Experimental Study of Using Fly Ash Cement Mortar As Rock Similar Materials

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Abstract. The simulation experiment with similar material model is becoming more and more popular along with the underground engineering push to the depths gradually, coring directly in the scence has biggish difficulties. The fly ash and cement mortar were used as the simulation material, the mechanical properties of the similar material were studied by changing the ratio of aggregate to cementations material, the replacement ratio of fly ash to cement, the ratio of water to cementations material and the particle size of sand. By compare the failure mode and the stress-strain curve before the peak, the feasibility of similar material to simulate shaly sands were studied, and reasonable suggestions for improvement were given, which can provide valuable references for model test research.

1. Introduction
In the analysis of stress and strain of geotechnical engineering, the model test is an important and effective method. It can explore many problems that are not easy to solve by using mathematical analysis methods, such as rock mass in elastic, plastic, viscous range until the excitation of failure, as well as motion and dynamics. It can also be combined with finite element, which not only preserves the inherent advantages of the model test, but also gives full play to the efficient mathematical calculation function, which greatly reduces the workload of repeated experiments [1, 2].

The theoretical basis of the model test is the similarity principle [3~7], which requires the model to be similar to the entity (prototype), and the model can react to the prototype. In the model test, selected the appropriate similar materials and reasonable ratio is the key of quantitative simulation [2, 3]. In this paper, fly ash and cement mortar were used as the similar material, and were studied in four aspects including the ratio of aggregate and cementitious material(sand-binder ratio), the replacement ratio of fly ash on cement, the ratio of water and cementitious material (water-binder ratio) and the particle size of sand.

2. The Research Status at Home and Abroad
In early 1960s, Italy expert E.Fumagalli pioneered the test technology of engineering geological mechanical model, the domestic research on rock similar material began in 1970s, including the Yangtze River Scientific Research Institute, Tsinghua University and Chinese Academy of Sciences Wuhan Institute of rock and soil mechanics and other units, through the test of many years, have made a large number of research results. Among them, Han Boli [9]has developed a similar material that composed of barite powder, rosin and alcohol mixture has been used in the structural model test of 9
large hydropower projects, this material has the advantages of high insulation, elastic modulus can be adjusted according to the film thickness, the disadvantage is the polychloroprene adhesive to the aggregate used in the coating containing toluene, evaporation is harmful to the human body; Ma Fangping, Li Zhongkui, Luo Guangfu [10] has successfully developed a geomechanical similar materials by gypsum or cement as a cementing agent, magnetite and natural river sand were used as aggregate and processed with water and additives, the material density is large, the physical and mechanical properties of materials is stable, cheap and easy to obtain, and harmless to people, it is a kind of ideal similar material but its drying time is too long. Zhang Qiangyong [11] from Shandong University has developed a new type of iron crystal sandstone soil by similar material, rosin alcohol solution as cementing agent, barite powder, iron powder and quartz sand as aggregate, the mechanical properties of the material are stable, the density is large, and the range of the change of the mechanical parameters is ideal. Zhang Qiangyong and Liu Dejun [12] has developed a similar material to simulate mudstone and rock salt, it is mainly composed of a mixture of alcohol and medical grade rosin or as cementing agent, aggregate for fine iron powder, barite powder and quartz sand, then made from a specific processing process, the basic physical and mechanical parameters, deformation characteristics and strength failure characteristics of the similar materials are basically similar to the mudstone and rock salt. Diao Xinhong, Hu Shugen [13] used bentonite, quartz sand, barite powder, rosin alcohol solution and gypsum as raw materials, the swelling properties and water absorption characteristics as the reference index, developed by orthogonal experiment of expansive rock similar material, study the influence of similar material content on mechanical properties.

3. Test of Lithologic Similar Material

3.1. Selection of Raw Materials

The selected similar materials require the similarity between the physical and mechanical properties of the prototype material. It should meet the following principles [1, 3, 8]:

Homogeneous and isotropic; 2) the elastic modulus of the material has a larger tuning range; 3) to change the ratio of material can make the mechanical properties of the composites varied greatly; 4) the chemical properties of the similar material are stable; 5) the raw materials are rich in source, low in price, convenient to make, fast in solidification and easy to form, which conform to the economic principle.

According to the above principles, similar materials should be composed of two parts [11], the first is the material used as a cement, such as paraffin, plaster, and cement; the other is the material, such as sand (a number of heavy metal powders, such as iron powder, can be added when needed), as the inert substance of the skeleton. The fly ash cement mortar similar material was studied in this paper, and its material is as follows: aggregate: river sand (grain size: 20 orders, 30 orders, 40 orders, 50 orders, 60 orders, 70 orders); cementing material: ordinary portland cement marked as P.C32.5 and fly ash (to replace the equal mass of cement as a cementing material in different percentage); other materials: tap water.

3.2. Manufacture and Test of Standard Specimen for Similar Materials

The specimen of similar material is a cylindrical standard part with a diameter of 50mm and a high 100mm, the standard specimen was made by a standard test piece making tool which was specially designed and processed by the project group, the standard specimen making tool can manage to suppress and remove the specimen, as shown in Figure 1.
3.2.1. The steps of making the standard test parts: 1) Before the test piece is made: first, remove the dust from the cast iron mold, then evenly coat a layer of release agent silicone oil on the inner wall of the trial mold, and sieve the river sand into 20, 30, 40, 50, 60 and 70 sizes with stainless steel sieves.

2) Mixing the similar materials: the ratio of sand and cement, respectively, the corresponding number of ash water powder weighing, weighing error is within 0.5%; materials are evenly mixed, then add the specified amount of water mixing; will mix 2~3 times into the test mode, the vibrated or side vibration side feeding method, to prevent delamination.

3) Pressing forming and stripping: the test mold is put on the mixing material to be pressed and molded on the standard specimen making tool. After four hous, the mold is demoulding.

4) The maintenance and marking of the specimen: the specimen is numbered, the date is marked, and the specimen is put in the dry and ventilated place.

3.2.2. The test process: Calculating the density of the specimen by formula (1)

\[ \rho = \frac{M}{V} \]  (1)

In the formula, \( \rho \) is the density, \( \text{kg/m}^3 \); \( M \) is the mass of specimen, \( \text{kg} \); \( V \) is the volume of the specimen, \( \text{kg} \).

Uniaxial compression strength measured by TAW-200 electronic multifunction mechanical test machine, in unconfined compression test of uniaxial compression. The average modulus of elasticity was determined by the measured stress-strain curve, calculation according to formula (2):

\[ E = \frac{\sigma}{\varepsilon} \]  (2)

In the formula, \( E \) is elastic modulus, \( \sigma \) is stress, and \( \varepsilon \) is strain.

3.2.3. Test operation steps: When the top pressure head of the test machine is about to contact the test piece, use the displacement control mode and the rate is kept as 1mm/min, limited displacement is 10mm, the ultimate goal is that the load is up to 0.2kN. When the load reaches 0.2kN, to use the load control mode, the speed is 0.05kN/S, click on "start recording experimental data.", after the standard specimen is damaged, the test machine should be stopped and the experimental data should be saved.

4. Test Results and Analysis
Similar experiments require that the model material have similar structural and destructive properties to the prototype material. A argillaceous sandstone is composed of cemented particles surrounded by
aggregate particles and has a more compact structure and smaller porosity. The model material is that river sand is used as aggregate, cement and fly ash as cementitious material, and it has a similar structure with the argillaceous sandstone. Figure 3 is a sampling site in Yanggu, Liaocheng, and figure 4 is a mudstone core.

Figure 3. The scence of taking the samples  
Figure 4. The core of siltstone

4.1. Comparison of the Mechanical Properties of the Similar Materials and the Argillaceous Sandstone

Figure 5. The uniaxial compressive stress-strain of the silty sandstone  
Figure 6. The typical stress-strain curve curves of the similar material specimen

Figure 5. and Figure 6 are the stress-strain curves of the uniaxial compression of the raw rock of the argillaceous sandstone and the samples of the similar materials, respectively. Figure 7 is the failure form of the uniaxial compression test of the raw rock and similar materials of the argillaceous sandstone, Figure 8 is the failure form of the three axis compression test of argillaceous sandstone original rock specimen and similar material specimen. By observing Figure 5 and Figure 6, it is found that the stress-strain relation curve of the uniaxial compression of the material and the stress-strain curve of the argillaceous sandstone are very similar before the peak value, it also experienced the stage of compaction, the elastic deformation to the stable development stage of the micro elastic fracture and the stage of the unstable failure and development. The post peak curve is different from the argillaceous sandstone, which is mainly related to the internal structure of the two materials and the properties of the material itself. From Figure 7 and figure 8, it is shown that the uniaxial and three axis strength failure modes of the similar materials and the argillaceous sandstone are basically the same, all of which belong to the single shear surface failure. Therefore, this paper considers that the material is similar to the compressive properties of the mudstone before the peak.
Mud-stones (left) and the analog material (right) mud-stones (left) and the analog material (right)

Table 1 is the physical and mechanical parameters of the mudstone core obtained through an indoor single axis experiment, table 2 is the physical parameters of the similar material obtained by an indoor single axis experiment. According to the similarity theorem [14]. It is known that the similarity ratio of the parameters of the original rock of the mudstone from Yanggu, Liaocheng and the model is as follows:

\[ C_E = \frac{E_p}{E_m} = 1.001 \quad C_\sigma = \frac{\sigma_p}{\sigma_m} = 0.995 \quad C_\mu = \frac{\mu_p}{\mu_m} = 1.014 \]

As a result, the same dimension is almost equal to the physical quantity, and the dimensionless ratio is close to 1, which basically satisfies the similarity theorem. Therefore, the proportioning of the sample 19# is in accordance with the proportioning of the single axial compression performance (pre-peak value) of the simulated raw rock from Yanggu Liaocheng.

**Table 1. Physic-mechanical parameters of the silty sandstone**

| raw rock material         | modulus of elasticity/GPa | compressive strength/MPa | Poisson ratio |
|---------------------------|---------------------------|--------------------------|---------------|
| Argillaceous sandstone (p)| 2.82                      | 16.23                    | 0.22          |

**Table 2. Physic-mechanical parameters of the test specimen of 19**

| Similar material | modulus of elasticity/GPa | compressive strength/MPa | Poisson ratio |
|------------------|---------------------------|--------------------------|---------------|
| Specimen 19# (m) | 2.812                     | 16.317                   | 0.217         |

Above all, through a large number of tests and indoor uniaxial tests, it has been proved that the structural characteristics, uniaxial and three axis test failure modes and stress-strain characteristics (pre-peak) and other aspects of this similar material is the same as the argillaceous sandstone. The feasibility of using this similar material to simulate the argillaceous sandstone has been preliminarily verified.
4.2. The Influence of the Proportioning of Aggregate and Cementitious Material

The ratio of water to glue, the ratio of cement to fly ash, and the size of sand grain remain the same, to study on the influence of sand-binder ratio on the mechanical properties of similar materials, the relationship between sand-binder ratio and mechanical properties as shown in Table 1 and Figure 9.

As can be seen from table 1 and Figure 9, the uniaxial compressive strength and modulus of elasticity of the material decrease obviously with the increase of the sand-binder ratio. This shows that the strength of fly ash cement mortar mainly depends on the coagulating force between the cementitious material and the aggregate.

When the proportion of sand and glue increases, the cementitious amount of cement in the material is reducing, meanwhile the contact area between the cementitious material and the aggregate, the condensation force between the cementitious material and the aggregate, and the uniaxial compressive strength of the material are reducing.

The average density of the specimen will increase first and then decrease with the increase of the sand-binder ratio, the maximum value is reaching when the ratio of sand-binder ratio is 2:1. It shows that the compactness of the specimen when the sand-binder ratio is 2:1 is better.

4.3. The Effect of Fly ash on the Substitution Rate of Cement

Fixing other ratio and changing the substitution rate of fly ash to cement to study the effect on the mechanical properties of similar materials. As it can be saw from table 1 and figure 10: With the increase of the substitution rate of fly ash, the uniaxial compressive strength and modulus of elasticity
of similar materials gradually decrease. When the substitution rate of fly ash at 5%~20%, the uniaxial compressive strength of the material decreases with the increase of the substitution rate of the fly ash; When the substitution rate of fly ash is more than 20%, the uniaxial compressive strength of the material decreases with the increase of the substitution rate of the fly ash, but the change tends to be gentle.

Therefore, with the increase of the amount of fly ash, the initial strength of the similar materials gradually decreases; With the increase of the amount of fly ash, the elastic modulus of the similar material decreases obviously, the elasticity of the material decreases and the toughness becomes stronger, the adjustment range of the compressive strength and the modulus of elasticity of the similar materials is increased, so the similar material is suitable for simulating the argillaceous sandstone.

The average density of the specimen decreases with the increase of the substitution rate of the fly ash, but the wave range is not large and between 1.855~2.025 g/cm³, it is shown that changing the substitution rate of fly ash in a certain range has little effect on the density of the specimen.

![Graph](image1.png)

**Figure 11.** The influence of water-binder ratio on the mechanical properties of test specimen

![Graph](image2.png)

**Figure 12.** The influence of sand particle size on the mechanical properties of test specimen

4.4. *The Influence of the Ratio of Water and Cementations Material*

From Figure 11, we can see the uniaxial compressive strength, modulus of elasticity and average density of the material decrease with the increase of water-binder ratio when only the water-binder ratio is changed. When the water-binder ratio becomes larger, the free moisture in the specimen increases, and the volume of the water increased accordingly. After the specimen is dry under natural condition, the space occupied by water becomes more fissures, the porosity of the specimen is greater...
and the density of the specimen is worse, so the density of the specimen reduced accordingly. The uniaxial compressive strength of the specimen is smaller with the increase of the tiny gap and the fine fissures. The uniaxial compressive strength of the specimen is smaller with the increase of the tiny gap and the fine fissures.

4.5. The Influence of Grain Size of Sand
The effect of sand grain size on the mechanical properties of the material is obvious, their influence on uniaxial compressive strength and modulus of elasticity is like Figure 12. It can be seen from the diagram that the density of the material, the uniaxial compressive strength and the modulus of elasticity all show a tendency to increase first and then decrease with the sand grain size from 20 mesh to 70 mesh (The 20~30 mesh is coarse sand, 40~60 mesh is medium sand, and 70 mesh is fine sand). When the sand grain size is 40 mesh, the uniaxial compression strength reached the maximum, which was 21.172 MPa.

The thinner the aggregate, the greater the water demand is when the sand glue is at the same time as the phase. At the same water-cement ratio, the specimen made of coarse sand is more free of free water in the specimen made of medium sand. In natural conditions, the more void or tiny cracks caused by air drying, and the greater the porosity is. Because the coarse aggregate only has coarse sand and no middle or fine sand in it, the gap between aggregate is very large, so it can not form a dense filling structure, so the uniaxial compressive strength is relatively low. When the grain size of the sand is from 40~70, it is the process from medium sand to fine sand, With the grain size of sand gradually becomes smaller, the mud content is larger and the void volume is greater that is easy to cause cracks in the mortar, and the tensile force between the aggregate sand is also smaller, which affects the strength of the material.

5. Conclusion
In this paper, a lot of experiments have been carried out on fly ash cement mortar specimens, and the change rules of mechanical properties of similar materials under different proportions have been found:

The samples made of fly ash cement mortar as similar materials have similar structural characteristics and failure forms with mudstone sandstone, the stress-strain curves of samples of similar materials and argillaceous sandstone are very similar before the peak value, it also experienced the stage of voids compression, the elastic deformation to the stable development stage of the micro elastic fracture and the stage of the unstable failure development. It is preliminarily considered that it is feasible to use the similar material to simulate the mechanical properties before the peak value of the mudstone.

The uniaxial compressive strength and the modulus of elasticity of the similar materials decrease with the increase of the sand-binder ratio.

With the increase of the substitution rate of fly ash, the uniaxial compressive strength and modulus of elasticity of similar materials gradually decrease, and its influence gradually becomes smaller; By adding the fly ash, the mechanical properties, such as the compressive strength and the modulus of elasticity of the similar materials, have more free adjustment space.

The uniaxial compressive strength, modulus of elasticity and average density of the material decrease obviously with the increase of water-binder ratio.

With the particle size from 20 to 70 mesh (the 20~30 mesh is coarse sand, 40~60 mesh is medium sand, and 70 mesh is fine sand), the uniaxial compression strength and modulus of elasticity of similar materials show a tendency to increase first and then decrease.

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