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Ultrasonic compaction of granular geological materials

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ABSTRACT

It has been shown that the compaction of granular materials for applications such as pharmaceutical tableting and plastic moulding can be enhanced by ultrasonic vibration of the compaction die. Ultrasonic vibrations can reduce the compaction pressure and increase particle fusion, leading to higher strength products. In this paper, the potential benefits of ultrasonics in the compaction of geological granular materials in downhole applications are explored, to gain insight into the effects of ultrasonic vibrations on compaction of different materials commonly encountered in sub-sea drilling. Ultrasonic vibrations are applied, using a resonant 20 kHz compactor, to the compaction of loose sand and drill waste cuttings derived from oolitic limestone, clean quartz sandstone, and slate-phyllite. For each material, a higher strain for a given compaction pressure was achieved, with higher sample density compared to that in the case of an absence of ultrasonics. The relationships between the operational parameters of ultrasonic vibration amplitude and true strain rate are explored and shown to be dependent on the physical characteristics of the compacting materials.

1. Introduction

The need to control the compaction of granular materials has been regarded as a vital element of improving performance in the pharmaceutical and manufacturing industries. For example, the densification or compaction of particles is an essential process in the production of tablet medications such as paracetamol, where a high breaking force limit is vital to prevent fragmentation or disintegration in product life. It has been demonstrated that this breaking force limit can be increased by increasing the density of the particulate, where the compaction process can be enhanced by generating particle motion in the substrate.

One of the earliest accounts of compaction control was published in 1961 [1], and detailed the need for improved densification of amalgam in the production of dental fillings. The motivation for this research was to promote an increase in compressive strength in the amalgam to reduce the likelihood of damage, such as fracture, before the material setting was complete. This was achieved through the regulation of condensation force, which in this case was the force required to compact the amalgam into the space required for the filling. The strength of the amalgam fillings was shown to be dependent on the condensation forces applied, where a general increase in strength was measured for higher condensation forces.

Research conducted in 1969 was an early attempt at incorporating ultrasonics into the amalgam compaction process [2]. However, it was concluded that the strength of the compacted form was independent of the method of compaction, for example pneumatic, ultrasonic or manual, but that the procedure for amalgam composition must be rigorously controlled. The application of ultrasonic vibrations to the compaction process was then introduced into other disciplines. For example, it was demonstrated in 1981 that ultrasonics could be used to produce high-strength plastic mouldings from polypropylene powder [3]. It was found that ultrasonics was more effective on compaction of smaller particle sizes, where higher strength moulds could be produced, and the pressure applied to the material did not significantly affect the mould strength. An important observation was that the resulting heating of the substrate material promoted increased fusion in the particles, thus improving the mould strength [3]. In 1990 it was shown that ultrasonics only contributes a significant effect to the compaction of substrate material if the compaction pressure is lower than a critical value [4]. By this time, ultrasonics had been utilised to increase Weibull modulus and density, and also to reduce the force required for compaction [4]. However, the effect of compaction pressure on the ability of ultrasonics to confer a notable change to substrate material was not well understood. It was shown that above a critical pressure, ultrasonic vibrations did

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not affect the green density. The critical pressure was determined to be related to how much the particles within a substrate could move, and was dependent on amplitude of ultrasonic vibration, application time, and the frequency. Further research into the application of ultrasonics in manufacturing processes continued with the production of high-strength ceramics [5,6], where ultrasonic vibrations were shown to reduce porosity, increase ceramic density, and improve grain homogeneity within the fabricated ceramic by eliminating a high proportion of agglomerates and spheroids.

Research continued to investigate the effects of ultrasonic compaction on the properties of substrate materials, but also concentrated on the reduction of measured force on the working tool. For example, it was found that the application of ultrasonics during compaction in the production of paracetamol and ibuprofen tablets significantly reduced the required pressure, thus decreasing the load on the compactor tool [7,8]. More recently, there has been an increased focus on the design of ultrasonic compactor tools, for example by using finite element analysis (FEA), to achieve high compaction performance [9–11]. FEA has enabled the tuned frequency and mode of vibration of the compactor to be controlled, whilst ensuring the mechanical properties of the compactor are sufficient to withstand the compaction loads.

In mechanical compaction, there exist two principal stages [12], summarised generally in Fig. 1. The first is reorientation of the particles within the sample, before a critical stress threshold is reached, where very high physical deformation, or a crushing, of the particles takes place. In this secondary compaction phase, the relative motion between particles is very high and particle packing is thereby enhanced [12]. For the compaction processes studied in this paper, the critical stress under different operational conditions of compaction is of interest. However, the influence of the physical characteristics of the granular geological materials is also very important. Although it has been reported that particle mineralogy and shape both affect the performance of an ultrasonic compaction process [12,13], the influence of geological materials is unclear. There has been conflicting evidence between different studies with respect to the influence of vibrations on densification [14], and it has been proposed that significant differences between the physical properties of the particles, such as grain size and density, are contributory factors. It has also been reported that there is a significantly increased density and particle distribution uniformity within the granular material achieved when ultrasonic excitation is superimposed on the compaction process [9].

Ultrasonic vibrations have been applied to granular material not just for compaction. For example, ultrasonic penetration into sand has been investigated for planetary drilling [18], where the application of ultrasonic vibrations has been shown to reduce the measured force on the penetrator/drill by generating fluidised behaviour in the granular material. In the vibration of granular material such as sand particles, it is known that there is a stage at which the particles begin to behave more like a fluid than a solid. This can be referred to as the fluidisation transition [14]. Convection motion has been shown to be influential in how the particles move from a solid-like state to fluid. There is also an intermediate region which is produced, and contains material which cannot be classed as either fully compacted or fluidised. A sample of material undergoing compaction could exist as solid, densely-packed material in one region, but fluidised in another. It has been reported that the physical properties of granular materials, such as the particle size and the density, can affect the densification [14], however it remains evident that three zones exist, comprising a lowermost marginally compacted area, a significantly compacted middle layer, and a fluidised top layer resulting from convection. The depth of the fluidised region has been reported to be only weakly linked to the initial sample density [14]. Porosity is a property of a material which is closely related to the density, and reduces as the density increases. It is known that the porosity within a sample of granular material depends on the particle size and shape, the material composition, and also the distribution of the particles [12].

The influence of the direction in which the vibrations are applied to the substrate has also been reported [9,14,19]. In one study, a test setup was manufactured to generate vibrations in the plane of the face of a cylindrical sample (horizontal) and in the axial (vertical) direction [9]. The distinction between the two directions was suggested to be important, because the motion of the particles can change as the granular material is agitated in different ways and settles into voids within the sample. In the case of horizontal vibrations, the rate of compaction increases with respect to ultrasonic vibration acceleration amplitude, however it was reported that these parameters are independent for vertical vibrations [19]. Therefore, horizontal vibrations appear to generate a higher level of compaction than vertical vibrations. In addition, it is known that for horizontal vibrations, the effect of acceleration amplitude decreases as the void ratio, which is a measure of the porosity in the sample, is reduced [19]. Applying ultrasonic vibrations has been found to be successful in reducing the number of voids in the production of white mineral trioxide aggregate (an endodontic cement), and also increases the density [15,16]. It was also suggested that the ultrasonic frequency and the duration of ultrasonic vibration could affect the arrangement of the particles within the endodontic cement sample [16]. It was demonstrated that if ultrasonic vibrations were applied to the material for too long, large voids were produced which could be detected using radiography. Other research into the application of ultrasonic

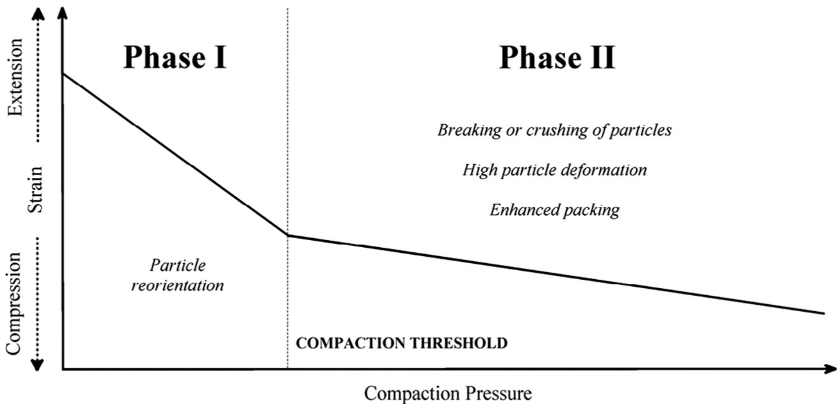

Fig. 1. Simplified schematic of mechanical compaction.