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Loading rate and ageing effects on the strength and deformation characteristics of polymer geogrids

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ABSTRACT: Loading rate and ageing effects on the strength and deformation characteristics of polymer geogrids were evaluated by performing tensile loading tests at different strain rates as well as with stepwise changes in the strain rate and multiple creep and stress relaxation loading during otherwise monotonic loading. Two types of fresh geogrids and another one aged for about eight years in a full-scale structure were used. It is shown that creep deformation is due to the viscous property of geogrid and is not a degradating phenomenon for the stiffness and strength of geogrid. It is shown that the aged geogrid has not deteriorated compared with the fresh one of the same type. It is suggested to define the design strength of a given geogrid for a relevant strain rate at failure irrespective of design life, correcting the rupture strength from fast tensile rupture tests for loading rate effects as long as the stiffness and strength do not degrade with time due to, for example, weathering and/or chemical deterioration. A non-linear three-component model is proposed, which can simulate very well the behaviour of the fresh and aged geogrids under wide loading histories.

1 INTRODUCTION

Geosynthetics, including polymer geogrids, are increasingly used to tensile-reinforce the backfill of permanent earth structures, including soil retaining walls and bridge abutments. It is particularly the case in conjunction with transportation facilities in Japan (Tatsuoka et al. 1997). It is the current design practice to classify tensile reinforcements into inextensible ones (like metal strips) and extensible ones (like polymer geogrids) based on the material stiffness. Correspondingly, it is often considered that geosynthetic-reinforced soil structures (GRS structures) would exhibit too large deformation, ignoring large effects on the behaviour of GRS structures of the three-dimensional structural geometry and arranging patterns in the backfill of reinforcement and interaction with the backfill. In this respect, the time effect on the strength and stiffness of polymer geogrids is often considered to be the most serious potential problem.

The time effect consists of the following two factors:

1) *Ageing effect*, defined as changes with time in the intrinsic material properties, such as elastic, plastic and viscous properties. Typical negative ageing effects for polymer geogrids take place by weathering and chemical deterioration processes.
2) *Loading rate effect*, taking place due to the viscous property of geogrid. This phenomenon includes effects of strain rate on the deformation and strength property, creep deformation and stress relaxation.

Therefore, for relevant estimation of design strength for a given lifetime and creep deformation of a given geogrid, accurate evaluation and correct interpretation of the time effect on the tensile load-strain behaviour of geogrids is of great significance.

It seems however that the ageing effect and loading rate effect are somehow mixed up in the current design practice. That is, the peak strength from tensile rupture tests at a relatively high strain rate (i.e., the unfactored strength) is reduced by using a relatively large creep reduction factor to obtain the design tensile strength for a specified design lifetime. It is also the case with the design strength for seismic design in some design codes. The creep reduction factor is determined based on creep-rupture curves, for which the creep rupture strength decreases with the increase in the design lifetime. This design method implicitly assumes that the most likely cause for the failure of GRS structures is the creep failure of geosynthetic reinforcement. Correspondingly, despite that creep deformation is a result of viscous property, it is often wrongly considered that creep is a degrading phenomenon for the strength and stiffness of geogrid (i.e., negative ageing effect). On the other had, some existing data show that the tensile strength of typical geosynthetics from loading tests performed after long-term creep loading is not particularly smaller than the value obtained from similar loading tests at the same strain rate performed before creep loading (e.g., Paulson & Bernardi 1997). It seems therefore that the present practice could be too conservative and misleading (e.g., Greenwood 1997 & 1998; Greenwood et al. 2001).

In this study, the ageing and loading rate effects of polymer geogrids are evaluated separately by performing a series of tensile loading tests on fresh and aged geogrids.

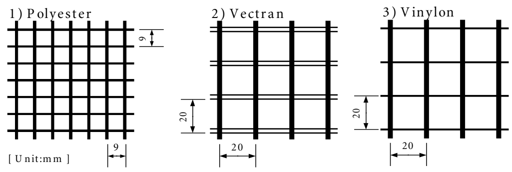
2 TEST METHOD AND TEST MATERIAL

The following three types of geogrids (Table 1) were used:

1) *Geogrid 1* (fresh polyester): The aperture was 9 mm in the longitudinal and transversal direction. The specimens consisted of three strands (Hirakawa et al. 2002).
2) *Geogrid 2* (fresh Vectran coated with Polyvinyl chloride resin): The aperture was 20 mm in the longitudinal and transversal direction. The specimens consisted of three strands (Kongkitkul et al. 2002).
3) *Geogrid 3* (aged Vinylon coated with Polyvinyl chloride resin): The aperture was 20 mm in the longitudinal and

Table 1. Physical and index properties of three geogrids.

Type	1)	2)	3)
Fiber material	Polyester	Vectran	Vinylon
Coating material	PVC	PVC	PVC
V_{max} [kN/m] (condition)	39.2 at 1 strand, 1%/min	66.6 at 20 cm, 1%/min	60.8 at 20 cm, 1%/min



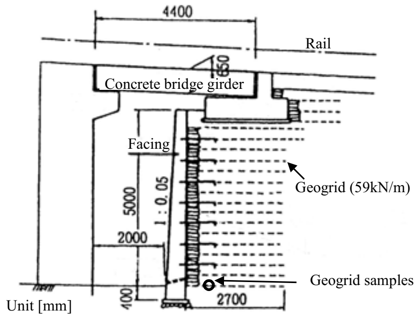


Figure 1. Cross-section of GRS bridge abutment (so-called Seibu-wall; Tatsuoka et al.1997)

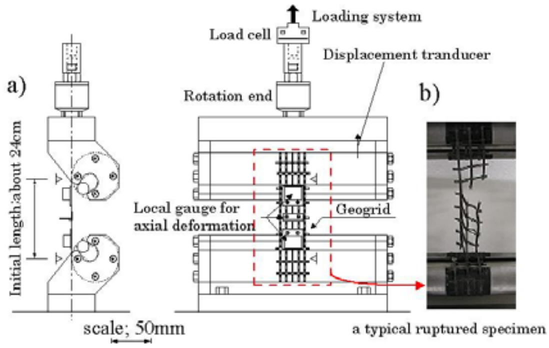


Figure 2. Tensile loading apparatus with a specimen; a) Setup of tensile tests, and b) a typical ruptured specimen (geogrid 3).

transversal direction. The specimens consisted of three strands.

Geogrid 3 was used to reinforce the backfill (well-graded gravel) of GRS bridge abutments supporting one of the busiest rapid transits (Seibu Line) in Tokyo for about eight years (from 1993 To 2001) (Tatsuoka et al. 1997; Figure 1). A full-height RC rigid facing was cast-in-place directly on the face of GRS walls constructed with help of gravel-filled gabions, wrapped-around with the geogrid, placed on the shoulder of each soil layer. When the structures were demolished in 2001, a number of geogrid samples were retrieved from the inside of the structures.

Figure 2 shows the tensile loading apparatus with a test specimen of geogrid 3. Axial tensile strains of the specimen were measured by using two laser displacement sensors, located at the center of the specimen with a gauge length of about 6 cm. The details of the apparatus are reported by Hirakawa et al. (2002).

3 TEST RESULTS AND DISCUSSIONS

3.1 Loading rate effects (geogrids 1 and 2)

Figure 3 shows the tensile load per width and axial strain relations from monotonic loading (ML) tests at constant strain rates ranging 0.01 - 20 %/min and a special test including step changes in the strain rate, creep and relaxation stages during otherwise ML. Significant loading rate effects can be seen in these test results. In particular, immediately after ML is restarted at a constant strain rate following a creep or stress relaxation stage and after a step increase in the strain rate, the geogrid shows high stiffness close to the elastic one. Subsequently, the load-strain relationship exhibits clear yielding and noticeable stress overshooting before rejoining the original one that would be obtained by continuous ML at the same constant strain rate. The behaviour that is opposite to the above takes place immediately after the strain rate is decreased stepwise.

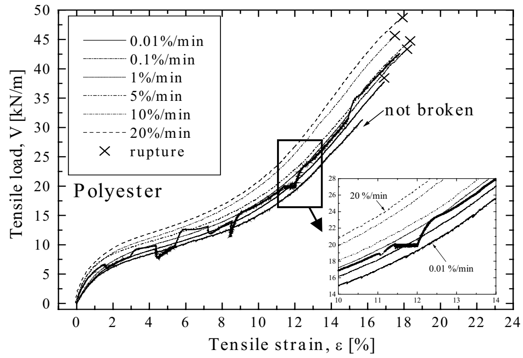


Figure 3. Measured tensile load–strain relationship from ML tests with and without step changes in the strain rate, creep and stress relaxation (geogrid 1).

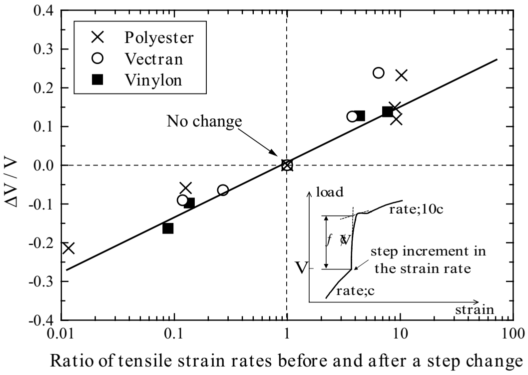


Figure 4. Load jump associated with a step change in the strain rate (geogrids 1, 2 and 3)

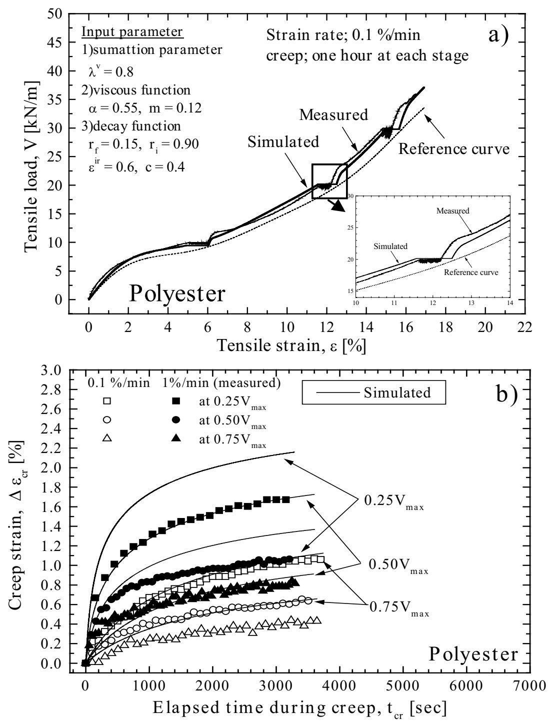


Figure .5 Measured and simulated a) tensile load-strain relationship from a ML test with creep loading; and b) time histories of creep strain (geogrid 1).

These test results indicate that the current load value and peak strength of the tested geogrid is essentially a function of the instantaneous strain and its rate (more accurately irreversible strain and its rate), independent of elapsed time elapsed since the start of loading. Figure 4 shows the measured ratios of load jump associated with step change in the strain rate to the instantaneous

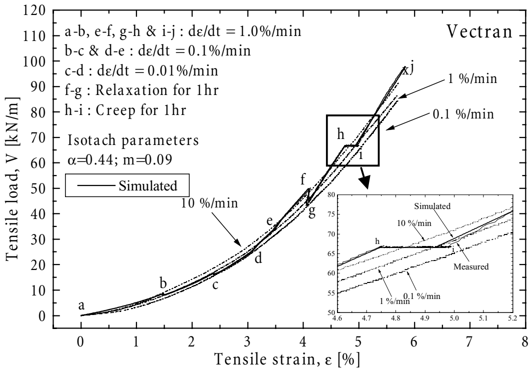


Figure 6. Measured and simulated tensile load-strain relationship from a ML test with and without creep loading (geogrid 2).

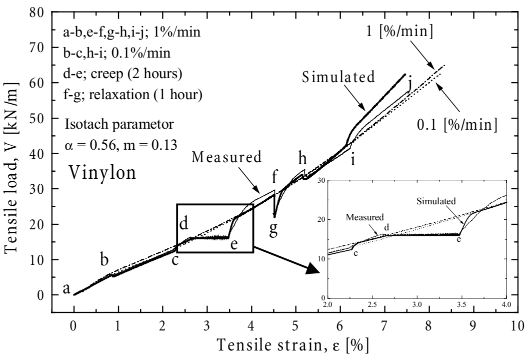


Figure 7. Measured and simulated load-strain relationship from ML tests at different strain rates and with creep loading (aged geogrid 3).

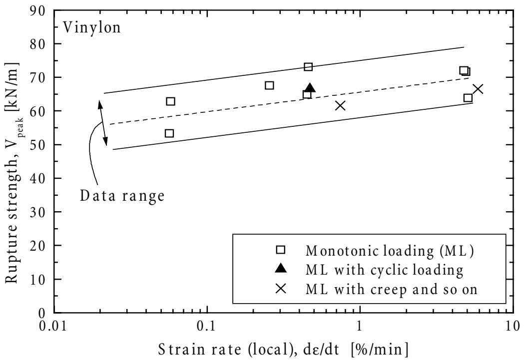


Figure 8. Rupture strength versus strain rate at rupture (aged geogrid3).

load plotted against respective ratios of the strain rates before and after a step change (in logarithmic scale) for the three types of geogrids tested in this study. It may be seen that the slope in this plot, representing the viscous property, is very similar among the three types of geogrid. This trend of viscous behaviour is one of the bases for constitutive modelling for geogrids asdescribed later in this paper.

The viscous property of geogrid 1 was evaluated also by performing creep tests at different load levels during otherwise ML (Figure 5a). Figure 5b shows the time histories of creep strain. The simulation is described later. The following trends of behavior may be seen from these figures:

1) The behaviour when ML is resumed at the original strain rate after each creep stage is very similar to the one when the strain rate is increased stepwise, as presented in Fig. 4. That is, creep deformation is due to the viscous property and it does not affect the peak strength of the geogrid, showing that creep is not a degrading phenomenon.

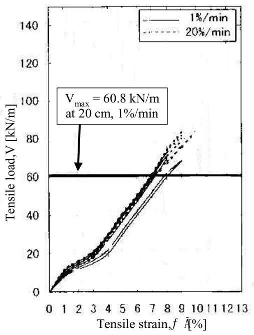


Figure 9. Measured load-strain relationships from ML tests at two different strain rates (fresh geogrid; Taiyo kogyo Co. Ltd. 2000).

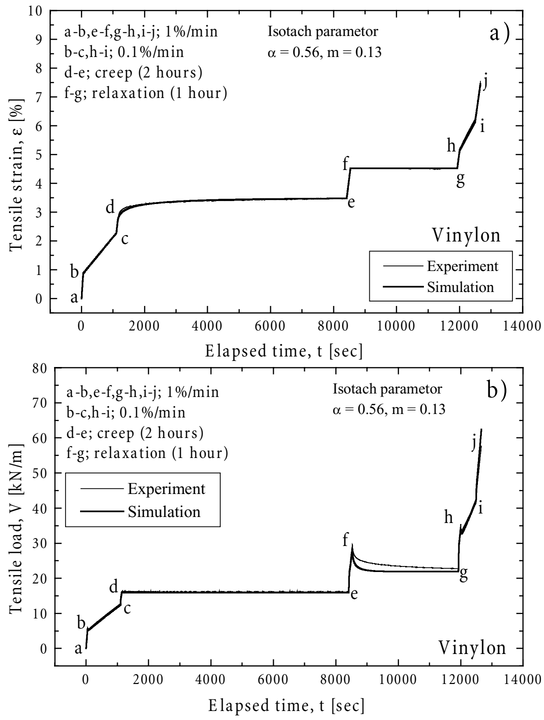


Figure 10. Measured and simulated tensile load-strain relationship with step changing in the strain rate, creep and stress relaxation; a) time history of strain, and b) time histories of load (aged geogrid 3).

2) The creep strain decreases with the decreases in the strain rate at the start of creep loading, while it decreases with the increase in the creep load level. These trends of behaviour can be simulated by a non-linear three-component model as show later.

Figure 6 shows test results for geogrid 2. The trends of behaviour are essentially the same with those presented in Figure. 3, except for that any clear stress-overshooting cannot be seen when ML is restarted after creep loading or stress relaxation and when the strain rate is increased stepwise.

3.2 *Loading rate and ageing effects (geogrid 3)*

Figure 7 shows the behaviour of geogrid 3 in ML tests at different strain rates (the other test results and the simulation are explained later). Figure 8 shows the summary of the measured tensile strengths as a function of strain rate at rupture. It may be seen that the loading rate effect on this type of geogrid is relatively small. Figure 9 shows the results from ML tests at relatively high strain rates (1 %/min and 20 %/min) that were obtained by using fresh samples (reported by the provider). It may be seen by comparing the results presented in Figures 7 and 8 and those in Figure 9 that ageing effects are very small with geogrid 3.

Figure 7 also shows the result from a ML test with step changes in the strain rate and creep and stress relaxation loading stages, which is similar to the ones presented in Figures 3 and 6. Figures 10a and b show the time histories of strain and load from. It may be seen that the trend of viscous property is essentially the same for the fresh and aged geogrids. With geogrid 3, the current load value is a function of instantaneous irreversible strain and its rate without exhibiting the stress-overshooting phenomenon, similarly to geogrid 2.

4 SIMULATION OF LOAD–STRAIN BEHAVIOUR

According to the non-linear three-component model (Di Benedetto et al. 2002; Tatsuoka et al. 2002), the tensile load per unit width of a given geogrid is decomposed as follows:

$$V = V^f(\varepsilon^{ir}) + V^v\left(\varepsilon^{ir}, \dot{\varepsilon}^{ir}, h_s\right) \qquad (1)$$

where $V^f(\varepsilon^{ir})$ is the inviscid load component that is a unique function of the instantaneous irreversible strain ε^{ir} for the ML case. The V^f - ε^{ir} relationship (called the reference relationship) was determined to fit to the general feature of the entire load-strain relationship for the respective geogrid. $V^v\left(\varepsilon^{ir}, \dot{\varepsilon}^{ir}, h_s\right)$ is the viscous load component that is a function of ε^{ir}, its rate $\dot{\varepsilon}^{ir}$ and the stress history parameter h_s, given as:

$$V^v(\varepsilon^{ir}, \dot{\varepsilon}^{ir}, h_s) = \lambda^v \cdot V^v_{iso}(\varepsilon^{ir}, \dot{\varepsilon}^{ir}) + (1-\lambda^v) \cdot V^v_{TESRA}(\varepsilon^{ir}, \dot{\varepsilon}^{ir}, h_s) \qquad (2)$$

where λ^v is the parameter to define the viscous property; $V^v_{iso}(\varepsilon^{ir}, \dot{\varepsilon}^{ir})$ is the isotach viscosity component, which is a unique function of the instantaneous values of ε^{ir} and $\dot{\varepsilon}^{ir}$. The test results presented in Figure 4 suggests that V^v_{iso} is proportional to the instantaneous inviscid stress V^f and given as:

$$V^v_{iso}(\varepsilon^{ir}, \dot{\varepsilon}^{ir}) = V^f(\varepsilon^{ir}) \cdot g_v(\dot{\varepsilon}^{ir}) \qquad (3a)$$

$$g_v(\dot{\varepsilon}^{ir}) = \alpha \cdot [1 - \exp\{1 - (\frac{\dot{\varepsilon}^{ir}}{\dot{\varepsilon}^{ir}_r} + 1)^m\}] \quad (\geq 0) \qquad (3b)$$

where $g_v(\dot{\varepsilon}^{ir})$ is the viscosity function; and α, m and $\dot{\varepsilon}^{ir}_r$ are the positive material constants, which were determined based on the test results presented in Figure 4 (Di Benedetto et al. 2002). $V^v_{TESRA}(\varepsilon^{ir}, \dot{\varepsilon}^{ir}, h_s)$ is the TESRA (temporary effects of strain rate and strain acceleration) viscosity component, given as:

$$V^v_{TESRA} = \int_{\tau=\varepsilon^{ir}_1}^{\varepsilon^{ir}} \left[d(V^v_{iso})\right]_{(\tau)} \cdot \{r(\varepsilon^{ir})\}^{\left(\varepsilon^{ir}-\tau\right)} \qquad (4)$$

where τ is the irreversible strain when the viscous stress increment $d(V^v_{iso})$ takes place; $\{r(\varepsilon^{ir})\}^{\left(\varepsilon^{ir}-\tau\right)}$ is the decay function for $d(V^v_{iso})$, decreasing from the initial value with the irreversible strain difference $\varepsilon^{ir} - \tau$; and $r(\varepsilon^{ir})$ is the parameter that decreases with ε^{ir} (Hirakawa et al. 2002)

With geogrids 2 and 3, the tensile load is basically a function of the instantaneous irreversible strain and its rate (the so-called isotach viscosity property), so $\lambda^v = 1.0$ for Eq. 2. Due to the features of the isotach viscosity, the load-strain relationships in ML tests at constant but different strain rates are separated from each other while the separation becomes larger with increase in the strain. On the other hand, both isotach and TESRA viscosities are mixed with geogrid 1. When the strain rate is changed stepwise, due to the features of the TESRA viscosity, the viscous effect becomes noticeable and subsequently decays as ML at a constant strain rate continues (Figure 3). $\lambda^v = 0.8$ was selected for geogrid 1.

The results of simulation were presented in Figures 5, 6 and 10. It may be seen that the proposed model can simulate rather accurately the viscous behaviour observed for a wide variety of stress histories for both fresh and aged geogrids. Similar results of simulation are also reported in Hirakawa et al. (2002) and Kongkitkul et al. (2002).

5 CONCLUSIONS

The following conclusions could be derived:

1) The tensile load-strain relation of the tested geogrids was a function of instantaneous irreversible strain, its rate and strain history, not of elapsed time since the start of loading.
2) With one geogrid, aged samples showed essentially the same strength and deformation properties as the fresh ones.
3) A non-linear three-component model is proposed, which could simulate very well the viscous property of the tested fresh and aged geogrids subjected to wide loading histories.

The design shear strength of soils and rocks is usually defined for a specified strain rate at failure as long as creep failure is not likely. It is considered that the shear strength does not decrease because of creep deformation, unless the deteriorating effects, such as those by weathering, take place during creep loading. That is, creep deformation is a viscous response of the material, not as a result of ageing effect. The test results presented in this paper show that the above is also the case with polymer geogrids.

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