Amirkabir Journal of Civil Engineering

Amirkabir J. Civil Eng., 54(6) (2022) 441-444
DOI: 10.22060/ceej.2021.19765.7255

Evaluation of the effect of shape of granular materials on uniaxial compressibility behavior by analytical and experimental methods

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ABSTRACT: Granular materials used today in many engineering projects, such as rockfill dams and railways, have a wide variety of shapes. This shape variation ranges from very sharp to perfectly rounded. The shape of the aggregates affects the mechanical properties of the grain, including fracture strength and internal friction angle. As a result, the mechanical behavior of the mass of granular materials depends on the shape of the grains. In order to investigate the effect of this property, different types of grains in the shapes of spheres, cylinders, cubes and pyramids, which include a wide range of shapes of natural aggregates, were made artificially in size range of 1.5 to 2.0 cm. Small-scale uniaxial compressibility tests were performed on each of the grain shapes under the same conditions including initial porosity ratio and maximum stress and after each experiment, the stress-strain behavior and the amount of breakage were obtained using the Hardin breakage factor. Then, the results were evaluated using an analytical model proposed by McDowell et al. based on the law of conservation of energy. This model has 7 parameters that depend on the initial conditions of the grains, material, shape, size and fracture strength of the grains. Comparison and evaluation of the results indicates the ability of the analytical model to predict the compressibility behavior of pyramidal grains. As the grains become angular, the compressibility and breakage of the materials increase. Also, with increasing the fracture surface energy of the material, the effect of shape on compressibility decreases.

Review History:

Received: Mar. 18, 2021
Revised: Sep. 13, 2021
Accepted: Nov. 01, 2021
Available Online: Nov. 14, 2021

Keywords:

Uniaxial compressibility
Shape effect
Weibull theory
Fractal theory
Grains

1- Introduction

Grain shape is an important factor affecting the mechanical behavior of granular materials used in rockfill dams, railway ballast and wherever these materials are subjected to high stresses. Generally, granular materials are categorized into two total shapes, angular and rounded. Angular materials are obtained through the blasting of quarries while rounded materials are obtained through river beds. This physical property influences mechanical characteristics such as compressibility, fracture strength, distribution of contact forces and friction between the grains [1, 2].

Previous laboratory researches mainly focused on comparing the behavior of granular materials with different shapes of rounded and angular [3, 4]. Whereas the shape of the grains was not applied as an independent parameter in the constitutive equations of the grains and its effect was not evaluated parametrically.

In this research, the model proposed by McDowell et al. [5] is used to evaluate the uniaxial compressibility behavior of granular materials in different shapes. To ensure the applicability of this model, uniaxial compression tests are performed on artificial granular materials that are made in four different shapes of sphere, cylinder, cube and pyramid but with the same volume. After evaluating the laboratory results with the above-mentioned analytical model and performing similar experiments on natural materials scaled with artificial granules, the compressibility behavior of granular materials is evaluated.

2- Methodology

2- 1- Analytical equation

In order to investigate the mechanical behavior of the granular materials mathematically, a constitutive equation needs to be used. Different forms of equations in terms of energy, fracture mechanic and critical state were proposed so far [6]. Each of these relations has its own advantages and disadvantages. But there is an important point that these relations did not take into account the grain shapes as an independent parameter. For this purpose, to apply the effect of shape on the behavior of granular materials, the model proposed by McDowell et al. (1996) is used [5]:

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$$q\delta\varepsilon_q^P + p'\delta\varepsilon_v^P = Mp'\delta\varepsilon_q^P + \frac{\Gamma ds}{V_s(1+e_0)} \quad (1)$$

q is the deviatoric stress, P' is the isotropic stress, $\delta\varepsilon^p_q$ and $\delta\varepsilon^p_v$ are the increments of shear plastic and volumetric plastic strains, respectively. Γ is the fracture surface energy of the material, Vs is the total volume of the grains, ds is the change in the side surface of the grains due to fracture and M is a parameter dependent on the friction of the material. Using the statistical theory of grain strength, proposed by Weibull (1939) [7] and fractal theory [8], the final form of the uniaxial compressibility equation of the granular materials will be as follows [5]:

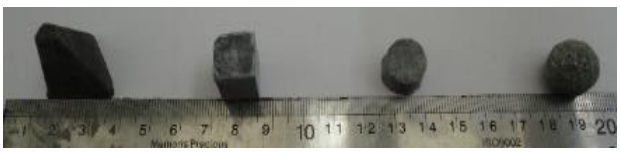
$$\delta e^P = \beta\left[\mathrm{Ln}\frac{1}{1-P_s}\right]^{0.5*(1-D)} \frac{\Gamma}{(1-\mu)d_0}\cdots (2-D)m\sigma_0^{0.5\times m(1-D)}\sigma^{((0.5\times m(D-1))-1)}\frac{d\sigma}{\sigma} \quad (2)$$

δe^P is the increment of void ratio, D is the fractal dimension, m is the Weibull modulus, μ is the coefficient dependent on friction, σ_0 is the characteristic strength and P_s is the survival probability of the materials and β is the shape factor. The behavior of the model depends on the value of 0.5×m(D-2)-1 which is named as convexity coefficient. Experimental results indicate that the convexity coefficient should be greater than zero.

2- 2- Experimental tests

Reactive powder concrete (RPC) can be considered as a suitable alternative material for modeling high-strength rock aggregates. Figure 1 shows the shape of the RPC grains.

Granite grains in the same size range as RPC grains (small scale) were prepared, either. It should be noted that to characterize the shape of the grains, the sphericity factor (S) defined by Cho et al. (2006) was used [1]. Loadings were performed in three forces of 4, 8 and 16 ton in a cylindrical mold with a diameter of 22.5 cm and height of 9 cm. The initial void ratio was 0.80 and constant at all tests. The values of force and displacement were recorded by a data logger and grading tests were performed after each test to measure the Hardin breakage factor [9].



Py	Cu	Cy	Sp
S=0.5	S=0.71	S=0.83	S=1

Fig. 1. The shape of grains made of RPC

3- Results and Discussion

The results of compressibility tests on RPC and granite grains are indicated in Figure 2.

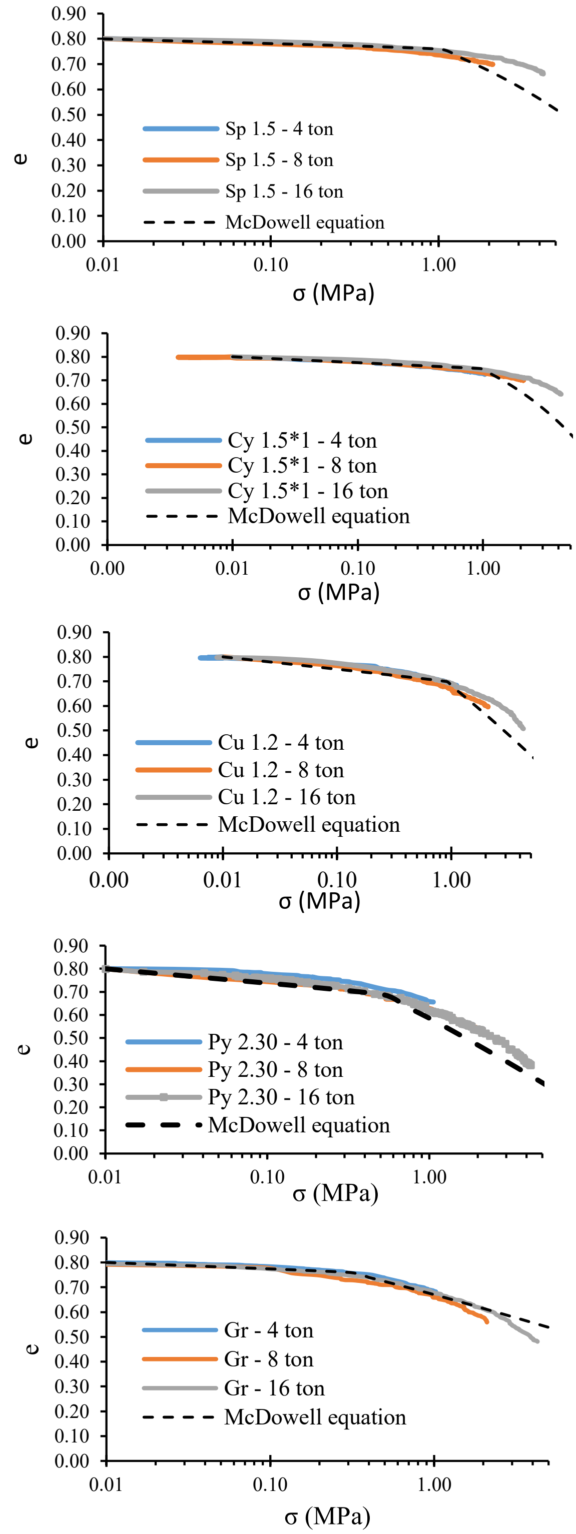


Fig. 2. Comparison of results of experimental tests and analytical model in the size range of 1 to 2.5 cm

Table 1. Breakage values and energy applied to RPC and granite grains

Stress (MPa)		Sp	Cy	Cu	Py	Gr
1.1	B_H	1.6%	1.6%	1.7%	2.4%	1.7%
	E(KJ/m^3)	24.6	28.0	47.3	76.3	94.7
2.1	B_H	4.1%	2.6%	4.9%	6.8%	3.9%
	E(KJ/m^3)	79.7	72.1	155.1	247.6	216.3
4.2	B_H	5.8%	7.6%	9.4%	16.3%	7.6%
	E(KJ/m^3)	272.2	322.3	543.5	784.6	500.0

It is important to note that in both RPC and granite specimens, the diagrams obtained from the analytical relationships were in very good agreement with the laboratory results (R^2=0.98). Granite grains are closer to pyramidal RPC grains in terms of sphericity index, but due to their high fracture strength, their compressibility decreases compared to the pyramids and tends towards the compressibility of the cubes.

Table 1 shows the breakage factors and the applied energy density for all experiments.

It is observed that with decreasing the sphericity index, the amount of applied energy and breakage that occurred in RPC aggregates has increased. The amount of this increase in breakage is higher for pyramidal grains than for other grains.

4- Conclusion

With decreasing sphericity, the amount of breakage and compressibility of materials has increased.

With increasing the fracture surface energy, the effect of shape on compressibility decreases.

McDowell analytical equation only considers the uniaxial compressibility behavior of pyramidal grains (d_{max}=2.5cm) with acceptable accuracy. However, for other grains with high sphericity, the development of a 3D model is necessary to predict the behavior of these grains.

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HOW TO CITE THIS ARTICLE

V. Gorbanpoor, M. Emami Tabrizi, H. Afshin, Evaluation of the effect of shape of granular materials on uniaxial compressibility behavior by analytical and experimental methods, Amirkabir J. Civil Eng., 54(6) (2022) 441-444.

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