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The friction-free compressibility curve of bentonite block

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Abstract

Compressibility curves are widely used to describe the compaction behavior of powders. The friction between the powder and the wall of the mold during compaction results in over-estimation of the compaction force. This paper presents a method to correct this effect and obtain a 'friction-free' compressibility curve. The method is based on the friction force distribution theory. By eliminating the effects of wall friction force and specimen geometry, it is possible to determine the real compaction behavior of powders. A series of uniaxial compaction tests were conducted to establish the validity of the friction-free compaction concept. The data obtained from tests for various aspect ratios and lubrication conditions are shown to tend towards a unique friction-free compressibility curve, once results have been corrected for frictional effects.

Keywords: Friction-free compressibility curve; Uniaxial compaction; Wall friction; Bentonite block

1. Introduction

Compaction is the process of densification that decreases pore size and porosity and causes particle rearrangement when particle assemblies are compressed. Powder compaction is widely used for shape forming in powder metallurgy (Guyoncourt et al., 2001; Mosbah et al., 1997), in the ceramic industries (Briscoe and Rough, 1998a,b), and in forming blocks of buffer material to be placed around waste canisters in the underground disposal of nuclear waste (Yong et al., 1986; Boonsinsuk et al., 1991; Johannesson et al., 1995; Japan Nuclear Cycle Development Institute, 1999; Marcial et al., 2002).

The excellent sealing and swelling properties of highly compacted bentonite or bentonite–sand mixture blocks have made them the primary candidates for the geological isolation of high-level radioactive wastes (Pusch, 1994). Bentonite buffer material placed around canisters and as overpack has long been a feature of disposal concepts for high-level wastes and spent fuel disposal programmes in a number of countries (Grindrod et al., 1999). Performance assessment of compacted bentonite-based buffer material and blocks involves considerable research on permeability, swelling mechanics and diffusion (Borgesson, 1985; Oscarson et al., 1990; Graham et al., 1992; Wiebe et al., 1998; Komine and Ogata, 1999; Grindrod et al., 1999; Kozaki et al., 1999). Johoannesson and his coworkers have recently conducted studies on the compaction characteristics and large scale industrial production of various shapes of bentonite blocks (Johannesson and Börgesson, 1998; Johannesson et al., 1995, 2000).

Both isostatic compaction and uniaxial compaction are used to produce blocks. The advantage of isostatic compaction is that friction problems are avoided, resulting in homogeneous blocks. However, isostatic compaction has two major drawbacks: (1) considerable time-consuming and costly preparatory work is required; (2) the blocks need to be trimmed by a saw or a lathe after compaction. Uniaxial compaction saves time and produces precisely shaped blocks that do not need to be reshaped after compaction. The uniaxial compaction technique is widely used

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in powder and ceramic industries and in buffer material research.

The major disadvantage of uniaxial compaction is that the blocks may become inhomogeneous due to friction between the block and the die. Block-die wall friction causes non-uniform packing densities within the blocks. High wall friction creates high stress gradients within the block, and can result in significant density fluctuations within the block (Briscoe and Rough, 1998a,b).

Wall friction may be reduced in several ways including (1) the use of low aspect ratio samples (i.e. low block height to diameter ratio, H/D); (2) the use of both an upper and a lower piston during compaction; (3) compacting the powder at a high water content; (4) the use of lubricant on the die. Many kinds of lubricants, such as calcium stearate powder, zinc stearate powder, molybdenum disulfide dry film or silicon oil, have been applied to reduce the effect of wall friction (Li et al., 1996; Briscoe and Rough, 1998a,b; Johannesson, 1999; Tien et al., 2004a,b). However, it is impossible to eliminate the wall friction completely, even though lubricants, two pistons, and a low aspect ratio/high water content samples are used. Because the mechanism of powder compaction and the influence of wall friction are complicated and not fully understood, the influence of wall friction on any specific material during compaction is usually investigated through experiments.

Compressibility curves (i.e. graphs of applied force vs. density during uniaxial compaction), usually referred to as "compaction curves" in powder metallurgy, [not to be confused with "compaction curves" in geotechnical engineering] have been widely used to describe the compaction behavior of powders. The density of a block under a specified applied stress can be determined from the compressibility curve; the applied stress required to achieve a specific density of compaction can also be estimated from the curve. Different experimental conditions (aspect ratio, water content, lubrication, etc.) will result in different compressibility curves (because of different friction force). The compressibility curve does not represent the true compaction behavior of this powder material because of the die-specimen interfacial friction forces acting during the test.

In this paper, an analytical method is described which allows the wall friction force to be determined and separated from the effect of block geometry. This compressibility curve, in which the effect of the friction force has been removed, will be referred to as the "friction-free compressibility curve." The curve is not influenced by the compaction boundary condition, and represents the true compressibility behavior of the powder material, i.e. it shows the real friction-free compressibility curve for that specific powder material.

A series of compaction tests were performed. To validate the accuracy of this friction-free compressibility curve, Two bentonite powders were selected for the experiments.

The relationship between the applied compaction force and the wall friction force were determined experimentally for bentonite blocks of various aspect ratios and die wall lubricants. The results were used to deduce the intrinsic 'friction-free compressibility curve' for the two bentonite powders.

2. Analytical model

The wall friction force produced is due to powder and die wall interaction during compaction. The magnitude of wall friction is governed by the density of the powder and the applied stress. The effect of the wall friction is to reduce the effective compaction force (and density) with depth, such that the effective compaction force at the top of the block will differ from that at the base. The measured density during the uniaxial compaction test is an "average density" over the depth of the block (the weight of powder/ total volume of the block). The measured compaction force (at the top of the block) indicated on the compressibility curve overestimates the actual compaction force since the average density of the powder is less than the density at the top of the block. For a higher aspect ratio block at the same density, the applied compaction force will be greater. Similarly, the transmission force measured at the base of the block is the minimum compaction stress within the block. It does not represent the effective compaction stress in the compressibility curve.

The first step towards establishing the average compaction force corresponding to the average density is to understand the distribution of wall friction with depth.

2.1. Method of differential slices

The friction force during compaction is taken to be the interface friction between the block and wall of the die. An analytical model for friction stress distribution along a die wall, based on the "method of differential slices" was introduced by Janssen in 1895, and extended by Walker in 1966 (Neederman, 1992). The simple analysis is based on the following assumptions: (1) the stresses are uniform across any horizontal section of the block; (2) the principal stress directions acting on the block are vertical and horizontal; (3) the friction stress f_w (see Fig. 1) between the block and die wall is represented by Coulomb's equation:

$$f_w = \mu_w \sigma_r + c_w \quad (1)$$

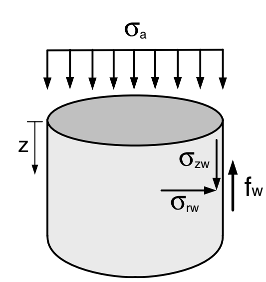

Fig. 1. Stress state in a bentonite block during compaction.