Strength and Deformation Characteristics of Fiber Reinforced Longdong Loess and Experimental Study of Modified Duncan-Chang Model

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Abstract. Fiber yarn reinforced loess is prepared through mixing plain loess with a certain proportion of polyester fiber yarn, which is formed by loosening, carding and cutting waste synthetic textile polyester fabric and has rough surface properties and good acid-alkali corrosion resistance. The strength and deformation characteristics of Longdong Loess reinforced by fiber yarn were studied. The test results show that the uniaxial compressive strength of fiber yarn reinforced loess increases with the increase of fiber yarn proportion and fiber yarn length, and decreases with the increase of fiber yarn fineness. Combined with the uniaxial compressive strength data of fiber yarn reinforced loess under the optimal water content and liquid limit water content, an index which can comprehensively reflect the reinforcement performance of fiber yarn reinforced loess is proposed—Fiber reinforced index. The shear stress-strain relationship of triaxial consolidation drainage of fiber-reinforced loess with different proportion of fiber yarn is strain hardening type. The hypothesis of hyperbolic form is in accordance with Duncan Chang model. By discussing the relationship between the parameters of fiber yarn reinforced loess and plain loess model, the empirical expression of model parameters considering the influence of fiber yarn reinforced loess is obtained. A modified Duncan-Chang E-B model reflecting the influence of different fiber yarn blending ratio was constructed. The rationality of the model is verified by comparing the test curve with the model prediction curve.

Keywords. Longdong loess, fiber yarn reinforcement, fiber reinforced index, Duncan Chang model, experimental study.

1. Introduction
Fiber reinforcement technology is the uniform mixing of a certain proportion of natural or artificial synthetic fibers into the soil. The purpose is to increase the strength of the soil body and enhance the resistance capacity to soil deformation. It is a new soil improvement and reinforcement technology that has been promoted in slope and roadbed engineering [1-4]. In recent years, this technology has
become popular and been gradually adopted by some projects in China. Regarding the reinforcement mechanism of fiber-reinforced soil, researchers worldwide have reached relevant conclusions through macroscopic indoor experiments and microscopic electron microscope scanning [5-13]. However, there are relatively few studies involving fiber reinforcement of loess. Longdong is located in northwestern China, and the loess in Longdong has complex engineering properties due to its special geological deposition state [14]. With the continuous advancement of the “One Belt One Road” strategy, Longdong loess deposit areas will welcome a new wave of construction. An in-depth study on the strength and deformation characteristics of fiber reinforced Longdong loess will have very important theoretical and practical significance. Currently, there is no existing indicator in the research community that can quantitatively reflect the influence of fiber mixture on the effect of soil reinforcement, and its related research is rarely reported. Through the analysis of relevant test data, a quantitative parameter that can reflect the actual reinforcement effect of fiber reinforced soil is proposed in this study, which will provide some support for practical engineering applications.

The constitutive relationship of fiber-reinforced soil has always been a difficult issue facing the academia. In recent years, with the promotional use of fiber-reinforced technology in real engineering applications, progress has been made in constitutive modeling research of fiber-reinforced soil. Main modeling ideas include, if the fibers slip when the fiber-reinforced soil fails, it should consider the establishment of an energy equalization model that can take into account the effects of anisotropy [15]; proportionally superpose the stress contribution of fiber and soil body structure respectively within the fiber-reinforced soil, establish fiber-reinforced soil equivalent-stress model [16]; the contributions of fiber and soil structure of the fiber-reinforced soil to the strength are respectively superimposed in proportion, considering the slippage state of the contacting surface between the fiber and soil particles, stress is superimposed based on the percentage volumes occupied by fiber and soil particles, establish fiber reinforced soil constitutive model based on the mixture theory [17]; abstract the fiber-reinforced soil as a combination of soil phase and fiber phase, consider the contribution of the stress increment from soil phase and fiber phase separately, and establish a two-phase constitutive model of fiber-reinforced soil based on the stress superposition principle [18]. The forms of the aforementioned models are relatively complex with many parameters, which are difficult to master by engineers and technical personnel in real engineering settings. Currently, among the commonly used engineering numerical analysis software, the Duncan-Chang nonlinear elastic model has been widely used in actual engineering practices because of its fewer parameters and easy determination [19]. Based on the theoretically mature Duncan-Chang model, through the analysis of relevant test data of fiber-reinforced soil, the model is corrected and improved accordingly, so that it can reasonably reflect the mechanical deformation characteristics of fiber-reinforced soil, and this can be one of the key directions of future research on the constitutive relationship of fiber-reinforced soil.

This paper intends to carry out uniaxial compressive strength test and triaxial shear test on Longdong loess reinforced by synthetic waste fabric fiber yarn to analyze its strength deformation characteristics; through uniaxial compressive strength test data, define a fiber reinforcement index expression that can comprehensively reflect the effect of fiber reinforcement on soil and has a clear physical meaning; through the analysis of the triaxial shear test data, a modified Duncan-Chang model that can reflect the effect of fiber yarn blending ratio is constructed. The research in this paper can provide some reference and lesson for judging the reinforcement effect of the actual engineering fiber yarn reinforced loess and the prediction of the stress and strain characteristics.

2. Experimental Plan and Method

2.1. Experimental Material
Soil for the test was taken from the roadbed of the DS-3 section of Huawu Road Project in Huachi County, Qingyang City, Gansu Province. The sampling depth was 2 m below the surface. The soil colour was grayish-yellow, and the section had macro pores and wormholes that were visible to the naked eye. There were also white calcified salt crystal nodules, which are typical of Q3 loess in Longdong area. The natural water content of the soil sample is 13.5%, the relative density is 2.72, the plastic limit water content is 17.5%, and the liquid limit water content is 27.9%. The indoor
compaction test was carried out, and the maximum dry density was 1.66 g/cm$^3$, and the optimal moisture content was 18.3%. The particle analysis curve of the soil sample was obtained through particle analysis test, as shown in figure 1.

![Figure 1. Particle distribution curve of Longdong loess.](image1)

It can be seen from figure 1 that the trend of the grading curve is relatively gentle. The calculated unevenness coefficient $Cu$ is 10.67, and the curvature coefficient $Cc$ is 1.16. It can be judged that the loess has a good gradation.

The fiber mixed in the sample is selected from the waste produced by the polyester grey fabric produced by the Northwest National Cotton No. 4 Factory, and the FS1500 type cloth shredder in the product appraisal room was used to open loose and comb the fabric into twisted polyester fiber yarn with set thickness. A QD850 fiber cutting machine was used to cut the polyester fiber yarn to the length set by the experiment. The reason why polyester fiber yarn was used as reinforcing material in this experiment is that, on the one hand, polyester fiber yarn has good acid and alkali corrosion resistance, and will not degrade or rot due to the increase of time after mixing with soil. In addition, polyester fiber yarn is not toxic, hence it will not pollute the soil after mixing. On the other hand, because the surface properties of fiber yarn are rougher than that of monofilament fibers, as shown in figure 2, the friction-like effect after contact with soil particles will be more ideal.

![Figure 2. Schematic diagram of fiber morphology.](image2)

2.2. Uniaxial Compressive Strength Test Design and Method

The uniaxial compressive strength test of fiber yarn reinforced loess was carried out under three different working conditions (i.e. different fiber blending conditions). Working condition 1, the length of the blended fiber yarn is 30 mm, the fiber yarn fineness is 60 dtex (Note: dtex is decitex, it is the weight of 10,000-meter fiber yarn, the unit of fiber thickness described in textile engineering), the fiber yarn blending ratios are 0.05%, 0.10%, 0.15%, and 0.20% respectively. In working condition 2, the proportion of fiber yarn mixed in the sample is 0.15%, the fiber yarn fineness is 60 dtex, and the fiber yarn length is 10 mm, 20 mm, 30 mm, and 40 mm respectively. Working condition 3, the proportion of the mixed fiber yarn is 0.15%, the fiber yarn length is 30 mm, and the fiber yarn fineness is 60 dtex, 90 dtex, 120 dtex, and 150 dtex, respectively. The above fiber yarn blending ratio is the percentage of dry soil mass under the same mass. The dry density of the sample was determined based on the degree of compaction of the on-site roadbed engineering construction. The on-site roadbed compaction is 0.94, so the dry density of the sample is about 1.56 g/cm$^3$. Under the three different
working conditions, the sample humidity configuration is divided into two groups. One group selects the optimal water content determined by the compaction test, which is 18.3%. At the same time, research has proved that in actual engineering, the increase in humidity is one of the biggest causes of fiber-reinforced soil failure [20]. The increase in water content of fiber-reinforced soil can cause the thickening of the bounding water film between soil particles, which reduces the friction between the reinforcement and the soil particles. The liquid limit water content, as the limit water content for the conversion of bound water to free water in the soil, has a great influence on the frictional resistance between the reinforced fiber and the soil particles. In order to test the strength deformation characteristics of fiber-reinforced soil under high humidity conditions, the water content of another set of samples was configured as the liquid limit water content of the soil. The test instrument adopts the CBR-1 bearing ratio tester produced by Nanjing Soil Instrument Co., Ltd. The sample is a cylinder with a diameter of 152 mm and a height of 170 mm.

2.3. Triaxial Shear Test Design and Method
In the triaxial shear test, the length of the mixed fiber yarn is 30 mm, the fiber yarn fineness is 60 dtex, and the fiber yarn mixing ratio is 0.05%, 0.10%, 0.15%, and 0.20%, respectively. The dry density of the sample was determined based on the degree of compaction of the on-site roadbed, which is 1.56 g/cm³, and the sample moisture content is configured as the optimal moisture content of 18.3%, the test water content. Test consolidation confining pressures were 50 kPa, 100 kPa, 200 kPa, and 400 kPa, using consolidated drainage shears. The sample is a cylinder with a diameter of 61.8 mm and a height of 125 mm.

3. Test of Uniaxial Compressive Strength of Fiber Yarn Reinforced Loess
3.1. Strength Deformation Characteristics of Soil Body under the Condition of Different Fiber Yarn Mixing Ratio (Working Condition 1)
Draw the stress-strain curve of two different moisture fiber yarn reinforced loess under the condition of different fiber yarn mixing ratio (working condition 1), as shown in figures 3.

![Figure 3. Stress-strain curve of fiber yarn reinforced loess (working condition 1).](image-url)
the same time. As the proportion of fiber yarns increases, the friction force also increases correspondingly. Macroscopically, it reflects that the uniaxial compressive strength of the sample increases with the increase of the fiber yarn blending ratio. It can be seen from figure 3(b) that when humidity increases to the liquid limit water content, the peak points of the stress-strain curve of the fiber yarn reinforced loess are all above the peak points of the plain loess curve. Compared with the peak point of the curve at the optimal water content, the peak of the curve at the liquid limit water content has a relative large reduction. When the fiber yarn blending ratio is 0.05%, 0.10%, 0.15%, and 0.20%, the uniaxial compressive strength of fiber yarn reinforced loess at the liquid limit water content is 29.2%, 29.9%, 31.0%, and 25.8% of the uniaxial compressive strength value at the optimal water content, respectively.

3.2. Strength Deformation Characteristics of Soil under the Condition of Different Fiber Yarn Length (Working Condition 2)

Draw the stress-strain curve of two different moisture fiber yarn reinforced loess under the condition of different fiber yarn length (working condition 2), as shown in figures 4.

![Figure 4. Stress-strain curve of fiber yarn reinforced loess (working condition 2).](image)

It can be seen from figure 4(a) that with the increase in length of the fiber blended yarn in loess, the peak point of the curve gradually moves up, indicating that as the length of the fiber blended yarn increases, the fiber yarn reinforced loess uniaxial compressive strength gradually increases. Compared with plain loess, the uniaxial compressive strength of fiber-reinforced loess can increase by 22.8%, 73.2%, 93.6%, and 120.4% when the length of the fiber-added yarn is 10 mm, 20 mm, 30 mm, and 40 mm. The possible reason could be that when sample fails under load, as the length of the mixed fiber yarn increases, the fiber yarn is less likely being pulled out from the failure surface of the sample when the sample is deformed, resulting in greater tensile stress, reflecting greater uniaxial compressive strength at macroscopic scale. It can be seen from figure 4(b) that when the humidity increases to the liquid limit water content, the peak point of the stress-strain curve of fiber yarn reinforced loess has a greater decrease compared with the peak point of the curve at the optimal water content. When the length of the fiber-added yarn is 10 mm, 20 mm, 30 mm, and 40 mm, the uniaxial compressive strength of the fiber yarn reinforced loess at the liquid limit water content is 29.5%, 23.4%, 29.6%, and 31.7% of the optimal water content, respectively.

3.3. Strength Deformation Characteristics of Soil under Different Fiber Yarn Fineness Conditions (Working Condition 3)

Draw the stress-strain curves of two different moisture fiber yarn reinforced loess under different fiber yarn fineness conditions (working condition 3), as shown in figures 5.
Figure 5. Stress-strain curve of fiber yarn reinforced loess (working condition 3).

It can be seen from figure 5(a) that as the fineness of the fiber blended in the loess decreases, the peak point of the curve gradually moves up, indicating that as the fineness of the blended fiber yarn decreases, the uniaxial compressive strength of fiber yarn reinforced loess gradually increases. When the fineness of the blended fiber yarn is 150 dtex, 120 dtex, 90 dtex, and 60 dtex, the uniaxial compressive strength of fiber yarn reinforced loess can increase by 51.3%, 67.2%, 86.9%, and 90.3% compared with plain loess. The possible reason could be that when the fineness of the fiber yarn is smaller, the fiber yarn is more widely distributed in the soil under the same mixing ratio (note: the mixing ratio is the mass ratio), and the net-like pulling effect is more significant. At the same time, the total surface area in contact with soil particles is larger than that of the finer fiber yarn, which makes the friction effect more obvious, reflecting that the uniaxial compressive strength gradually increases as the fineness of the mixed fiber yarn decreases. It can be seen from figure 5(b) that when humidity increases to the liquid limit water content, the peak points of the stress-strain curve of fiber yarn reinforced loess reduce compared with the peak points of the curve at the optimal water content. When the yarn fineness is 150 dtex, 120 dtex, 90 dtex, and 60 dtex, the uniaxial compressive strength of the fiber yarn reinforced loess is at 32.7%, 31.8%, 30.6%, and 31.2% of the liquid limit water content.

4. Construction of Fiber Reinforcement Index and Its Change Relationship

4.1. Construction of Fiber Reinforcement Index Expression

Through the analysis of the uniaxial compressive strength test data of fiber yarn reinforced loess in section 2, it can be seen that adding a certain amount of fiber yarn material to plain loess can significantly increase the strength of the soil. The test also explained the impact of fiber yarn mixing ratio and specification. The test also analyzed the stress-strain relationship of fiber yarn reinforced loess under the condition of liquid limit water content, and pointed out that under the condition of liquid limit water content, the strength of fiber yarn reinforced loess was lower than that under optimal water content condition. The increase in humidity greatly affects the reinforcement effect of the fiber in the soil.

The purpose of soil reinforcement is to obtain higher strength and better stability, so as to improve its performance in actual engineering. It has been proved that the reinforcement mechanism of fiber-reinforced soil mainly relies on the bonding force and frictional resistance between the fiber and the soil particle interface and the interweaving between the reinforced fibers. When the humidity of the fiber-reinforced soil increases, due to the thickening of the bonding water film between the soil particles, the lubrication effect between the fiber and soil particles is more significant; hence, the friction work that the fiber needs to overcome is also reduced when the soil particles are rearranged in the interface during the pulling and stretching process, leading to reduced frictional resistance between the fiber and soil particle interface. In the meantime, due to the increase in humidity between soil particles, the corresponding cohesion power also decreases, and eventually leading to reduced strength, which can also be seen from the data analysis in section 2. However, there is still no quantifiable index to describe the strength of fiber-reinforced soil and the degree of strength reduction under different fiber blending conditions. In view of this, based on the stress-strain related data of the uniaxial
compressive strength test of the fiber yarn reinforced loess in section 2, an expression of the fiber reinforcement index is proposed as equation (1), which can quantitatively describe the effect of fiber reinforcement on the soil.

\[
I_r = \frac{F_r}{F_d} = \frac{q_r}{q_l} \quad \frac{q_l}{q_{rl}}
\]

In equation (1), \( q \) is the uniaxial compressive strength value of plain loess (unreinforced), kPa; \( q_r \) is the uniaxial compressive strength value of fiber-reinforced loess, kPa; \( q_l \) is the uniaxial compressive strength value of plain loess with liquid limit water content (Unreinforced), kPa; \( q_{rl} \) is the uniaxial compressive strength value of fiber-reinforced loess at liquid limit water content, kPa.

In the expression of fiber reinforcement index, the expression of the numerator and denominator can be discussed separately. The molecular \( F_r \) can describe the reinforcement performance of fiber-reinforced loess, which is called fiber reinforcement factor. The larger the \( F_r \) value, the greater the difference between the uniaxial compressive strength \( q_r \) of fiber-reinforced loess and the uniaxial compressive strength \( q \) of plain loess, which can directly indicate a better reinforcement effect of fiber-reinforced loess. Since the liquid limit water content is a critical water content for the conversion of bounding water to free water in soil particles, when fiber-reinforced loess is at the threshold of liquid limit water content, the interface bonding force and frictional resistance between the fiber and soil particles weaken at varying degrees, and the interwoven fibers also slip in the soil as the humidity increases. At this point, the fiber reinforcement performance will gradually decrease, so that the failure will lead to the destruction of the soil body. The denominator \( F_d \) can describe the loss of effectiveness leading to fiber reinforced soil failure, which is called the fiber failure factor. The smaller the \( F_d \), the greater the difference between the uniaxial compressive strength \( q_d \) of fiber-reinforced loess and the uniaxial compressive strength \( q_l \) of plain loess at the liquid limit water content, it means that the uniaxial compressive strength of fiber-reinforced loess \( q_{rl} \) becomes greater. In other words, when water content reaches the liquid limit, the uniaxial compressive strength of both fiber-reinforced loess and plain loess will decrease to varying degrees. However, due to the difference in soil properties, particle gradation, and fiber properties (fiber blending ratio, fiber length, fiber fineness, and fiber surface properties, etc.), it will result in variation in the uniaxial compressive strength \( q_r \) of fiber reinforced loess. The smaller the \( q_r \), the faster the loss of the reinforcement effect, i.e., the greater the \( F_d \); the larger the \( q_r \), the loss of the reinforcement effect slows down. It can also be said that \( F_d \) can indirectly reflect the failure performance of fiber reinforced loess.

When there is no reinforcement in the soil, \( q \) and \( q_r \) in the numerator \( F_r \) are equal, that is, the numerator \( F_r \) is equal to 1, which also means that the fiber reinforcement index \( I_r \) equals to 1. Therefore, the minimum value of the fiber reinforcement index \( I_r \) is set to 1 (i.e., there is no fiber reinforcement in the soil). With the addition of fibers, the fiber reinforcement index \( I_r \) increases accordingly. When the molecular \( F_r \) reflecting the direct strengthening effect of fiber-reinforced soil is larger, and the denominator \( F_d \) reflecting the failure performance of fiber-reinforced soil is smaller, the fiber-reinforced soil has a good strengthening effect. It can be said that fiber reinforcement index \( I_r \) can comprehensively reflect the actual reinforcement effect of different fiber states (including fiber addition ratio, fiber length, fiber fineness, fiber surface state, etc.) under certain humidity and density conditions.

4.2. Relationship of Covariation of Fiber Reinforcement Index

Based on the uniaxial compressive strength relationship curve of fiber yarn reinforced loess in second 2, according to the fiber reinforced index expression proposed in this study, the reinforcement factor \( F_r \) and failure factor \( F_d \) of fiber yarn reinforced loess under three different working conditions can be calculated, as shown in table 1.
Table 1. Fiber yarn reinforced loess reinforcement factor $F_r$ and failure factor $F_d$.

| Condition 1 | Condition 2 | Condition 3 |
|-------------|-------------|-------------|
| **Fiber yarn blending ratio %** | **F_r** | **F_d** | **F_r** | **F_d** | **F_r** | **F_d** |
| 0.05        | 1.40        | 0.70        | 10       | 1.23        | 0.76        | 150       | 1.51        | 0.65       |
| 0.10        | 1.76        | 0.54        | 20       | 1.76        | 0.66        | 120       | 1.67        | 0.67       |
| 0.15        | 1.91        | 0.40        | 30       | 1.90        | 0.40        | 90        | 1.82        | 0.67       |
| 0.20        | 2.55        | 0.36        | 40       | 2.20        | 0.38        | 60        | 1.90        | 0.65       |

It can be seen from Table 1 that the fiber reinforcement factor $F_r$ shows a gradual increase trend with the increase of fiber yarn blending ratio and fiber yarn length, and shows a gradual increasing trend with the decrease of fiber yarn fineness. The fiber failure factor $F_d$ shows a gradual decrease trend with the increase of fiber yarn blending ratio and fiber yarn length, and basically remains unchanged with the decrease in fiber yarn fineness. The above trend shows that by appropriately increasing the proportion of fiber yarn in the soil and the fiber yarn length can significantly improve the reinforcement performance of the soil, and at the same time help to improve the stability of the fiber reinforced soil under high humidity conditions. By reducing the fineness of fiber-reinforced soil can improve the strengthening ability of fiber-reinforced soil to a certain extent, but it has limited effect in improving the stability of fiber-reinforced soil under high humidity conditions.

In real engineering, engineers and technicians can use the fiber-reinforced index $I_r$ to comprehensively reflect the strengthening performance of fiber-reinforced soil at a certain density and humidity state under different fiber mixing processing conditions.

5. Triaxial Shear Test of Fiber Yarn Reinforced Loess

By sorting the triaxial shear test data, it is possible to draw the stress-strain relationship curve and volume deformation curve of fiber yarn reinforced loess under the same confining pressure and different fiber yarn blending ratios at optimal water content, as shown in figure 6 and figure 7.

![Triaxial stress-strain curve of fiber yarn reinforced loess.](image-url)
It can be seen from figure 6 that under the conditions of the same confining pressure and different fiber yarn blending ratios, the stress-strain curve of fiber yarn reinforced loess has no obvious peak point, they all belong to the trend of strain hardening. The stress-strain curves of fiber yarn reinforced loess are all located above the curve of plain loess. Under the same axial strain condition, with the continuous increase of fiber yarn blending ratio, the curve gradually moves up, it is that the shear stress of fiber yarn reinforced loess gradually increases. This shows that adding a certain proportion of fiber materials to plain loess can significantly improve the shear strength of the soil. As the test’s confining pressure increases, the stress-strain curve of fiber yarn reinforced loess gradually gets closer, which indicates that the magnitude of the confining pressure has a greater impact on the reinforcement effect of the soil. When the test confining pressure is low, the reinforcement effect is obvious. With the increase in confining pressure, the reinforcement effect of the soil gradually weakens.

![Figure 6. Triaxial curve of fiber yarn reinforced loess.](image)

It can be seen from figure 7 that under the same confining pressure but different fiber yarn blending ratios, the fiber yarn-reinforced loess body deformation curve is below the plain loess body deformation curve. With increasing fiber yarn blending ratio, under the same axial strain condition, the body deformation of fiber yarn reinforced loess gradually decreases, indicating that adding a certain proportion of fiber yarn material to plain loess can effectively improve the soil’s deformation resistance ability.

![Figure 7. Triaxial curve of fiber yarn reinforced loess.](image)

| Fiber yarn blending ratio μ/% | Cohesion c/kPa | Internal friction angle φ/° |
|-----------------------------|---------------|---------------------------|
| 0.00                        | 49.22         | 26.9                      |
| 0.05                        | 56.1          | 27.3                      |
| 0.10                        | 71.11         | 26.8                      |
| 0.15                        | 95.23         | 27.2                      |
| 0.20                        | 107.62        | 27.1                      |
It can be seen from table 2 that the cohesion of fiber yarn reinforced loess is higher than that of plain loess. With the increase of fiber yarn blending ratio, the cohesion of fiber yarn reinforced loess gradually increases; the internal friction angle of reinforced loess does not change significantly, and with the increase of fiber yarn blending ratio, the internal friction angle of fiber yarn reinforced loess also remains basically unchanged. This suggests that mixing a certain proportion of fiber yarn in loess does not have much effect on the arrangement and distribution of loess particles, which means that the properties of the loess-like shear failure surface mixed with fiber yarn materials remain basically unchanged.

6. Modified Duncan-Chang Model and Related Parameters of Fiber Yarn Reinforced Loess

6.1. Brief Description of Duncan-Chang E-B Model

According to Condner’s suggestion [19], the soil stress-strain relationship conforming the characteristics of strain-hardening hyperbola is expressed using the following equation.

\[\sigma_1 - \sigma_3 = \frac{\epsilon_1}{a + b \cdot \epsilon_1}\]  
(2)

In equation (2), \(\sigma_1\) is the axial stress, kPa; \(\sigma_3\) is the test confining pressure, kPa; \(\epsilon_1\) is the axial strain, %; \(a\) and \(b\) are the relevant parameters of triaxial shear test respectively. \(a\) is the reciprocal of the initial tangent modulus \(E_i\), and \(b\) is the reciprocal of the asymptote of the stress-strain curve.

Taking the derivative of equation (2), the tangent modulus under certain test confining pressure conditions can be obtained as follows:

\[E_i = \frac{d\sigma_1}{d\epsilon_1} = E_i \left[1 - \frac{R_f(\sigma_1 - \sigma_3)}{(\sigma_1 - \sigma_3)_f}\right]^2\]  
(3)

In equation (3), \(E_i\) is the tangent modulus, kPa; \(E_i\) is the initial tangent modulus, kPa; \(R_f\) is the failure ratio; \((\sigma_1 - \sigma_3)_f\) is the failure shear stress, kPa; where \((\sigma_1 - \sigma_3)_f\) can be expressed using the following equation.

\[(\sigma_1 - \sigma_3)_f = \frac{2c \cos \phi + 2\sigma_3 \sin \phi}{1 - \sin \phi}\]  
(4)

In equation (4), \(c\) is the cohesion, kPa; \(\phi\) is the internal friction angle, °. The ultimate shear stress is,

\[(\sigma_1 - \sigma_3)_{ult} = \frac{2(c \cos \phi + \sigma_3 \sin \phi)}{R_f(1 - \sin \phi)}\]  
(5)

Substituting equation (4) into equation (3) can obtain,

\[E_i = E_i \left[1 - \frac{R_f(\sigma_1 - \sigma_3)(1 - \sin \phi)}{2c \cos \phi + 2\sigma_3 \sin \phi}\right]^2\]  
(6)

In conventional triaxial test, the bulk modulus \(B\) can be expressed by the following equation,

\[B = \frac{dP}{d\epsilon_v} = \frac{1}{3} \frac{d\sigma_1}{d\epsilon_v} = \frac{1}{3} \frac{(d\sigma_1 - d\sigma_3)}{d\epsilon_v}\]  
(7)

In equation (7), \(B\) is the bulk modulus, kPa; \(\epsilon_v\) is the volume strain, %.
6.2. Fiber Yarn Reinforced Loess Parameter Determination of Modified Duncan-Chang E-B Model

By transforming equation (2), the following equation can be obtained,

\[ \frac{\varepsilon_1}{\sigma_1 - \sigma_3} = a + b \cdot \varepsilon_1 \]  \hspace{1cm} (8)

Parameters \( a \) and \( b \) in equation (8) are the intercept and slope in the linear expression, respectively. However, the stress-strain curve in the experiment often deviates greatly when it transforms the \( (\sigma_1 - \sigma_3) - \varepsilon_1 \) hyperbolic relationship into the \( \varepsilon_1 / (\sigma_1 - \sigma_3) - \varepsilon_1 \) linear relationship at the initial and near failure section. In order to reduce the influence of human factors, when calculating the values of \( a \) and \( b \), the fitted straight line passes through the characteristic points with stress levels of 0.7 and 0.95 respectively [21]. The linear fitting relationship \( \varepsilon_1 / (\sigma_1 - \sigma_3) - \varepsilon_1 \) relationship of plain loess and fiber yarn-reinforced loess under different test confining pressure conditions is shown in figure 8.

![Figure 8. \( \varepsilon_1 / (\sigma_1 - \sigma_3) - \varepsilon_1 \) Relationship curves.](image)

Through the fitting relationship in figure 8, the initial tangent modulus \( E_i \) of the soil and the limit value \( (\sigma_1 - \sigma_3)_{ult} \) of the generalized shear stress can be obtained. The generalized failure shear stress \( (\sigma_1 - \sigma_3) \) determined by the stress-strain curve in figure 6 can be used to calculate the failure ratio \( \text{Rf} \) of the sample. \( \text{Rf} \) is the average of all failure ratios, which is approximately 0.511.

According to figure 8, the derived stress and strain related parameters of plain loess and fiber yarn reinforced loess are shown in table 3. According to Yanbu’s suggestion [22], the relationship between the initial tangent modulus of plain loess and fiber yarn reinforced loess and the test confining pressure can be expressed using the following equation:

\[ E_i = K \cdot P_3 \left( \frac{\sigma_3}{P_3} \right)^n \]  \hspace{1cm} (9)

In equation (9), \( E_i \) is the initial tangent modulus, kPa; \( \sigma_3 \) is the test confining pressure, kPa; \( K \) and
n are the corresponding test parameters, which are dimensionless quantities; Pa is the atmospheric pressure, about 101 kPa.

**Table 3. Relevant parameters of soil stress and strain.**

| Confining pressure /kPa | Fiber yarn mixing ratio /% | a      | b      | Ei/kPa  | (σ₁-σ₃) ult/kPa | Rf   |
|-------------------------|---------------------------|--------|--------|--------|----------------|------|
| 50                      | 0.00                      | 0.0321 | 0.00281| 3086.4 | 355.9          | 0.494|
|                         | 0.05                      | 0.0242 | 0.00232| 4166.7 | 431.1          | 0.497|
|                         | 0.10                      | 0.0191 | 0.00214| 5347.6 | 467.3          | 0.579|
|                         | 0.15                      | 0.0145 | 0.00201| 6944.4 | 497.5          | 0.640|
|                         | 0.20                      | 0.0103 | 0.00192| 10121.2| 520.8          | 0.499|
| 100                     | 0.00                      | 0.0256 | 0.00207| 4048.6 | 483.1          | 0.444|
|                         | 0.05                      | 0.0161 | 0.00145| 6250.1 | 689.7          | 0.424|
|                         | 0.10                      | 0.0108 | 0.00126| 9708.7 | 793.7          | 0.566|
|                         | 0.15                      | 0.0098 | 0.00111| 9923.8 | 900.9          | 0.479|
|                         | 0.20                      | 0.0076 | 0.00092| 14084.5| 1086.9         | 0.638|
| 200                     | 0.00                      | 0.0141 | 0.00096| 7299.3 | 1041.7         | 0.465|
|                         | 0.05                      | 0.0123 | 0.00085| 8264.5 | 1176.5         | 0.326|
|                         | 0.10                      | 0.0092 | 0.00076| 11113.1| 1315.8         | 0.680|
|                         | 0.15                      | 0.0087 | 0.00066| 12890.5| 1515.2         | 0.503|
|                         | 0.20                      | 0.0066 | 0.00052| 16393.4| 1923.1         | 0.596|
| 400                     | 0.00                      | 0.0088 | 0.00049| 12987.1| 2040.8         | 0.443|
|                         | 0.05                      | 0.0076 | 0.00047| 14285.7| 2127.7         | 0.455|
|                         | 0.10                      | 0.0064 | 0.00044| 15873.1| 2272.7         | 0.478|
|                         | 0.15                      | 0.0061 | 0.00041| 16949.2| 2439.1         | 0.502|
|                         | 0.20                      | 0.0052 | 0.00040| 20161.2| 2509.9         | 0.522|

According to equation (9), the (Ei/Pa) - (σ₁-σ₃/Pa) relationship curve of plain loess and fiber yarn reinforced loess can be drawn in logarithmic coordinates, and the model parameters K and n under different test confining pressure conditions can be obtained, as shown in table 4, the related fitting curve is shown in figure 9.

**Figure 9. Relationship between initial tangent modulus and confining pressure.**

**Table 4. Model parameters K and n.**

| Fiber yarn ratio /% | K    | n     |
|--------------------|------|-------|
| 0.00 (Element of the loess) | 45.9 | 0.707 |
| 0.05               | 53.8 | 0.653 |
| 0.10               | 71.9 | 0.489 |
| 0.15               | 91.5 | 0.407 |
| 0.20               | 131.1| 0.322 |
It can be seen from figure 9 that the initial tangent modulus of plain loess and fiber yarn reinforced loess gradually increases with the increase of test confining pressure. From table 4, it can be seen that the model parameter K increases when the proportion of fiber yarn blending increases. The model parameter n gradually decreases with the increase of fiber yarn blending ratio. Suppose the model parameters of plain loess are $K_0$ and $n_0$, and K and n are the model parameters of fiber yarn reinforced loess mixed with different proportions of fiber yarn, the relationship between ($K-K_0$) and the proportion of fiber yarn blending ratio can be approximated by an exponential function, as shown in figure 10, equation (10).

$$K - K_0 = A_1 \cdot e^{A_2 \cdot \mu}$$  \hspace{1cm} (10)

$$n_0 - n = A_3 \cdot \ln \mu + A_4$$  \hspace{1cm} (11)

In equation (11), $A_3$ and $A_4$ are test parameters, and their values are 0.234 and 1.833 respectively. Knowing the model parameters $K_0$ and $n_0$ of plain loess, combining equations (10-11) can obtain the model parameters K and n of fiber yarn reinforced loess under certain fiber yarn mixing ratio. Substituting equations (10-11) into equation (9), the initial tangent modulus of fiber yarn reinforced loess can be obtained considering the influence of fiber yarn mixing ratio. As shown in equation (12).

$$E_i = (K_0 + A_1 e^{A_2 \mu}) \cdot P \left( \frac{\sigma_0}{P_a} \right) (n_0 - A_3 \ln \mu - A_4)$$  \hspace{1cm} (12)

In equation (12), $A_1$ and $A_2$ are test parameters, and their values are 4.34 and 1,543.1 respectively. Combining table 2 in Section 5, suppose the cohesion of plain loess and fiber yarn reinforced loess are $c_0$ and c, respectively, the relationship between ($c-c_0$) and fiber yarn mixing ratio is approximately linear, as shown in figure 12 and equation (13).
In equation (13), $A_5$ and $A_6$ are test parameters, and their values are 35,736 and -11.375 respectively.

The cohesion $c_0$ of plain loess is known, and the cohesion $c$ of fiber yarn reinforced loess can be obtained using equation (13).

The internal friction angle does not change significantly with the increase of fiber yarn mixing ratio; it can be considered as approximately unchanged, and the average value can be taken as about 27.1°.

In this study, following Duncan [19], set the bulk modulus corresponding to the stress level at 0.7, and assumes that there is the following relationship between the bulk modulus $B$ and different test confining pressures:

$$ B = k_b \cdot P_a \left( \frac{\sigma_3}{P_a} \right)^m $$

In equation (14), $B$ is the bulk modulus, kPa; $\sigma_3$ is the test confining pressure, kPa; $k_b$ and $m$ are the relevant test parameters, which are dimensionless quantities; $P_a$ is the atmospheric pressure, about 101 kPa.

According to equation (14), draw relationship curve of plain loess and fiber yarn reinforced loess $(B/Pa)$ ~ $(/Pa)$ in logarithmic coordinates, the model parameters $k_b$ and $m$ under different test confining pressure conditions can be obtained. As shown in table 5, the relevant fitting curve is shown in figure 13.
It can be seen from figure 13 that the bulk modulus of plain loess and fiber yarn reinforced loess gradually increases with the increase of test confining pressure. From table 5, it can be seen that the model parameter $K_b$ increases with the proportion increase of fiber yarn mixing ratio. But the model parameter $m$ decreases gradually with the increase of fiber yarn mixing ratio. Suppose the model parameters of plain loess are $K_{b0}$ and $m_0$, and $K_b$ and $m$ are the model parameters of fiber yarn reinforced loess mixed with different proportions of fiber yarn. The relationship between $(K_b - K_{b0})$ and the proportion of fiber yarn mixing can be approximated by an exponential function, as shown in figure 14, equation (15).

$$k_b - k_{b0} = A_7 \cdot e^{A_8 \mu}$$

(15)

In equation (15), $A_7$ and $A_8$ are test parameters, and their values are 5.35 and 1.213.2 respectively.

The relationship between $(m_0 - m)$ and the proportion of fiber yarn mixing can be approximated by a logarithmic function, as shown in figure 15 and equation (16).

$$m_0 - m = A_9 \cdot \ln \mu + A_{10}$$

(16)

In equation (16), $A_9$ and $A_{10}$ are test parameters, and their values are 0.0903 and 0.7415 respectively.

The model parameters $K_{b0}$ and $m_0$ of plain loess are known, and the model parameters $K_b$ and $m$ of fiber yarn reinforced loess can be obtained by combining equations (15-16).

Substituting equations (15-16) into equation (14) respectively, the bulk modulus of fiber yarn reinforced loess can be obtained considering the influence of fiber yarn mixing ratio. As shown in equation (17).

$$B = (k_{b0} + A_7 \cdot e^{A_8 \mu}) \cdot P \left(\frac{\sigma_1}{P_a}\right)^{(m_0 - A_9 \cdot \ln \mu - A_{10})}$$

(17)

To verify the validity of the modified Duncan-Chang E-B model of fiber yarn reinforced loess in this study, the soil at the slope of the construction site at Xihuachi Primary School, Heshui County, Qingyang City, Gansu Province, is selected for verification. Soil sample at the depth of 5m below the ground surface was collected. The soil was grayish yellow with large bulges visible to the naked eye,
which is typical to Longdong Q3 loess. The natural dry density of the soil sample is 1.392 g/cm³, natural water content is 15.5%, soil specific gravity is 2.72, plastic limit water content is 17.6%, and liquid limit water content is 27.9%. The initial dry density of the sample prepared in the experiment is 1.45 g/cm³, and the initial water content is 17.5%. Set the fiber yarn mixing ratio in the loess to 0.05%, 0.10%, 0.15%, and 0.20%, respectively, the sample mixing fiber yarn length is 30 mm, and the fiber yarn fineness is 60 dtex. Combining equations (2-3), (5), and (9), the loess stress-strain curve, with consideration of the influence of fiber yarn mixing ratio, can be obtained. The fiber yarn reinforced loess is listed when the test confining pressure is 200 kPa and 400 kPa respectively. Comparisons between the experimental value of the stress-strain curve and the calculated value of the model are shown in figures 16.

Figure 16. Comparison of stress-strain curves of fiber yarn reinforced loess.

In figures 16, the scattered points of the data are the experimental values, and the solid line is the stress-strain curve of fiber yarn reinforced loess calculated using the modified Duncan-Chang E-B model. By comparison, it is found that the test values are very close to the model calculations, which proves the validity of the modified Duncan-Chang E-B model taking into consideration of the influence of fiber yarn mixing ratio in predicting the stress-strain relationship of fiber yarn reinforced loess.

7. Conclusion
This study conducted uniaxial compressive strength test and triaxial consolidation drainage shear test of fiber yarn reinforced Longdong loess. The strength deformation characteristics of fiber yarn reinforced loess were systematically analyzed. The Duncan-Chang EB model of fiber yarn reinforced loess was modified and analyzed, and relevant parameters of the model were discussed. The research has reached the following conclusions:

The uniaxial compressive strength of fiber yarn reinforced loess increases with the increase of fiber yarn blending ratio and fiber yarn length, and decreases with the increase of fiber yarn fineness.

Based on the analysis of uniaxial compressive strength data of fiber yarn reinforced loess, construct the expression of fiber reinforcement index that can comprehensively reflect the fiber reinforcement performance, and analyze the relationship between it and the performance index of the blended fiber.

The triaxial shear stress-strain curve of the fiber-yarn-reinforced loess exhibits a strain-hardening hyperbolic change form, which conforms to the assumption of the Duncan-Chang model. By analyzing the relationship between model parameters of fiber-yarn-reinforced loess under the condition of different fiber yarn blending ratios with that of plain loess, an empirical expression of model parameters considering the influence of fiber yarn reinforcement is obtained; subsequently, a modified Duncan-Chang EB model that can reflect the influence of different fiber yarn blending ratios is developed.

By comparing the test curve with the modified Duncan-Chang E-B model prediction curve, it is found that the test value is relatively close to the model calculated value, which proves that the model is reasonable.
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