

# Study on Constitutive Model of Air-foam-Treated Lightweight Soil Based on Static Triaxial Test

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**Abstract.** Foamed Cement Banking filling technology is one of the most effective methods in soft foundation treatments, such as the bumping at joints of a bridge-road, the different settlement of subgrade broadening and the stability problem of a high-filling embankment. To study on the characteristics of stress and strain for air-foam-treated lightweight soil, specimens were prepared at an optimized mixing ratio, and triaxial tests were conducted for strain and stress fitting. An ideal elastic-plastic model was used to simplify the relationship of strain and stress in an engineering sense, plus numerical simulation. The research results have great significance for addressing the issues of the stress-strain relationship, selecting design parameters and guiding engineering application with respect to air-foam-treated lightweight soil.

## 1. Introduction

Air-foam-treated lightweight soil is a lightweight soil-engineering material prepared by mixing hardener, water, and prepared foam with soil in a specific ratio, featuring lightness, adjustable strength, high mobility and self-standing ability, ease of construction, and durability. By reducing the inner-foundation stress by lightening the soil itself, the extra stress exerted on foundation can be lowered by a large extent, which inhabits the sedimentation of and damage to the soft-foundation embankment and enlarges the safety and stability coefficient. By doing so, the soil pressure on underground structures can also be reduced, and the structural safety and service life can be prolonged [1-4]. Foamed Cement Banking filling technology is one of the most effective methods in soft foundation treatment. It provides a valuable technological means for bumping prevention at the joints of a bridge-road, decreases the different settlement caused by subgrade broadening, and enhances the stability of a high-fill embankment \ [5-8].

Wako noted that the foremost concern for air-foam treated lightweight soil is maintaining stable density [9]. Tsuchida analysed the density of air-foam treated lightweight soil in different construction periods by drill hole sampling [10]. The Japan Institute of Road Corporation has conducted a pilot study on the strength of light soils as a mixture of standard sand and bubbles. Tsuchida used dredged muck to prepare air-foam treated lightweight soil and conducted the compression test accordingly. The results show that the yield stress of the air-foam treated lightweight soil is related to the uniaxial



compressive strength  $q_u$  [11]. Most of the existing research themes relate to the mixing ratio, density, and strength, but few deal with stress-strain characteristics and the constitutive relation of air-foam-treated lightweight soil [12].

To this end, in order to examine the characteristics of stress and strain for air-foam-treated lightweight soil, specimens were prepared at an optimized mixing ratio, and a triaxial test was conducted for strain and stress fitting. An ideal elastic-plastic model was used to simplify the relationship of strain and stress in an engineering sense, as well as numerical simulation. The research results have great significance for addressing the issues of the stress-strain relationship, selecting design parameters and guiding engineering applications with respect to air-foam-treated lightweight soil.

## 2. Air-foam-treated light weight sample preparation

### 2.1. Material and equipment for test

Experiment materials: Chongqing Diwei 42.5R grade ordinary Portland cement as cementitious materials, engineering waste as raw material soil (dried, refined and sieved through 1 mm sieves), homemade efficient foaming agent, and tap water [13].

Test equipment: JJ-5 planetary cement mortar mixer, 39.1×80 cylinder die trials, HBY-40B standard constant temperature and humidity curing box, WE-600 universal testing machine, strain control three-axis compression device, WGD702 high and low temperature test chamber, electronic balance, etc.

### 2.2. Mixing ratio of design and specimen fabrication

The mechanical properties of air-foam-treated lightweight soil are changeable with bubble content, cement content and water content. The mixing ratio of design materials were determined as in Table 1, which has 4 groups of samples and 3 variables, with the quality of dry soil as the criteria. Under the mixing scheme, a certain amount of raw soil was weighed and poured into the mixer together with a quota of cement, and the rotation speed was set at 100 rpm. Then, with some water and foaming agent that had been diluted according to a specific proportion, the authors stirred the mixture well using a blender. Finally, the mixture was encased in a 39.1×80 cylinder mould before being cured for 24 h in a standard curing box. The cured specimen would be demoulded and cured one extra time before reaching the design age and undergoing the performance test.

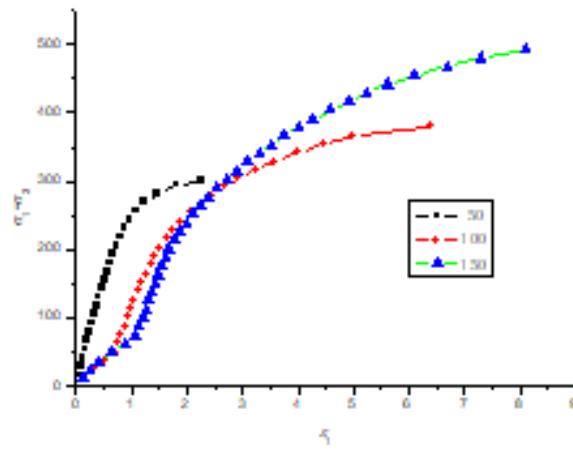
**Table 1.** Raw material mixing ratio schemes for air-foam treated lightweight soil sample preparation

No.	Bubble content %	Cement content %	Water content %
A1	8	20	55
A2	10	20	55
A3	12	20	55
A4	8	20	70

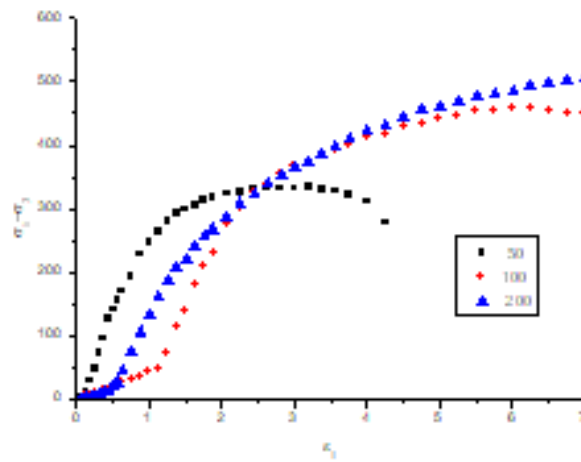
## 3. Experiment on triaxial compression of air-foam-treated lightweight soil and result analysis

### 3.1. Experiment on the triaxial compression of air-foam treated lightweight soil

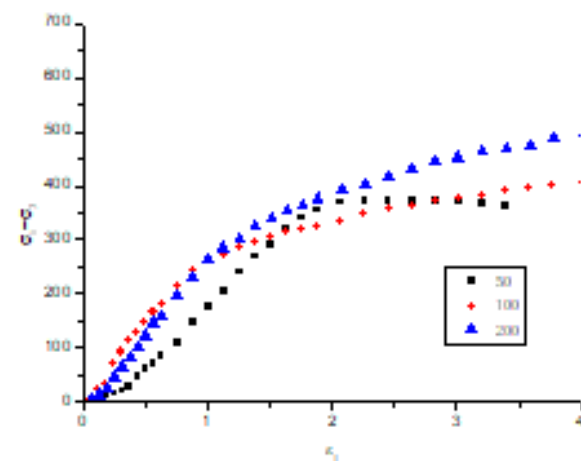
To study the mechanical properties of the air-foam-treated lightweight soil under the condition of triaxial stress, the above specimens were selected to carry out the non-consolidated undrained shear test at the confining pressures of 50,100, and 150 kPa, respectively, with the strain control method. The test results are shown in following figures (from Figure1 to Figure4).



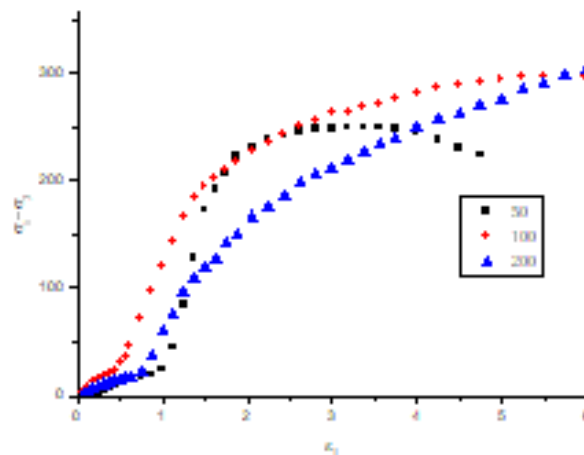
**Figure 1.** Triaxial test results for A1.



**Figure 2.** Triaxial test results for A2.



**Figure 3.** Triaxial test results for A3.



**Figure 4.** Triaxial test results for A4.

### 3.2. Result analysis

As seen from the figures, despite the change of mixing ratio, the principal stress difference increases with the increase of confining pressure, and the stress-strain curve can be divided into the compaction phase, the linear elastic phase and the plastic deformation phase.

In the compaction phase, the stress-strain curve is concave, especially under high confining pressure. The concave performance is insignificant when the confining pressure is low, because the air-foam treated lightweight soil begins to deform in the form of internal consolidation under the action of axial force and the consolidation degree is higher under high confining pressure.

In the linear elastic phase, the stress-strain relationship is basically linear. The elastic threshold is related to the mixing ratio and confining pressure. When the mixing ratio is fixed, the threshold will be larger if the confining pressure is higher.

In the plastic deformation stage, the air-foam-treated lightweight soil presents two different characteristics: strain softening and strain hardening. The strain softening characteristics are obvious in the low confining pressure state of the bubble soil with various mixing ratios. The high-water-content soil exhibits strain softening under different confining pressures, especially under low confining pressure. In spite of this phenomenon, air-foam treated lightweight soil that is full of pores can hardly reach saturation in common triaxial experimental apparatus. When the confining pressure is high, the stress-strain curve shows the shape of strain hardening, because the stress increases without marked peak values as the strain rises in this stage.

## 4. Establishment of air-foam-treated lightweight soil constitutive relationship

### 4.1. Curve fitting

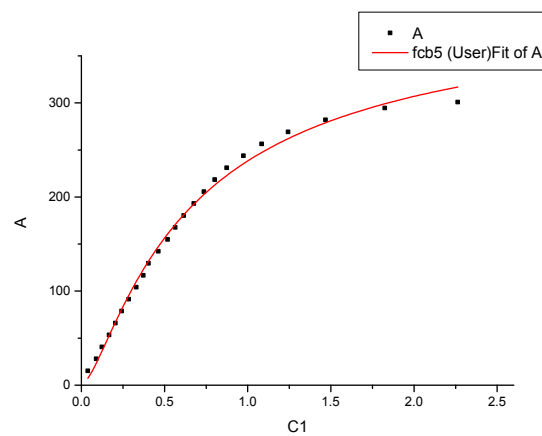
Through the analysis of the triaxial stress-strain curve, it can be seen that the stress-strain relationship is affected simultaneously by the confining pressure and the mixing ratio. Due to the variability of internal porosity and material in homogeneity, the air-foam treated lightweight soil actually presents the features of a loose porous medium, and it is difficult to establish the soil's constitutive relation from the coupling effect of the void ratio and the confining pressure. Meanwhile, as a remoulded soil, air-foam treated lightweight soil has adjustable structures, which are unsuitable for traditional approaches to constitutive relations or relevant models. To solve the mixing-ratio-related problem of difference and randomness between physical soil properties, it is possible to construct a constitutive model in a generalized sense and accordingly determine the function of a certain characteristic quality of an air-foam-treated lightweight soil structure, depending on the principal mixing factors [12]. What is more, some external influencing factors are introduced into the model, such as temperature,

moisture and stress state. Under some mathematical law, a multi-factor coupling composite function is established, which can reveal the nature of soil mechanics.

Such a model is effective in addressing the problem of difference and randomness between physical soil properties but fails to extend into a structural model that reflects factors like mixing ratio and confining pressure. The large number of influencing factors and the difficulty of putting these factors into engineering use also restrict the model's utility. To facilitate engineering application, the authors fitted the stress-strain curves of strain softening/hardening air-foam-treated lightweight soil in triaxial tests at different mixing ratios and stress states, in order to have a chance to establish constitutive relationships.

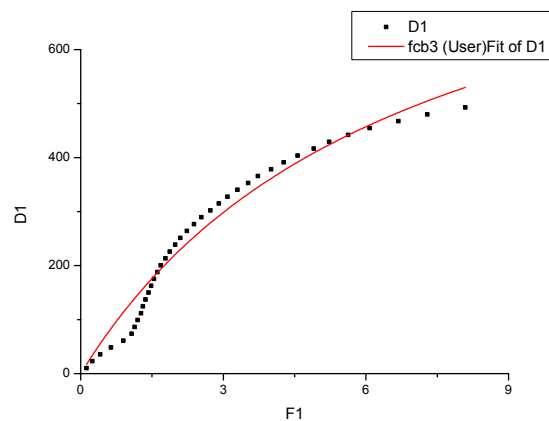
The strain softening curve was fitted with the Prevost softening model:

$$\sigma_1 - \sigma_3 = \varepsilon_1(a + c\varepsilon_1)/(a + b\varepsilon_1)^2 \quad (1)$$



**Figure 5.** The results of triaxial compression test for A4.

Where  $a$  is the reciprocal of the initial tangent modulus,  $b$  is the asymptotic value of the deviation stress limit, and  $c/b2$  is the residual strength. The stress-strain curve of A1 is fitted with the curve under the confining pressure of 50 kPa, and the results are shown in Fig. 5.



**Figure 6.** Triaxial test results of A4

Where  $a$  is the reciprocal of the initial tangent modulus, and  $b$  is the asymptotic value of the deviation stress limit. The authors took the example of the stress-strain curve fitting of A1 under the confining pressure of 150 kPa, and the result is shown in Figure 6.

Figure 5 shows that the stress-strain curve of strain softening strain is better. It can be seen from Figure 6 that the stress-strain curve of the strain hardening is basically consistent with the measured value. Nevertheless, as the fitting error in the compaction stage is relatively high (as a result of the porous characteristics of the air-foam treated lightweight soil), the fitting result would be better if this stage was skipped.

#### 4.2. Constitutive relationship

From the test results and the fitting curves, the proportion of the curve in the compaction phase to the whole curve is small, and accordingly, the authors simplified the analysis by integrating the compaction phase and the linear elastic phase as a whole. Meanwhile, considering that air-foam-treated lightweight soil is generally used in places with low levels of stress (such as a soil foundation), the authors unified the strain hardening stage and strain softening stage as the ideal plastic stage.

In the elastic phase, soil deformation is non-linear according to the incremental nonlinear model under the generalized Hooke's law, but it can be regarded as linear and isotropic in the case of micro-incrimination [14]:

$$\sigma_{ij} = D_{ijkl} \epsilon_{kl} \quad (2)$$

where  $D_{ijkl}$  is the elastic matrix, and  $\sigma_{kl}$  and  $\epsilon_{kl}$  are the stress tensor and the strain tensor, respectively.

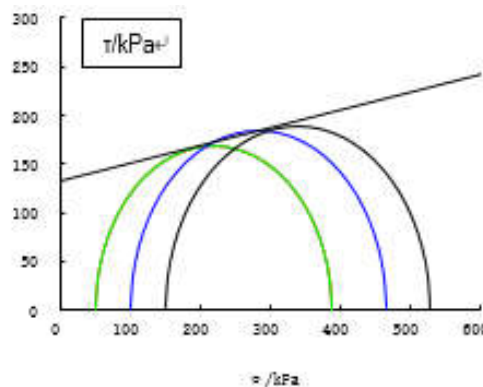
In the ideal plastic stage, the incremental stress-strain relationship is:

$$d\sigma_{ij} = D_{ijkl}^{ij} \epsilon_{kl} \quad (3)$$

#### 4.3. Elastic modulus, cohesion and internal friction angle

As per the hypothesis of ideal elastic-plasticity for air-foam-treated lightweight soil, whether such soil enters the yield stage is judged by the Mohr-Coulomb criterion. With the static-force triaxial compression test, the authors plotted the non-consolidated unstrained shear strength envelop curve for A1 in Figure 7, under the cohesion  $c$  of 130.1 KPa and the internal friction angle of  $6.03^\circ$ . The elastic modulus can be determined by MURC [15]:

$$E_c = 250q_u \quad (4)$$



**Figure 7.** Non-consolidated unstrained shear strength envelope curve.

## 5. Conclusion

In this paper, to study on the characteristics of stress and strain for air-foam-treated lightweight soil, specimens were prepared at an optimized mixing ratio, and a triaxial test was conducted for strain and stress fitting. An ideal elastic-plastic model was used to simplify the relationship of strain and stress in an engineering sense, as well as numerical verification. The research results are:

(1) Despite the change of mixing ratio, the principal stress difference increases with the increase of confining pressure, and the stress-strain curve can be divided into compaction phase, linear elastic phase and plastic deformation phase.

(2) The stress-strain relationship is affected simultaneously by confining pressure and mixing ratio, presenting the features of strain softening and strain hardening. The strain softening curve is well fitted with the Prevost softening model, while the strain hardening curve is well fitted with the Duncan-Chang hyperbolic model.

(3) The stress-strain curves under the ideal elastic-plastic model fit well with the stress-strain curve under low-confining pressure. However, with the increase of the stress, the deviation of numerical simulation results from the test result is enlarged. Considering that air-foam treated lightweight soil is generally used in places with low levels of stress (such as in soil foundation), the authors simplify the stress-strain relationships as ideal elastic models, which can meet the requirements of engineering.

As a remoulded soil, air-foam-treated lightweight soil has adjustable structures, which are unsuitable for traditional approaches to constitutive relations or relevant models. To solve the mixing-ratio-related problem of difference and randomness between physical soil properties, constructing a generalized constitutive model with theoretical value and pragmatic meanings is still worthy of further research.

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