Investigation into mechanical behaviour of loess-wheat straw mixtures

Wen-Chieh Cheng i), Xin Jin ii), Lin Wang iii), Zhong-Fei Xue iii), Louis Ge iv) and Annan Zhou v)

i) Professor, Shaanxi Key Laboratory of Geotechnical and Underground Space Engineering, School of Civil Engineering, Xi’an University of Architecture and Technology, 13, Yanta Rd., Xi’an 710055, China.
ii) Ph.D student, Shaanxi Key Laboratory of Geotechnical and Underground Space Engineering, School of Civil Engineering, Xi’an University of Architecture and Technology, 13, Yanta Rd., Xi’an 710055, China.
iii) Graduate student, Shaanxi Key Laboratory of Geotechnical and Underground Space Engineering, School of Civil Engineering, Xi’an University of Architecture and Technology, 13, Yanta Rd., Xi’an 710055, China.
iv) Professor, Department of Civil Engineering, National Taiwan University, 1, Sec. 4, Roosevelt Rd., Taipei 10617, Taiwan.
v) Senior Lecturer, School of Engineering, Royal Melbourne Institute of Technology, 124 La Trobe Street, Melbourne VIC 3000, Australia.

ABSTRACT

Most residential houses in Loess Plateau of Northwest China have been built five decades ago. The wheat straw retrieved after crop harvesting has always been mixed with the loess to construct house walls. In spite that the extreme climate has already caused a series of extensive natural hazards (e.g., earthquake), the residential houses are well functioned until nowadays. This unique phenomenon drives this study to investigate the mechanical behaviour of the mixture of loess and wheat straw. Thus, uniaxial compressive strength tests and strain-controlled and stress-controlled direct shear tests are implemented on the loess-wheat straw mixture specimens. By adding the wheat straw to the specimens, the failure mode is transfers from the “shear failure” to the “ductile (barrel-shaped) failure” under uniaxial compression loading conditions. Compared to the loess specimens, the loess-wheat straw mixture specimens demonstrate its superior ability of withstanding larger shearing stresses as subjected to similar shear displacements. The gained insights guide the design of upcoming sustainable infrastructures.

Keywords: loess, wheat straw, ductility, shear failure

1 INTRODUCTION

Since rapid urbanisation has significantly impacted the surrounding environment (Cheng et al. 2018b; Wang et al. 2018; Duan et al. 2018; Shen et al. 2017), environment-friendly, high strength construction material with good durability may resolve the raised problem despite many grouting technologies available (Hu et al. 2018; Toraldo et al. 2018; Cheng et al. 2017a, b, 2018a; Wang et al. 2015, 2016; Holter et al. 2016; Ni et al. 2016; Andrade et al. 2011; Gonzalez-Corominas et al. 2015; Vaitkevičius et al. 2016; Tang et al. 2016; Chen et al. 2014). In Northwest China, our ancestors built their houses by introducing the loess-wheat straw mixture for which wheat straw has been regarded as a by-product after crop growth stages. Some records available show that such residential houses built already five decades can be well functioned until nowadays (see Fig. 1). This unique phenomenon drives this study to investigate the mechanical behaviour and ductility nature of the loess-wheat straw mixture. Due to this reason, a series of laboratory experiments including unconfined compressive strength (UCS) tests and strain-controlled and stress-controlled direct shear tests were conducted.

The objectives of this study are (i) to analyse the results of a series of UCS tests and strain-controlled and stress-controlled direct shear tests, (ii) to investigate the impacts of the percentage additive of wheat straw in weight and water content on the mechanical behaviour and ductility of loess-wheat straw mixture specimens, and (iii) to give design guidelines of future sustainable infrastructures.

Fig. 1. Residential house built by the loess-wheat straw mixture.

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2 SPECIMEN PREPARATION AND LABORATORY EXPERIMENTS

2.1 Loess-wheat straw mixture specimen preparation

Prior to the laboratory experiments, great amounts of wheat straw retrieved from the Loess Plateau located in Northwest China were boiled with distilled water and due to this reason, the wheat straw got softened (see Fig. 2).

Fig. 2. Wheat straw before (right-hand side) and after (left-hand side) the treatment.

The wheat straw were subsequently mixed with the Q₄ loess for preparing the loess-wheat straw mixture specimens. In accordance with Massachusetts Institute of Technology (MIT) soil classification system, grading curves for the Q₄ loess can be presented, as shown in Fig. 3. The loess-wheat straw mixture specimens were prepared at the moisture contents ω of 14%, 18%, and 22%, respectively. For the loess-wheat straw mixture specimens with the same moisture content, various percentage additives of the wheat straw of 0.3, 0.45, 0.6, and 0.75, respectively, were introduced.

Fig. 3. Grading curves for Q₄ loess.

2.2 Unconfined compressive strength test

The unconfined compressive strength tests were performed on the loess-wheat straw mixture specimens prepared at the moisture contents ω of 14%, 18%, and 22%, respectively. The loading ram displaced at a rate of 0.45mm/min. The experimental results are shown in Fig. 4.

Fig. 4. Axial stress-strain relationships of the loess-wheat straw mixture specimens at (a) ω=14%, (b) ω=18%, and (c) ω=22%.

2.3 Strain-controlled direct shear test

The strain-controlled direct shear tests were also performed on the loess-wheat straw mixture specimens of 62 mm in diameter and 20 mm in height. The direct shear apparatus made in Nanjing, China was utilised to investigate their shear stress-displacement relationships, as shown in Figs. 5-7. The specimens of same moisture content were sheared at the vertical loads of 100 kPa, 200 kPa, and 300 kPa, respectively. While the shearing rate of 0.8 mm/min was applied to the strain-controlled direct shear tests.
Fig. 5. Shear stress-displacement relationships of the loess-wheat straw mixture specimens at $\omega=14\%$ against (a) vertical load of 100 kPa, (b) vertical load of 200 kPa, and (c) vertical load of 300 kPa.

Fig. 6. Shear stress-displacement relationships of the loess-wheat straw mixture specimens at $\omega=18\%$ against (a) vertical load of 100 kPa, (b) vertical load of 200 kPa, and (c) vertical load of 300 kPa.
2.4 Stress-controlled direct shear test

Since the strain rate significantly affects the particle dislocation interactions, the stress-controlled direct shear tests were implemented twice on the specimens of 305 mm (length) by 305 mm (width) by 200 mm (height). The 0% and 0.75% additive of wheat straw were considered in the direct shear tests. In this study, the large direct shear apparatus, Geocomp ShearTrac III, was utilised enabling their shear displacement-time relationships against the shear stresses varying from 25 to 125 kPa to be investigated, as shown in Figs. 8-10.

3 ANALYSIS AND DISCUSSIONS

3.1 Unconfined compressive strength test

As can be seen, the maximum axial stress for the loess-wheat straw mixture specimens at the moisture content of 14% was descended from 392 to 365 kPa while the percentage additive of wheat straw was raised from 0 to 0.75%. However, the associated axial strain was increased from 1.1 to 2%. In Fig. 4b, the maximum axial stress for the loess-wheat straw mixture specimen at the moisture content of 18% presented a descending tendency with the increasing percentage additive of wheat straw; the maximum axial stress decreased from 226 to 204 kPa as the percentage additive of wheat straw was raised from 0 to 0.75%. The corresponding maximum axial strain was however increased from 16 to 28%. Similar axial strain and stress variations shown in the previous two figures can also be found in Fig. 4c. In Fig. 4c, the maximum axial stress for the loess-wheat straw mixture specimen at the moisture content of 22% showed an descending tendency with the increasing percentage additive of wheat straw; the maximum axial stress declined from 175 kPa for 0% additive of wheat straw to 165 kPa for 0.75% additive of wheat straw. But the corresponding axial strain was raised from 27 to...
The greater the percentage additive of wheat straw, the smaller the maximum axial stress, and the larger the associated axial strain. These phenomena are most likely due to the fact that the wheat straw worked with the “honeycomb” structure of loess formed in the stratum deposition process to form a mixed structure with superior ability of withstanding larger plastic strains before failure. The failure mode was transferred from “shear failure” for the specimens with small percentage additives of wheat straw to “ductile failure” for the specimens with large percentage additives of wheat straw (see Fig. 11).

3.2 Strain-controlled direct shear test

The percentage additives of wheat straw of 0.3, 0.45, 0.6, and 0.75 and the normal pressures of 100, 200, and 300 kPa were first applied to the specimens at \(\omega=14\%\). The cohesion \(c\) was reduced from 72.3 kPa for 0.3% wheat straw additive to 52.5 kPa for 0.75 % wheat straw additive. While the friction angle \(\phi\) was increased from 48.4 to 61.3 deg. The same percentage additives of wheat straw and normal pressures were applied to the specimens at 18% and 22%, respectively. Similarly, the \(c\) values were in an inverse relation to the wheat straw additive, while the \(\phi\) values were in a direct relation to the wheat straw additive; their shear strength parameters measured at \(c=59.5-52.5\) kPa, \(\phi=41.5-49.5\) deg. and \(c=66.2-55.2\) kPa, \(\phi=34.1-46.5\) deg., respectively. The greater the amount of wheat straw additive, the smaller the cohesion, and the larger the friction angle. This phenomenon indicates that the loess-wheat straw mixture specimens behaved as a “sand-like” material rather than a “clay-like” material as subjected to a greater amount of the wheat straw additive. Since the wheat straw additive largely promoted the effect of particles inter-locking, particles dislocation and/or rearrangement became more difficult. Additionally, greater normal pressures, e.g., 200 kPa or 300 kPa, also made particles dislocation and/or rearrangement more difficult. This was clearly reflected via the strain hardening behaviour after the specimens underwent the shear displacement of 1.7 mm.

3.3 Stress-controlled direct shear test

While performing the stress-controlled direct shear tests, the loess specimen was sheared by 25 kPa in the first stage and by 50 kPa and 75 kPa, respectively, in the second and final stages. The maximum shear displacement reached 0.28 mm in the first stage, with the small strain rate of 0.065 mm/min. The maximum shear displacement rose to 11.2 mm in the second stage, with the moderate strain rate of 0.153 mm/min. The maximum shear displacement increased sharply to 50 mm in the final stage, with the largest strain rate of 19.425 mm/min. Similar stress-controlled direct shear test was again implemented on the loess-wheat straw mixture specimen. This specimen was incrementally sheared up to the maximum shearing stress of 125 kPa, with a shearing stress increment of 25 kPa. The shearing stress for the loess-wheat straw mixture specimen corresponded to 75 kPa as subjected to the shear displacement of 12.23 mm. The shearing stress for the loess specimen measured at 50 kPa as subjected to similar shear displacements (i.e., 11.15 mm). Compared to the loess specimen, the loess-wheat straw mixture specimen possessed a superior ability of withstanding greater shearing stresses as subjected to similar shear displacements.

4 CONCLUSIONS

Based upon the experimental results of a series of tests primarily aimed to investigate the mechanical behaviour and failure mode of the loess-wheat straw mixture specimens and discussion made, the following conclusions can be drawn:

(1) Compared to the loess specimens, the wheat straw worked with the “honeycomb” structure

![Fig. 11. Failure mode of specimen subjected to uniaxial loading: (a) loess specimen, (b) loess wall of house in Northwest China, (c) loess-wheat straw mixture specimen, and (d) loess-wheat straw mixture wall of house.](image-url)
of loess to form a new structure capable of withstanding larger plastic strains before failure. By adding the wheat straw to the specimens, the failure mode was transferred from “shear failure” to “ductile (barrel-shaped) failure”.

(2) The results from the strain-controlled direct shear tests indicate that the loess-wheat straw mixture specimens behaved as “sand-like” materials as subjected to a greater amount of the wheat straw additive. As the wheat straw additive significantly promoted the effect of particles inter-locking, particles dislocation and/or rearrangement became more difficult. Increasing the moisture content seemed to weaken the effect of particles inter-locking.

(3) According to the results of the stress-controlled direct shear tests, compared to the loess specimens the loess-wheat straw mixture specimens possessed a superior ability of withstanding greater shearing stresses as subjected to similar shear displacements.

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