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Drop impact behaviour on alternately hydrophobic and hydrophilic layered bead packs

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ABSTRACT

A high level of water repellency in soils has an impact on soil hydrology, plant growth and soil erosion. Studies have been performed previously on model soils; consisting of close packed layers of glass spheres (140–400 μm in diameter), to mimic the behaviour of rain water on water repellent soils. In this study measurements were performed on multi-layered bead packs, to assess the interaction of water drops impacting layers consisting of different hydrophobic and hydrophilic layers. A high speed video camera was used to record the impact behaviour of water droplets on the bead packs focussing on the spreading of the droplet and the subsequent rebound behaviour of the droplet. Observations were made from the videos of the liquid marble effect on the droplet, whereby hydrophobic particles form a coating around the droplet, and how it differed depending on the arrangement of hydrophobic and hydrophilic layers within the bead pack. The droplet release height was varied in order to establish a relationship between impact velocity and the degree to which liquid marbling occurs, with higher impact speeds leading to a greater degree of liquid marbling. Measurements were also made to find the transition speeds between the three rebound conditions; rebound, pinning and fragmentation, showing an overall decrease in pinning velocity as the bead size increased.

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1. Introduction

Hydrophobicity is normally defined by the size of the contact angle of a water droplet on a surface. A more water repellent surface will result in a droplet exhibiting a high contact angle when in contact with the surface (Shirtcliffe et al., 2010). In the case of a rough surface, such as soil, water will typically take on one of two different wetting states, Fig. 1. The Cassie–Baxter state is where the water cannot infiltrate the gaps between the surface roughness, leaving a layer of trapped air below the liquid (Cassie and Baxter, 1944). In the Wenzel state the

liquid infiltrates the gaps and increases the surface contact area (Wenzel, 1936). While chemically induced hydrophobicity has a contact angle upper limit of $\approx 120^\circ$, as shown by fluoropolymers such as polytetrafluoroethylene (PTFE) (Zisman, 1964); complex surface topography can increase the contact angle even further, with super-hydrophobic materials having a contact angle of over 160° .

Typically the minerals found naturally in soils, e.g. silica in sandy soils, display hydrophilic properties. However, with the addition of contaminants, such as oils, other naturally occurring organic matter, the soil particles can become hydrophobic

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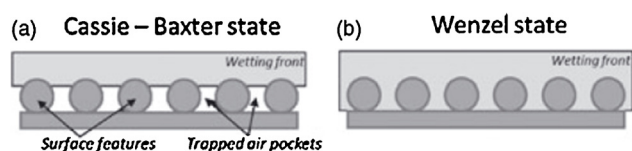


Fig. 1 – Diagram showing the (a) Cassie–Baxter and (b) Wenzel states of wetting. (Hamlett et al., 2013).

(Doerr et al., 2000; Ellerbrock et al., 2005; Atanassova and Doerr, 2010). Due to their granular nature, soil particles will form a matrix with a hierarchical structure with individual grains providing a rough topography; and each individual particle also possessing a rough surface. Combining this rough surface structure with the chemical water repellency of the organic compounds, a soil matrix can achieve high levels of hydrophobicity (McHale et al., 2005; McHale et al., 2007; Shirtcliffe et al., 2006; Bachmann and McHale, 2009).

Such high levels of hydrophobicity can have a number of deleterious effects on the natural landscape. Soil erosion during rainfall can become more pronounced (Terry and Shakesby, 1993), due to reduced water infiltration and hence an increase in surface runoff. The reduced infiltration results in drier soils that can also lead to an increase in wind erosion (DeBano, 2000). In addition there may be a corresponding reduction in the germination and growth of vegetation with the lower availability of water within the soil matrix.

Previous work has attempted to model the effects of water drop impacts on soils by using glass beads as a model soil (Hamlett et al., 2011, 2013; Ahn et al., 2013). Hamlett et al. (2013) investigated the behaviour of water drop impacts on bead packs (a layer of close packed, immobile beads with two layers of close packed, loose beads on top) which consisted of a single type of wettability (either hydrophobic or hydrophilic) throughout the entire depth of the bead pack. The authors investigated the pinning behaviour of the bead packs, where the droplet strikes the bead pack, spreads out, recoils and then cannot fully rebound from the surface and remains attached to the surface upon recoil, see Fig. 2.

This study expands on this and investigates the effect of layers of different hydrophobicity throughout the depth of the bead pack on both the drop impact behaviour and on the formation of liquid marbles (Aussillous and Quere, 2001; Nguyen et al., 2010). The effect on drop penetration and liquid marbling of mixing of hydrophobic and hydrophilic particles in powder beds was investigated by Nguyen et al. (2009), finding a reduction in drop penetration as the proportion of

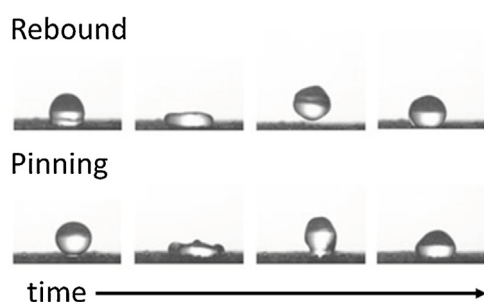


Fig. 2 – Images, taken from a high speed video recording, show the difference between rebound and pinning behaviour of a droplet impacting on a fixed, particulate surface.

hydrophobic particles increases. In this study the hydrophobic and hydrophilic particles are formed into discrete layers.

2. Experimental method

The experiment involved the creation of a number of bead packs, using glass beads between 140 μm and 400 μm (Worff Glaskugeln GmbH, Germany). Beads were ordered in a number of different colours in order to distinguish different layers within the bead packs. Before the bead packs could be created the beads were sieved and treated to make them either hydrophobic or hydrophilic. To sort the beads they were placed into small-scale sieves (Endecotts Ltd, UK) and an Endecotts Minor 200 sieve shaker (Endecotts Ltd, UK) to separate them into size categories. The categories used in this study are 140–160 μm , 160–180 μm , 180–200 μm , 250–300 μm and 400 μm , which correspond to fine and medium sized sandy soils (Soil Survey Division Staff., 1993).

Both hydrophobic and hydrophilic beads were needed for this study, and this required two separate processes. The first step was common to both types of beads and involved the beads being immersed in HCl (30 vol%) for 24 h, then rinsed thoroughly with deionised water (DI) until a strip of indicator paper showed that the DI water, after rinsing the beads, was neutral. Finally the beads were then placed in an oven at 80 $^{\circ}\text{C}$ for 3 h in order to dry the beads completely.

To make the hydrophobic beads, some of those previously cleaned with HCl were treated using Granger's Extreme Wash-In (Grangers, UK). A solution of Granger's in DI was prepared (5 vol%) and the beads were immersed in the solution for 1 hour. The beads were then dried in an oven at 80 $^{\circ}\text{C}$ for 3 h. Using a DSA 10 contact angle meter (Krüss, Germany) and analysed using DSA software (Krüss), the hydrophobised beads showed contact angles from 117 $^{\circ}$ to 133 $^{\circ}$. The contact angle of each bead size was measure twice, showing no correlation between bead size and contact angle and a standard deviation of 5.60. A contact angle of 133 $^{\circ}$ is comparable to a contact angle of 130 $^{\circ}$ found by McHale et al on sand particles approximately 200 μm in size (McHale et al., 2005).

The hydrophilic beads were made by applying a titanium oxide coating to the surface of the beads. While glass is typically hydrophilic after being cleaned with HCl (Hamlett et al., 2013), the colour coating on the beads caused them to be hydrophobic. The beads were placed into a small dish and then into an Emitech K575X sputter coater (Quorum Technologies Ltd, UK). Titanium was sputtered onto the beads for 3 min at a current of 150 mA; the beads were then agitated and sputtered again to coat all sides of the beads. Next the titanium coated beads were place into an ozone cleaner (BIO-FORCE Nanosciences, USA) for 20 min in order to produce an oxide layer on the surface of the beads. Water droplets placed onto the ozone treated beads immediately imbibed into the bead pack, as a result it was not possible to take contact angle measurements.

The bead packs consisted of three layers, a close packed base layer which was fixed in place and two loose layers on top of this. To produce the base layer, a mono layer of beads was fixed to a microscope slide using double sided tape. The fixed layer was then sputtered with Ti for 3 min at 150 mA and then gold (Au) for 3 min at 85 mA. If hydrophobic base layers were needed, they were treated with Granger's as above; hydrophilic base layers had a further layer of Ti sputter as above and then ozone treated as above to form an oxide layer. To form the

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