学　位　論　文　内　容　の　要　旨

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Methods for estimating permanent deformation of unsaturated aging railroad ballast under cyclic loading

(繰返し荷重下の不飽和経年劣化鉄道バラストの永久変形量の推定法に関する研究)

Ballasted track structure is one of the typical track structures for traditional railways in Japan. In general, track deteriorations with a continuous decrease in the load bearing capacity or increase in the permanent deformation are always observed at ballasted tracks mainly due to the degradation of ballast particle size and shape, referred to as “aging” in this study, induced by repeated train loads. In addition, the increase in fine fraction content caused by aging also affects the permeability and water retentivity of the ballast. However, the current Japanese design standard adopts a semi-empirical formula to estimate the permanent deformation of ballast for the construction of new lines, any method for calculating permanent deformation of ballast observed at aged lines has not been proposed by considering the effects of water content and aging, which may reduce the prediction accuracy of the maintenance cycle of ballasted tracks. Therefore, it is meaningful to evaluate the impact of aging on hydro-mechanical behavior of unsaturated ballast, and to further predict the permanent deformation by some estimation models, so as to improve the track structure design and reduce maintenance costs.

For this purpose, this study first examines the validity of the Los Angeles Abrasion (LAA) test in the preparation of aged ballast. It indicates that the LAA test can reproduce the grain size distribution and particle shape for in-situ aged ballast obtained from the actual railway track. To evaluate the influence of aging on the hydraulic properties of unsaturated ballast, the water retentivity and coefficient of permeability for fresh and aged ballasts are determined by water retention tests and saturated/unsaturated permeability tests, respectively. The results of water retention tests prove that the aging induces significant increase in water retentivity compared with fresh ballast, due to the presence of fine fraction content. Besides, the results of saturated/unsaturated permeability tests show that the coefficient of permeability of aged ballast is lower than that of fresh ballast, while the relative coefficient of permeability of fresh ballast is more significantly affected by degree of saturation.

In terms of shear strength, the influence of aging on the shear strength behavior of unsaturated ballast is examined through a range of monotonic loading triaxial compression tests. Test results show that the effective shear strength parameters of fresh ballast under fully drained conditions (CD test) are close to those under fully undrained conditions (CU test), regardless of water content. However, for the aged ballast, its effective shear strength parameters are more suitable to be determined through the CU test due to low permeability. Besides, the aging reduces the effective internal friction angle of ballast, while it increases the total cohesion as compared with fresh ballast, especially under the high saturation condition. Regarding the effect of water content, the shear strength of both materials has a decreasing tendency as water content increases, and the declining trend of shear strength is more

noticeable for aged ballast.

On the other hand, it is of great significance to predict the cumulative plastic deformation of the ballasted track under repeated train loads. Thus, the influence of aging on the permanent deformation of unsaturated ballast is evaluated through a series of cyclic loading triaxial compression tests. It indicates that the permanent deformation of ballast under cyclic loading is seriously affected by water content and aging, and the increasing trend of permanent deformation becomes more remarkable in such a case where both water content and fine fraction content increase. Besides, the results of the CU test indicate that the aged ballast may have a greater positive excess pore water pressure at the beginning of cyclic loads as compared with those of the CD test, which further boosts the development of permanent deformation, especially under the saturated condition. Furthermore, the applicability of two estimation models (i.e., UIUC model and SSE model) on the prediction of permanent deformation of unsaturated ballast is also verified in this study. It shows that the effect of water content on permanent deformation of fresh and aged ballasts can be effectively estimated by UIUC model and SSE model, which are possible to predict the cumulative plastic deformation of actual ballasted tracks with different water contents and degrees of aging. The findings of this study show that aging has adverse effects on the hydro-mechanical behavior as well as permanent deformation of unsaturated ballast. Therefore, the effects of aging and water content on the load bearing capacity and cumulative plastic deformation of ballasted tracks should be considered comprehensively in the actual railway design, which is of great significance to improve the track structure design and reduce maintenance costs.

The thesis includes 8 Chapters. Chapter 1 introduces the background, literature review, objectives, and organization of this study. Chapter 2 introduces the features of test apparatus, like water retention apparatus, saturated/unsaturated permeability apparatus, and medium-size triaxial apparatus used in this study. Chapter 3 describes the test materials and test methods. Chapter 4 evaluates the hydraulic properties of unsaturated ballast based on water retention test and saturated/unsaturated permeability tests. Chapter 5 discusses the influence of aging on shear strength of unsaturated ballast based on monotonic loading triaxial compression test. Chapter 6 discusses the influence of aging on permanent deformation of unsaturated ballast based on cyclic loading triaxial compression test. Two methods for estimating the permanent deformation of unsaturated ballast are presented in Chapter 7. Lastly, Chapter 8 summarizes the conclusions of this study and gives the recommendations for future studies.