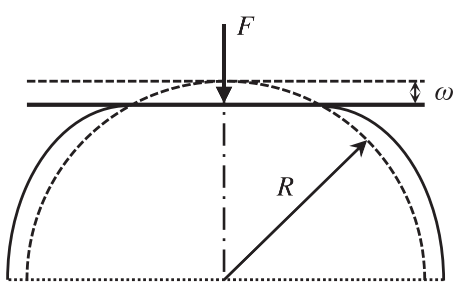

Fig. 1. A deformable solid sphere pressed by a plate. Definition of the contact interference ω.

Eqs. (5) and (6) are used in the determination of the Young's modulus of iron ore pellets.

2.2. Compression of an irregular test piece

Two very common indirect tensile strength test methods for rock and other brittle materials are the Brazilian disc test [14] and the point load test [15]. In the Brazilian disc test a compressive force is applied diametrically to a thin disc. The maximum tensile stress occurs in the middle and is determined by the Brazilian disc theory. The validity of the method has been investigated in [16,17] and has for instance been used for the determination of tensile strength in metal powder compacts [18,19]. A drawback of this method is the shape of the test pieces that has to fulfil the plane stress condition. Such a shape is hard to produce for many materials, as in the case for iron ore pellets.

A theoretical and practical study of the stress state in an irregular sphere-like test piece subjected to the point load test is given in [15]. The results show that the stress state in an irregular test piece subjected to concentrated loads may be, in the vicinity of the axis of loading, much the same as that in a perfectly spherical test piece compressed diametrically. According to their results the maximum tensile strength, S_t for an irregular test piece occur near the centre and is approximately given by

$$S_t = c\frac{F}{2\pi R^2} \tag{7}$$

where F is the applied force and $2R$ is the distance between the points of loading. The constant c is experimentally determined and takes a value between 1.21 and 1.36 in the centre of the test piece for rock materials. Following a vertical line from the centre to the load point, the value of c increases slightly with the distance to a maximum value of 1.4 near the centre for rock samples. For more details, see [15]. A schematic view of the two-point load test is shown in Fig. 2.

As a measure of the irregularity of the specimens, a shape index, η, is derived. The minimum diameter, D, is divided by the average diameter, $\bar{D}$, of the specimens according to

$$\eta = \frac{D}{\bar{D}} \tag{8}$$

The average diameter is calculated as the diameter of a sphere with the same mass, M, and density, ρ, as the specimen.

$$\bar{D} = \sqrt[3]{\frac{6M}{\pi\rho}} \tag{9}$$

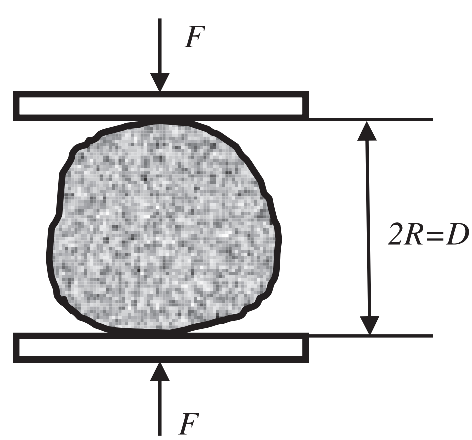

Fig. 2. Explanatory sketch of a two-point load test on an irregular test piece.