Influences of water content and fine fraction content on permanent deformation of ballasts

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ABSTRACT

In this paper, the effects of water content and fine fraction content on permanent stains of ballasts were studied by the laboratory element tests. The experimental results show that the increasing trend of permanent strain becomes more remarkable in such a case where both water content and fine fraction content increase. Besides, the UIUC rutting model was evaluated to estimate the effects of water content and fine fraction content on permanent deformation of ballasts by comparing the experimental results. The results show that the UIUC rutting model can well estimate the permanent deformation of ballast with various water contents and fine fraction contents.

Keywords: permanent deformation; water content; fine fraction content; UIUC rutting model

1 INTRODUCTION

Track deteriorations are always observed at ballasted tracks due to the permanent deformation of railroad ballast. In this case, Lekarp et al. (2000) pointed out that the permanent deformation of the aggregate materials was affected by stress level, moisture content, fine fraction content, grading and so on. For example, the increase in fine fraction content seriously alters the deformation-strength characteristics of the ballast, depending on the amount of fouling materials mixed with clean ballast (Lackenby et al. 2007; Dareeju et al. 2015). Besides, Ishikawa et al. (2017) revealed that both water content and fine fraction content may have serious influences on mechanical properties of the ballast. However, these studies only examined the experimental results, and the estimation models for permanent deformation of ballast were not proposed. It is noted that though the Japanese design standard for railway structures and commentary (RTRI 2012) adopts an experimental equation to estimate permanent deformation of railroad ballast for the construction of new lines, any method for calculating permanent deformation of railroad ballast observed at aged conventional lines has not been proposed by considering the effects of water content and fine fraction content.

On the other hand, several models have been proposed to estimate the permanent deformation of pavement materials under repeated traffic loads so far (e.g. Monismith et al. 1975; Lekarp et al. 2000). For example, the UIUC rutting model was established to estimate permanent deformation of pavement materials under repeated traffic loads considering the effects of applied stress levels and shear strength properties (Qamhia et al. 2016). Previous studies (Chow et al. 2014a, 2014b) have shown that the UIUC rutting model can well estimate permanent deformation of pavement materials. In this study, in order to improve the prediction precision of ballast settlement and the versatility of the Japanese design standard, the applicability of the UIUC rutting model on the estimation of permanent deformation for ballast with different water contents and fine fraction contents under repeated train loads will be verified by considering some uncertain effects which are not verified in the UIUC rutting model, like the effects of ballast fouling and fluctuation in water content. For this reason, first the effects of water content and fine fraction content on permanent deformation of ballast under repeated traffic loads are examined by a series of laboratory element tests. Next, compared with the results of cyclic loading tests, the applicability of the UIUC rutting model is verified by considering influences of water content and fine fraction content.

2 TEST MATERIALS

In general, Japanese railroad ballast is composed of angular, crushed and hard andesite stone. Proper grading of ballast according to the Japanese railway specification has a grain-size distribution ranging from 10 to 60 mm. Clean ballast (CB) and fouled ballast (FB) are employed as test materials in this study. Here, the term “1/1CB” and “1/1FB” refer to the full-scale clean ballast and full-scale fouled ballast, respectively. As sh-

Table 1. Experimental conditions and results.

Test name	Sample	Water content	σ'_{net} (kPa)	ρ_{dc} (g/cm^3)	D_c (%)	S_r (%)	q_{max} (kPa)	ϕ' (deg.)	c (kPa)
ML test	1/2CB	Air-dried	20.0	1.562	94.5	4.42	237.5	58.9	0
ML test	1/2CB	Unsaturated (s=20kPa)	20.0	1.529	92.6	6.72	200.0	55.3	2.34
ML test	1/2CB	Saturated	20.0	1.552	93.9	100	185.0	55.3	0
ML test	1/2FB	Air-dried	20.0	1.967	90.3	7.73	230.4	58.4	0
ML test	1/2FB	Unsaturated (s=20kPa)	20.0	1.928	88.6	53.4	168.5	52.6	2.28
ML test	1/2FB	Saturated	20.0	1.916	88.0	100	153.9	52.6	0
CL test	1/2CB	Air-dried	20.0	1.571	95.1	4.22	-	-	-
CL test	1/2CB	Unsaturated (s=20kPa)	20.0	1.568	94.9	6.86	-	-	-
CL test	1/2CB	Saturated	20.0	1.541	93.3	100	-	-	-
CL test	1/2FB	Air-dried	20.0	1.951	89.6	6.09	-	-	-
CL test	1/2FB	Unsaturated (s=20kPa)	20.0	1.870	86.1	54.7	-	-	-
CL test	1/2FB	Saturated	20.0	1.930	88.7	100	-	-	-

own in Fig. 1, 1/1CB has the proper grading, while 1/1FB contains more fine fractions due to particle crushing caused by repeated train loads and/or finer material intrusions caused by mud-pumping and so on. These full-scale ballasts have the same grain size distribution as those for CB and FB extracted from actual railway tracks in Japan. However, in this paper, the small-scale clean ballast (1/2CB) and the small-scale fouled ballast (1/2FB) were employed as test materials due to the constraint of the specimen size in the medium-size triaxial apparatus. 1/2CB has half mean grain size of the 1/1CB with a parallel gradation (Fig. 1). 1/2FB has 26.5 mm cut-grain-size distribution of 1/1FB. It is noted that 1/1FB is an artificial mixed soil composed of 1/1CB, gravel (C-30) and kaolin mixture (6:3:1 mixture in weight ratio). Accordingly, soil properties of fine-grained soil in fouled ballast (FB) are different from in-situ ones.

Fig. 2 shows soil water characteristic curves (SW CCs) of test materials obtained from water retention tests, together with fitting curves proposed by Fredlund and Xing (1994). According to test results, the SWCC of 1/2FB is on the right side of 1/2CB, and the residual degree of saturation (S_{rr}), which can be determined through the fitting curves, of 1/2FB (S_{rr}= 46.1%) is much higher than that of 1/2CB (S_{rr}=6.5%). This is considered ascribable to the fact that fouled ballast is well graded and has higher fine content as compared with clean ballast. These results show that ballast fouling due to the increase in fine fraction contents induces the rise in the water retentivity. Thus, when other test conditions are constant, the fine fraction content may affect the shear strength and permanent deformation of ballasts due to the increase in the water retentivity.

3 TEST METHODS

Monotonic and cyclic triaxial compression tests were performed by the medium-size triaxial apparatus developed by Ishikawa et al. (2014). A cylindrical specimen with initially 300 mm in height and 150 mm in diameter was prepared with air-dried ballasts in five layers. For details of the test apparatus, Ishikawa et al. (2014) was to be referred. A medium-size cylindrical specimen was prepared as follows: Air-dried sample (w=1.69% for 1/2CB and 1.80% for 1/2FB) was placed into the cylindrical mold in five layers step by step, each layer has 60 mm in thickness. Subsequently, each layer was compacted by a vibrator in 3 minutes with constant compaction energy so as to attain the degree of compaction (D_c) of 93.0% for 1/2CB and 90.0% for 1/2FB. The uniform of specimen was ensured with low variations in density. Table 1 shows test conditions of all triaxial compression tests conducted in this study.

Monotonic loading (ML) tests were performed under three different water contents, namely “air-dried”, “unsaturated” (suction (s)=20 kPa) and “saturated” in conformance with the standards of Japanese Geotechnical Society (Method for CD triaxial compression test on soils, JGS 0524-2009 & Method for triaxial compression test on unsaturated soils, JGS 0527-2009). Each specimen was sheared by applying an axial deviator stress at a designated axial strain rate of 0.05%/min under fully drained condition, and the shearing stage stopped when the axial strain reached 15% regardless of water content and fine fraction content. Note that for unsaturated specimen, both pore air and pore water are allowed to drain.

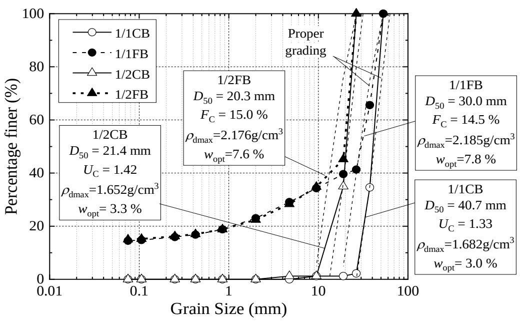


Fig. 1. Grain-size distributions of material (Ishikawa et al. 2017).

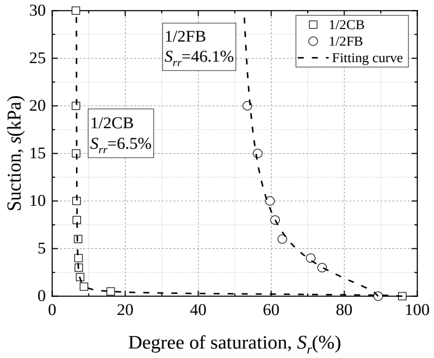


Fig. 2. SWCCs of test materials (Ishikawa et al. 2017).

Table 2. Regression parameters of Monismith's model.

Sample	1/2CB Air-dried	1/2CB Unsaturated	1/2CB Saturated	1/2FB Air-dried	1/2FB Unsaturated	1/2FB Saturated
A	0.422	0.656	1.313	0.563	0.563	5.000
B	0.102	0.148	0.105	0.041	0.266	0.063
R^2	0.937	0.882	0.800	0.956	0.955	0.933

Table 3. Input parameters of UIUC rutting model.

Sample	1/2CB Air-dried	1/2CB Unsaturated	1/2CB Saturated	1/2FB Air-dried	1/2FB Unsaturated	1/2FB Saturated
σ_d (kPa)	80	80	80	80	80	80
σ_f (kPa)	25.77	27.11	27.11	25.92	28.21	28.21
τ_f (kPa)	20.69	22.77	22.77	20.94	24.27	24.27
$\tau_{\max}$ (kPa)	42.64	41.51	39.16	42.19	39.23	36.95
SSR	0.485	0.548	0.581	0.497	0.619	0.657

Table 4. Regression parameters of UIUC rutting model.

Formula	UIUC rutting model				
Parameters	A	B	C	D	R^2
1/2CB	0.224	0.07	1.296	6.535	0.973
1/2FB	0.802	0.061	1.228	8.258	0.954

In cyclic loading (CL) tests, after isotropic consolidation, the axial deviator stresses in sinusoidal waveform ranged from 10 kPa to 80 kPa were cyclically applied to the specimen under the fully drained condition in the same way as for ML tests mentioned above. The number of loading cycles was 10,000, and the loading frequency of 1 Hz was selected.

4 RESULTS AND DISCUSSIONS

4.1 Estimated by Monismith's model

Fig. 3 shows the measured permanent stains of fouled and clean ballasts with different water contents. Each test result is fitted with the exponential model ($\varepsilon_p=AN^B$) proposed by Monismith et al. (1975). From the figure, it is revealed that permanent strains of ballast are seriously affected by the water content and the fine fraction content, and the increasing trend of the permanent strain becomes more remarkable in such a case where both water content and fine fraction content increase. Besides, it indicates that the exponential model can well estimate the permanent strain of ballast under cyclic loads. Table 2 shows the regression results for the parameter values of the model. However, these parameter values are quite discrete and the physical meaning of each parameter is not clear, which limits the development of the model.

4.2 Estimated by UIUC rutting model

The UIUC model also belongs to the exponential model, while its input parameters can be determined by ML tests compared to the estimation model in Section 4.1. Thus, in this section, the applicability of the UIUC rutting model is evaluated by estimating test results. In this model, the applied deviator stress levels and effects of shear stress ratio should be considered in the prediction of permanent deformation as shown in Eq. (1).

$$\varepsilon_p = AN^B\sigma_d^C\left(\frac{\tau_f}{\tau_{\max}}\right)^D \quad (1)$$

where, ε_p=Permanent strain; σ_d=Deviator stress; τ_f= Shear stress acting on failure plane; σ_f=Normal stress acting on failure plane; $\tau_{\max}$=Shear strength determined by $c+\sigma_f\tan\phi'$; c=Total cohesion; ϕ'=Effective friction angle, and A, B, C, D=Regression parameters.

In the UIUC rutting model, the concept of Shear Stress Ratio ($SSR=\tau_f/\tau_{\max}$) defined as the ratio between the applied shear stress and the shear strength, was used to identify the stress values in CL tests. Fig. 4 reveals relationships between the maximum permanent strain ($\varepsilon_{p,10000}$) and the SSR with different water contents. The $\varepsilon_{p,10000}$ appears to vary exponentially with respect to the SSR. It can be inferred that the $\varepsilon_{p,10000}$ of the test material is affected by the value of SSR irrespective of water content and fine fraction content. The input and corresponding regression parameters of the model are shown in Tables 3 and 4, respectively. In Table 4, 1/2FB shows higher A and D values than those of 1/2CB; meanwhile, 1/2CB and 1/2FB share similar B and C values. These results indicate that the fouled ballast shows a higher initial permanent deformation, and that the effect of *SSR* on permanent deformation becomes more pronounced as the fine fraction content increases.

4.3 Effects of water content and fine fraction content

Fig. 5(a) compares measured and estimated permanent strains of 1/2CB with different water contents. From the figure, the estimated values by UIUC rutting model are consistent with the measured ones by same regression parameters, even though water contents are different. It indicates that the influence of water content on permanent deformation of 1/2CB can be well estimated by the model. Besides, in order to evaluate the applicability of this model

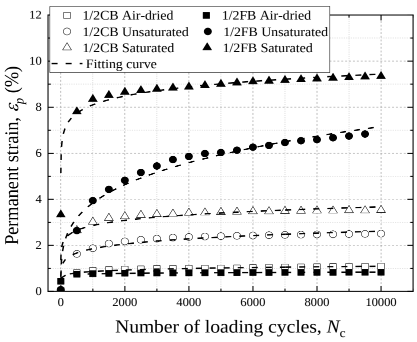


Fig. 3. Relationships between ε_p and N_c in CL tests.

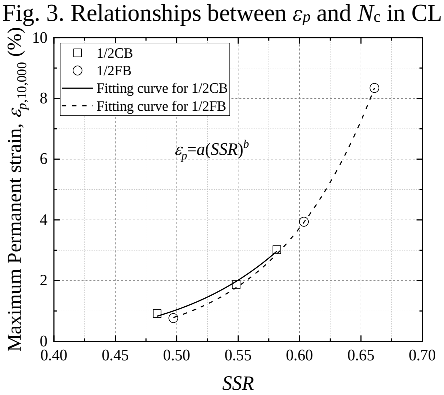
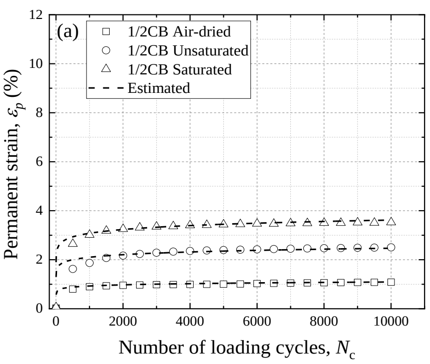


Fig. 4. Relationships between $\varepsilon_{p,10000}$ and *SSR*.



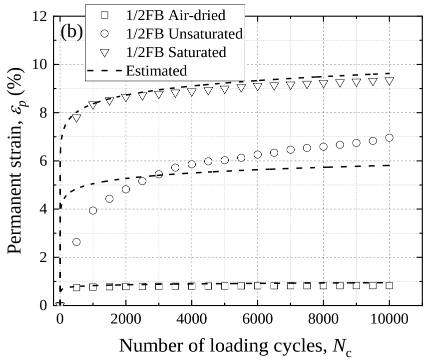


Fig. 5. Variations of ε_p with N_c: (a) 1/2CB, (b) 1/2FB.

in terms of fine fraction content, Fig. 5(b) shows measured and estimated permanent strains of 1/2FB with different water contents. It is noted that regression parameter values of 1/2FB are different from those of 1/2CB. From the figure, the estimated value of 1/2FB are close to the measured value, although there is a small difference between them under unsaturated condition. This indicates that the influence of water content on permanent deformation for ballast can be well evaluated by UIUC rutting model with regression parameters selected depending on ballast materials.

5 CONCLUSIONS

The following findings are mainly obtained from this study:

(1) Permanent strains of ballasts under repeated loads are seriously affected by the water content and the fine fraction content, and the increasing trend of permanent strain becomes more remarkable in such a case where both water content and fine fraction content increase.

(2) Influences of water content and fine fraction content on permanent deformation of ballast can be effectively estimated by UIUC rutting model.

However, considering that results in this study are obtained under limited experimental conditions, the applicability of the model still needs further evaluation in the future by comparing with more test results.

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