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Interpretations on how the macroscopic mechanical behavior of sandstone affected by microscopic properties—Revealed by bonded-particle model

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ABSTRACT

Macroscopic mechanical properties of sandstones, such as uniaxial compressive strength and Young's modulus were found to be significantly affected by their petrographic properties, e.g. the porosity ***n*** and the grain area ration ***GAR***. The intricate relationship between the macroscopic properties of sandstones and their petrographic or microscopic properties necessitates further study in exploring how the microscopic properties influence the macroscopic mechanical behavior.

In this research, numerical analyses based on the bonded-particle model, the microscopic properties of which originated from the bonded strength and stiffness, were thus conducted as a systematic study aiming at unraveling these microscopic mechanisms. A series of tests was conducted, and the results were compared with the actual behavior of sandstone. A numerical model comprised of three types of particles, grain particles ***GP***, matrix particles ***MP*** and porous matrix particles ***PP***, was accordingly proposed to represent the sandstone. The results of analyses demonstrated how the petrographic parameter ***GAR*** and porosity ***n*** determined the proportions and the numbers of ***GP***, ***MP*** and ***PP***. The strength and stiffness of these bonds were estimated based on back analyses. Accordingly, the results of parametric study indicate that matrix particles tend to have stronger bonding strength yet softer stiffness, when compared to the grain particles.

1. Introduction

Sandstone is a detrital sedimentary rock composed of rock fragments and mineral grains. The macroscopic mechanical behavior of sandstones, the uniaxial compressive strength (***UCS***) (ISRM, 1981) for instance, is inherently affected by the microscopic properties of the sandstone, e.g. the mineral types, porosity, bonding strength, etc. of the constituting particles. How do these microscopic properties of sandstones affect the macroscopic mechanical behavior of these rocks had been focus of interests in a number of recent researches. The influence of microscopic factors on the macroscopic strength of rock, were studied by various researchers with regard to the following aspects:

a) Mineralogical composition—The quartz content may contribute positively to the uniaxial compressive strength of sandstones (Smart et al., 1982; Gunsallus and Kulhaway, 1984; Shakoor and Bonelli, 1991). Nevertheless, there are situations that the quartz content of sandstones has no effect on their strength (Bell, 1978; Barbour et al., 1979; Dobereiner and De Freitas, 1986).
b) Cement and matrix—The strengths of sandstones are closely related to their cementation. Sandstones with higher cement content tend to have higher strength than those with lower cement content (Clough et al., 1981; David et al., 1998). The type of cement also affects the sandstones' strength. For instance, sandstones with silica or calcareous cement have higher strength than the ones with clay mineral cement (Vutukuri et al., 1974). The term “matrix” is often referred to the fine particles between the grains. In sedimentology, these fine particles in fact include “matrix” deposited during sediment processes and “matrix” formed during diagenetic processes. In practice, especially when observing thin sections, it is difficult to distinguish the cement content within the fine particles. Hereinafter, the term “matrix” used in this work refers to the mixture of fine particles including both matrix and cement. As such, the matrix may exhibit bonding strength owing to the cement content within it.
c) Grain size—The effect of grain size on the strengths of sandstones may vary in accordance with the particular types of rocks studied. It has been found that increase in grain sizes results in decrease in uniaxial compressive strength for greywacke (Singh, 1988). While in other cases, there are no correlation between the grain size and the strength (Shakoor and Bonelli, 1991; Plachik, 1999).
d) Grain particle packing—The compactness of grain particle packing can be described by parameters such as the packing density, the grain contact, and the grain area ratio (***GAR***), which is defined as the ratio between the grain area and the total area in the selected range of the specimen image (Ersoy and Waller, 1995). Dobereiner and De Freitas (1986) suggested the strength of sandstones has no obvious correlation with the packing density, but positively correlates to the grain contact. Bell (1978) and Bell and Culshaw (1993),

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however, suggested higher packing density results in higher material strength.

Furthermore, other fundamental physical properties such as porosity, unit weight, and water content have been correlated to the uniaxial compressive strength of rocks (Dyke and Dobereiner, 1991; Hawkins and McConnell, 1992; Jeng et al., 1994; Hatzor and Plachik, 1997, 1998; Plachik, 1999; Jeng et al., 2002, 2004; Lin et al., 2005; Weng et al., 2005, 2008; Tsai et al., 2008). It was showed the strength decreases with increasing porosity and water content, and increases with increasing unit weight.

Jeng et al. (2004) and Weng et al. (2005) performed mechanical experiments and petrographic analyses on 13 different sandstone layers collected from the Western Foothill Range in Taiwan. The voids between particles can be either empty or partly filled with matrix materials. It has been found that fracture surfaces tend to go through particle–particle contacts or in between matrix when the sandstone is dry or wet, respectively (Lin et al., 2005).

In addition, since grains, matrix and porosity constitute the whole sandstone; how these entities affect the macro behavior is of interest. Through petrographic analysis, the influences of microscopic parameters (or petrographic parameters) on the macroscopic mechanical behaviors had been studied. Two parameters, the porosity $\boldsymbol{n}$ and the grain area ratio ***GAR*** were found to be the key parameters (Jeng et al., 2004). As a result, the uniaxial compressive strength (***UCS***) can be related to porosity $\boldsymbol{n}$ and ***GAR*** as shown in Eq. (1).

$$\mathrm{UCS} = \left(133.7 \cdot e^{-0.107n}\right)(3.2 - 0.026\,\mathrm{GAR}) \tag{1}$$

Unit: MPa

Furthermore, the deformability (Young's modulus ***E***) was found to be related to porosity $\boldsymbol{n}$ and ***GAR*** as well (Jeng et al., 2004) and can be expressed as:

$$\mathrm{E} = \left(36.3 \cdot e^{-0.106n}\right)(0.354 + 0.017\,\mathrm{GAR}) \tag{2}$$

Unit: GPa

From Eq. (2), it indicates that the Young's modulus of sandstones decreases with increasing porosity $\boldsymbol{n}$ and with decreasing ***GAR***. It should be noted that the porosity $\boldsymbol{n}$ typically ranges between 5% and 25%, and ***GAR*** ranges between 20% and 75% for the studied sandstones. These two empirical equations, Eqs. (1) and (2), represent how the macroscopic strength and deformability of natural sandstones are related to porosity $\boldsymbol{n}$ and ***GAR***. These empirical equations have been compared to sandstone worldwide (Bell and Culshaw, 1993, 1998; Ulusay et al., 1994) and were found to be consistent with the behavior of sandstones studied.

These two equations are adopted as the key relations to be met when validating and modifying numerical models and later analyses.

Some of the microscopic properties of rock can be directly measured or observed. For instance, the type of mineral and packing of grains can be measured from observing the thin sections of rocks under microscope. However, some other properties, e.g. the strength of matrix or the bonding strength of the grains, are difficult to measure directly. Moreover, in studying the influence of a particular microscopic factor, it would be ideal if the factor of interest could be varied while the other factors remained unchanged. Unfortunately, when natural rocks are used, frequently more than one factor will vary from specimen to specimen, rendering it difficult to evaluate, on identical bases, the unbiased influence of a particular factor.

There is very little study on the effect of matrix strength and stiffness on the macroscopic strength of rock. Despite these difficulties, a numerical model that is capable of accounting for the discrete packing nature of grains and the bonding strength, can serve as convenient means in studying the influence of microscopic properties on the macroscopic behavior of rock. Among the existing discrete numerical models, bonded-particle model (BPM) possesses the desirable requirements mentioned above, and this model was firstly tested and eventually adopted in this research. By using BPM, the bonding strength between the matrix and the grain can be systematically varied and the corresponding variation of macroscopic mechanical behavior can be observed. As a result, clarification on the effects of the matrix on mechanical behaviors of sandstones is accordingly obtained.

2. Methodology—a modified bonded-particle model

The framework of this study is illustrated in Fig. 1. Before adopting BPM for studying microscopic mechanisms, the numerical model must be tested and modified until it shows adequate macroscopic mechanical behavior. Therefore, as shown in Fig. 1, uniaxial compress tests were simulated and compared (*Steps 1* and *2*) and the results were verified (*Verification I*).

As such, the uniaxial compression was first modeled using BPM, and it was revised iteratively until it yields reasonable macroscopic uniaxial compression behavior (similar uniaxial compressive strength and Young's modulus). This test also serves the purpose of determining BPM's microscopic parameters. After the test, a 2-dimensional numerical model was found to be capable of yielding a reasonable macroscopic mechanical response and was thus adopted as the tool for further analyses.

2.1. Setup of the modified BPM

In this study, a bonded-particle model (Potyondy and Cundall, 2004), which enables assembly and bonding of discrete circle particles, is considered for simulating the aggregation and cementation of the sandstone. Intuitively, the bonded-particle model differs from the natural sandstone in the following aspects: (1) the grains of nature

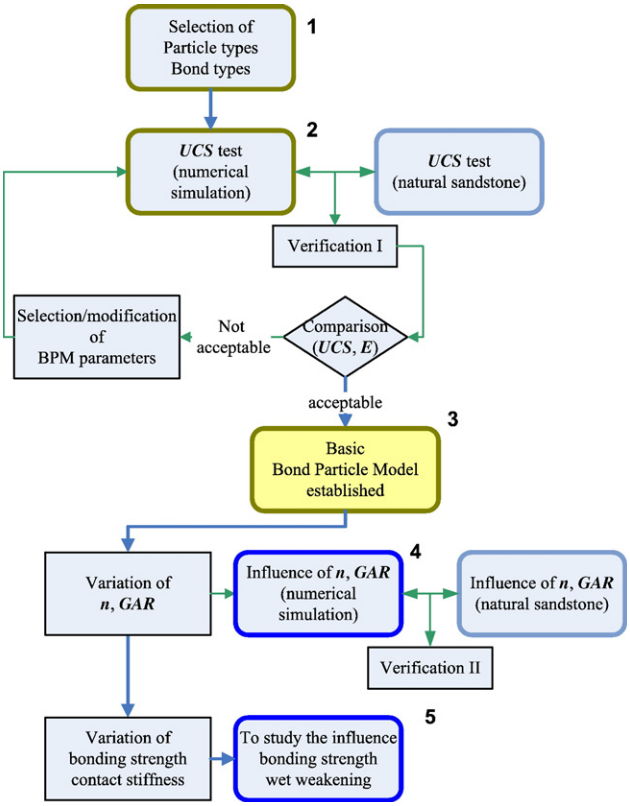

Fig. 1. Schematic illustration of the framework of this research.