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Pore geometry as a control on rock strength

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ABSTRACT

The strength of rocks in the subsurface is critically important across the geosciences, with implications for fluid flow, mineralisation, seismicity, and the deep biosphere. Most studies of porous rock strength consider the scalar quantity of porosity, in which strength shows a broadly inverse relationship with total porosity, but pore shape is not explicitly defined. Here we use a combination of uniaxial compressive strength measurements of isotropic and anisotropic porous lava samples, and numerical modelling to consider the influence of pore shape on rock strength. Micro computed tomography (CT) shows that pores range from sub-spherical to elongate and flat ellipsoids. Samples that contain flat pores are weaker if compression is applied parallel to the short axis (i.e. across the minimum curvature), compared to compression applied parallel to the long axis (i.e. across the maximum curvature). Numerical models for elliptical pores show that compression applied across the minimum curvature results in relatively broad amplification of stress, compared to compression applied across the maximum curvature. Certain pore shapes may be relatively stable and remain open in the upper crust under a given remote stress field, while others are inherently weak. Quantifying the shape, orientations, and statistical distributions of pores is therefore a critical step in strength testing of rocks.

1. Introduction

Numerical and experimental studies of strength across material sciences, biomechanics, and geology, show a strong link between porosity and strength in both natural and manufactured porous materials: an increase in porosity or pore size is typically associated with a decrease in brittle strength and fracture toughness (Fig. 1: e.g. Al-Harthi et al., 1999; Palchik, 1999; Sabatakakis et al., 2008; Heap et al., 2009, 2014; Lian et al., 2011; Meille et al., 2012; Schaefer et al., 2015). Fig. 1 shows that although there is a broad inverse relationship between strength and porosity, strength ranges substantially for a given porosity. Notably, it is typical for studies of the strength of porous rocks to tacitly assume isotropic pore shape. The mechanical response of rocks that exhibit foliations (e.g., bedding, banding, or fractures) is strongly controlled by the relative orientation of the applied load and foliation plane (i.e. the β-angle: e.g. Paterson and Wong, 2005). In the case of fractures, which are often modelled as penny-shaped cracks (i.e. oblate ellipsoidal pores, with semi-axes $a = b \gg c$), the aspect ratio (which we define here as c/a, such that a high aspect ratio approaches a sphere with value 1, and a low aspect ratio approaches 0) is so low ($\ll 0.1$) that compression applied to the short axis facilitates elastic closure and strengthening; compression parallel (or at a low angle) to the crack long axes promotes opening and weakening (e.g. Sibson, 1985). Rocks can also contain prolate to oblate pores with aspect ratios between those of spherical pores and planar discontinuities (i.e. aspect ratios in the range 0.1–1.0). In such cases, elastic closure of the short axis dimension is not possible for most rocks, and the mechanical response should be expected to differ from rocks containing penny shaped cracks. Pore geometry, and the resulting mechanical influence, is poorly documented in studies of rock strength. Here we use physical and mechanical characterisation of minimally weathered, 750–1500 year old olivine–tholeiite lava (henceforth, *basalt* lava) from the south flank of Kilauea Volcano, Hawai'i, to constrain the effect of relatively high aspect ratio pores (i.e., vesicles with aspect ratios >0.1) on rock strength, through a combination of Uniaxial Compressive Strength (UCS) tests, and numerical modelling. We show that pore geometry – not just the scalar quantity of porosity – provides a fundamental control on rock strength. Therefore, unless pore geometry is well characterised and the effective bulk orientation of the pores are known with respect to the principal stress axes, mechanical test results are not directly comparable.

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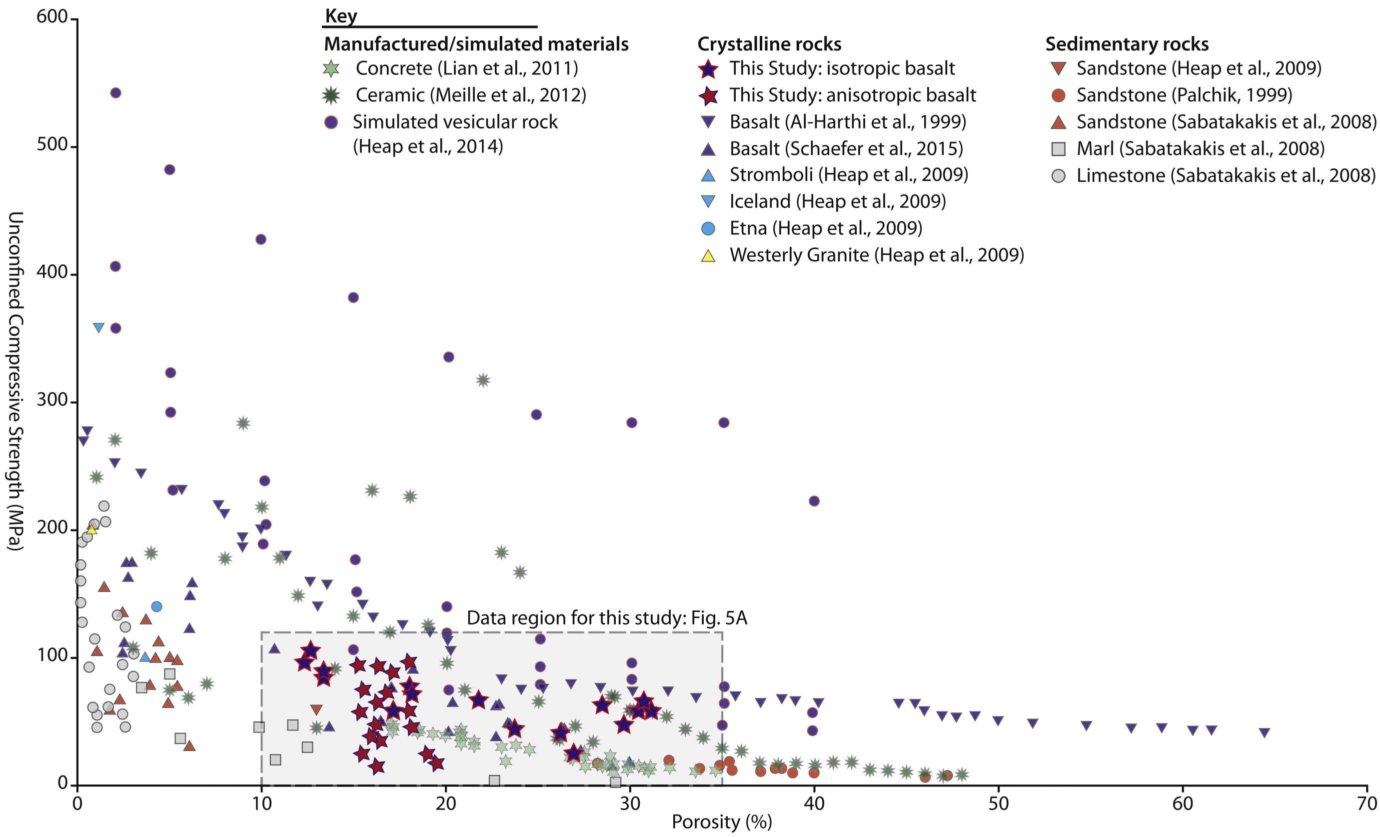

Fig. 1. The relationship between pore fraction and the strength of porous materials. Grey box highlights experimental data for this study.

2. Background and methods

2.1. Kilauea pahoehoe lava

Small volume tholeiitic pahoehoe lavas are emplaced as non-channelised, inflated sheets on the subhorizontal (1–2°) south flank of Kilauea Volcano. Sheet flows have been observed as thin layers (10–50 cm thick), inflating to thicknesses as great as 4 m (e.g. Hon et al., 1994). Samples were collected from exposed lavas along open portions of the ENE-WSW striking Kulanaokuaiki fault, located at the eastern end of the Koa'e fault system, 6–7 km south of Kilauea's summit caldera (Fig. 2). Normal faults in the Koa'e system develop at shallow depths (<5 km: e.g. Lin and Okubo, 2016) with the early stages of fault propagation associated with the opening of extension fractures that reactivate pre-existing cooling joints, where observed in the near surface (e.g., Duffield, 1975). The Kulanaokuaiki fault accommodates 0 to 15 m of displacement (Duffield, 1975), and was most recently active during the December 1965 eruption of Kilauea. Careful characterisation of several lavas exposed in the fault footwall reveals a distinctive 3-zone physical stratigraphy based on the total volume and geometry of vesicles and the scale of joint patterns: (1) a top of 18–31% porosity, with sub-spherical vesicles up to 4 mm in diameter; (2) a core of 12–13% porosity, with sub-spherical vesicles up to 1.5 mm in diameter; and (3) a base, of 15–19% porosity, with oblate or amalgamated vesicles up to 15 mm in diameter. The thickness of these three zones scale proportionally with the thickness of a lava, and representative samples were targeted for each zone. Basalt lava samples for this study are fine grained with porphyritic texture; phenocrysts are dominantly of olivine and plagioclase, set in a matrix of plagioclase and pyroxene. Olivine phenocrysts are typically euhedral up to 1.00–1.25 mm in size.

Field and hand sample observations show that oblate vesicles in the basal zone are aligned sub-horizontally, parallel to bedding; in the lava core and top zones, the minor fraction of non-spherical vesicles appear to be randomly oriented. Porosity was obtained for samples from each zone, using the submerged-mass saturation and calliper method, following the International Society for Rock Mechanics (ISRM) suggested methodology (Bieniawski and Bernede, 1979). Porosity in these basalt lava samples is primarily in the form of vesicles, but hereafter we will refer to all sample porosity as *pores*.

2.2. CT and volume analysis

Lava samples were analysed using a Nikon XT225 Metris X-ray computed tomography (X-ray CT) scanner to determine total porosity, and pore shape. Sample cores were imaged via a series of X-ray slices resulting in ∼3000 images collected at 0.12° increments in a 360° rotation. The X-ray beam attenuates in a known way with material density (e.g. Roche et al., 2010); this allows the X-ray signal to be mapped to material density. Images are assigned discrete digital grey values (0–255) according to the material density, represented by voxels: pixels in 3-dimensional space (*x*, *y*, *z* coordinates). Using the 3-D image volume graphics package, VGStudio, each sample volume was reconstructed using a threshold procedure to derive an isosurface to define material boundaries. The isosurface was manually derived for each sample to find the best fit to the real surface area and define volumes of solid space (white voxels) and background (black voxels). Inversion of the grey scale of the solid material within each sample isolated the lowest densities – the empty pores (vesicles) – and permitted the accurate determination of the volume, and geometry, of pore spaces in each of the lava samples. The average voxel resolution for the technique, using 37 mm diameter cores, is ∼50–70 µm. Values

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