Technical Paper by V. N. Kaliakin, M. Dechasakulsom and D. Leshchinsky

Investigation of the Isochrone Concept for Predicting Relaxation of Geogrids

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ABSTRACT: Due to the perceived complexity of relaxation tests, the relaxation response of geosynthetics has, in the past, been predicted from isochronous curves generated from creep tests. However, the validity of such an approach has not been extensively investigated. Using experimental data from in-isolation creep and relaxation tests performed on eleven different geogrids, the validity and limitations of using creep isochronous curves to predict relaxation response of geogrids has been investigated. Acceptable agreement between predicted and experimental relaxation response was rather limited, being observed for specimens tested at low initial load levels and for materials exhibiting relatively large creep strains. With minor exceptions, the experimentally measured force relaxation was under predicted by using the isochrone approach. Nonetheless, it appears that for the geogrids tested, overall accurate relaxation response cannot be predicted from isochronous curves constructed using creep data.

KEYWORDS: Geogrid, Stress relaxation, Creep, Polyethylene, Polyester, Polypropylene, Isochronous curves.

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1. INTRODUCTION

The time dependent behavior of geosynthetics is typically characterized by creep and stress relaxation response. Yet, as evident from a review of the pertinent literature (Koerner et al., 1993), such behavior has primarily been studied by means of the results of creep tests. The relative lack of relaxation studies has primarily been attributed to two factors (Leshchinsky et al. 1997). First, current simplified design procedures are based on the simple interpretation of creep test data, and thus do not require stress relaxation results. Second is the perceived complexity of relaxation tests relative to creep tests. In the latter the tensile load is maintained constant and the resulting strains are measured with time. In relaxation tests, the strain developed immediately following load application is maintained constant via a reduction of the tensile load with time; such a test inevitably requires relatively sophisticated apparatus with feedback control.

In order to avoid the complexities associated with relaxation tests, researchers have sought to indirectly generate relaxation data through the use of isochronous creep curves or isochrones. Isochrones are plots of (constant) load or stress versus strain recorded at various times during a creep test (Figure 1a). The curve associated with $t = 0$ represents curve of instantaneous response. Since the applied load remains constant in a creep test, the construction of an isochrone for a given time realistically requires data from creep tests at three or more load levels. Having constructed a series of isochrones, the conjecture is that the load-strain-time relation described by these curves likewise applies for relaxation tests. Consequently, for a given value of strain, the resulting reduction in load with time is obtained directly from the isochrones (Figure 1b).

For many years, isochronous creep curves have been used to represent the time dependent behavior of metals {Rabotnov, 1969). Their use to facilitate the representation of time dependent response of geogrids was advocated by McGown et al. (1984, 1985), and subsequently used by several researchers (e.g., Andrawes et al. 1986; Kabir, 1988; Greenwood 1990; Duval 1993; Rimoldi and Montanelli 1993; Moraci and Montanelli 1996; Müller-Rochholz et al. 1998). As applied to geosynthetics, the isochrone concept is, strictly speaking, applicable to the linear viscoelastic range of the response; i.e., for relatively small strains.

Also introduced by McGown et al. (1984, 1985) was the notion of the "isochronous stiffness" (I_{SC}) of the geosynthetic, which is equal to the instantaneous secant slope of the isochrone at various levels of strain. Although values of I_{SC} do not correspond with those measured directly from load-strain curves, plots of I_{SC} versus time for different strains have subsequently been used by several researchers to quantify its reduction with time (Andrawes et al. 1986; Kabir, 1988) and with temperature (Bush 1990). A second measure of stiffness commonly used in quantifying the response of plastics, the so-called "tensile creep modulus", has also been defined from isochronous curves (Rimoldi and Montanelli 1993; Moraci and Montanelli 1996). In this case, the modulus is equal to the instantaneous secant slope of the isochrone for a given load level and temperature.

The use of isochrones by design engineers for selecting the appropriate design load and elongation for the given life of a structure has also been advocated (Rimoldi and Montanelli 1993).

The only attempt to validate the basic assumption that creep and relaxation response can be related through isochronous curves appears to be the work presented by Greenwood (1990). In this work the creep and, to a lesser degree, relaxation of polypropylene (PP) and polyester (PET) geotextiles and a polyethylene (PE) geogrid was investigated. Having constructed isochrones from the creep test data, Greenwood (1990) compared the relaxation response predicted from the isochrones with that measured experimentally. He concluded that the agreement between predicted and measured results was good at strains below 5 percent; i.e., at levels typically expected in design. This conclusion is consistent with the intended range of applicability of the isochrone concept as applied to geosynthetics; i.e., at small strains.

In light of the fact that no other effort appears to have been made to validate the basic assumption that creep and relaxation response of geosynthetics can be related via the isochrone concept, it follows that further study of the issue is warranted. The objective of this paper is thus to gain insight into the validity and limitations of the isochrone concept as it applies to the time dependent response of geogrids.

2 BACKGROUND

Requisite to an investigation of isochronous curves is the availability of high-quality experimental results of both creep and relaxation tests for a particular set of materials. The present investigation is limited to several geogrids typically used for reinforcing slopes and walls. It uses experimental results generated by Dechasakulsom (1997) and described by Leshchinsky et al. (1997). To this are added the results of subsequent tests performed by Heffernan (1998) that employed the same experimental apparatus and serve to broaden the database. In particular, Heffernan (1998) performed creep and relaxation tests on the same materials tested by Dechasakulsom (1997), but at a lower initial stress level. In addition, creep and relaxation tests were performed on polypropylene geogrids, a material not tested by Dechasakulsom (1997).

Since further details regarding the experimental apparatus and the testing procedure have been given in Leshchinsky et al. (1997), they are not repeated here.

2.1 Description of Geogrids Tested

Creep and stress relaxation test results for eleven different geogrids, from three manufacturers, constitute the database for the present investigation. All eleven geogrids were tested in-isolation. The physical properties of the geogrids are listed in Table 1. Also listed in Table 1 is the ultimate short-term strength of each of the geogrids, as determined according to the wide-width tensile strength test ASTM D 4595. To ensure consistent results, at least three ultimate strength tests were conducted for each type of geogrid. The test results were compared with strength values reported in the manufacturer’s literature; the agreement was generally within less than 5%.

For the creep and relaxation tests, four load levels were typically applied to each type of geogrid, namely: 30, 40, 60 and 80 percent of the ultimate tensile load. For the creep tests, these loads were maintained constant. For the relaxation tests, these represent the initial loads (the initial strains imposed in the relaxation tests were thus equal to those measured at the initiation of the creep tests). However, for Geogrids C1, C2, C3, D1 and D2, the 80 percent value required a relaxation rate in excess of the capacity of the testing system. Consequently, these specimens were tested only for relaxation at initial loads of 30, 40 and 60 percent of their ultimate strength. In addition, creep tests on Geogrids D1 and D2 were not performed at 80 percent of ultimate.

To ensure repeatability of the test results, more than one test was performed on a given geogrid at a given load level; the degree of repeatability attained is shown in Leshchinsky et al.

(1997). For practical reasons (e.g., time constraints and the total number of tests performed) the duration of each creep and relaxation test did not exceed 30 days.

It is important to note that all of the tests were conducted at or above the currently allowable load values for design. However, current design values are selected so as to produce creep rupture at the end of the life of the structure (typically 100 years); to observe the phenomenon of relaxation or creep within the present test duration of 30 days, higher loads is thus necessary. Furthermore, since a major objective of this experimental study was to determine whether the current design reduction factors for creep can be further lowered if one accounts for stress relaxation, it is in fact necessary to conduct tests at loads exceeding current recommended values. It is important to note that the subject of reduction factors is beyond the scope of the present paper and is thus not discussed further herein.

2.2 Test Results

The creep and stress relaxation test results for the PET Geogrids A1, A2 and A3 are shown in Figures 2, 3 and 4, respectively. For the creep tests performed at approximately 80 percent of the ultimate strength, geogrids A1 and A2 exhibited brief periods of tertiary creep that culminated in rupture of the specimens. Herein, tertiary creep is defined as a portion of the response in which the creep strain rate increases, possibly leading to failure (rupture) of the material. Because of the scale used in Figures 2 and 3, the periods of tertiary creep are not readily evident. When subjected to loads of 60 percent of ultimate, the three geogrids exhibited varied levels of creep strain, and did not enter the tertiary regime. At loads of 30 and 40 percent of ultimate, the strain rate was somewhat lower than that of the 60 percent of ultimate load specimens. For the stress relaxation tests conducted at loads of 80, 60, 40 and 30 percent of ultimate, the tensile force decreased by an average of 31, 32, 32 and 35 percent, respectively. The largest variation in measured values was noted for the 60 percent of ultimate load specimens where, in one case, the initial force was reduced by approximately 50 percent. After one month, the rate of relaxation in the A1, A2 and A3 geogrids was negligible.

The creep and stress relaxation test results for the PET Geogrids B1, B2 and B3 are shown in Figures 5, 6 and 7, respectively. When creep loads of 80 percent of ultimate load were applied, the Geogrids B1, B2 and B3 all ruptured (again, due to the scale used in Figures 5 to 7, the tertiary phase is not readily evident). At loads of 60, 40 and 30 percent of ultimate, the specimens all exhibited a relatively low strain rate and total creep strain. For the stress relaxation tests conducted at loads of 80, 60, 40 and 30 percent of ultimate, the tensile force decreased by an average of 23, 29, 30 and 35 percent, respectively. The variation in relaxation values for the B1, B2 and B3 geogrids was less than for the A1, A2 and A3 geogrids.

The creep and stress relaxation test results for the HDPE Geogrids C1, C2 and C3 are shown in Figures 8, 9 and 10, respectively. In the creep tests, all of the specimens subjected to loads of 60 and 80 percent of the ultimate exhibited periods of tertiary creep followed by rupture. For the case of specimens at 80 percent of ultimate, this rupture was particularly rapid, occurring 100 to 200 minutes after initiation of creep. Under loads of 30 and 40 percent of ultimate, the C1, C2 and C3 geogrids appeared to have reached a plateau after a few days of loading, thus exhibiting a very low creep strain rate. During the stress relaxation tests, the C1, C2 and C3 geogrids exhibited rather substantial decreases in tensile force. In particular, at loads of 60, 40 and 30 percent of the ultimate, the force decreased by an average of 53, 58 and 64 percent respectively.

The creep and stress relaxation test results for the PP Geogrids D1 and D2 are shown in Figures 11 and 12, respectively. For the D1 geogrids, loading was applied in the weak direction; for the D2 geogrids, loading was applied in the cross-machine direction. With the exception of the relaxation tests performed on the D1 geogrid, all tests used single rib specimens. In the case of relaxation testing of the D1 geogrid, limitations in the testing apparatus simply precluded the use of a single rib. Since rupture was not observed, all creep tests ran for the entire duration of 30 days. For the stress relaxation tests conducted at loads of 60, 40 and 30 percent of ultimate, the tensile force decreased by an average of 74, 68 and 66 percent, respectively.

To summarize the creep performance of the geogrids tested, note that, with the exception of the PET Geogrid A3 (Figure 4), all of the specimens ruptured when loaded to 80 percent of the ultimate strength. As shown in Figures 8 to 10, rupture of the HDPE geogrids was preceded by the onset of pronounced tertiary creep followed by rupture. Although PP Geogrids D1 and D2 did not rupture, they likewise exhibited a rather pronounced tertiary response (Figure 11 and 12). At a given load level, the HDPE and PP geogrids exhibited higher creep strains and total strains as compared to the PET geogrids; however, the initial strains in the PET geogrids were higher than in the HDPE geogrids. The above observations are in agreement with the findings of Greenwood and Myles (1986) who noted that, upon initial loading, PET yarns exhibit relatively high elongation; the subsequent (creep) strains are, however, quite low.

As noted previously in Leshchinsky et al. (1997), from a micromechanical point of view it would be expected that geogrids exhibiting large creep strains should also exhibit large amounts of force reduction under stress relaxation conditions. This is explained by the fact that in both cases the long-chain molecules comprising the polymeric material must rearrange themselves to eventually achieve equilibrium with the applied load or deformation. For the geogrids tested, the above hypothesis was indeed supported. The PET geogrids exhibited relatively low creep strains and force relaxation. The HDPE and PP geogrids, on the other hand, exhibited rather large creep strains and force relaxation.

3 ISOCHRONES GENERATED FROM CREEP DATA

As previous noted, isochrones are plots of stress versus strain recorded at various times during a creep test (Figure 1a). The isochrones associated with the present investigation were constructed for six times, namely 0.1, 1, 60, 600, 6000 and 43200 minutes after initiation of the creep tests. The extrapolated portions of all isochrones are represented with dashed lines. Such extrapolation is inherently necessary because creep tests cannot be performed at every load level.

The isochrones associated with the PET Geogrids A1, A2, A3, B1, B2 and B3 were rather similar in shape. Consequently, only the isochrones associated with geogrid B1, which are representative of all the PET geogrid isochrones, are shown (Figure 13). These curves are seen to be in rather close proximity to one another. This is explained by the previously noted observation that PET geogrids exhibit relatively little strain during creep. In addition, even for specimens exhibiting creep rupture, the tertiary phase of response had a relatively short duration. Consequently, the isochrones associated with later elapsed times will not be shifted too far from the other isochrones. Similar characteristics for isochrones associated with PET specimens can be seen in Greenwood (1990).

The isochrones associated with the Geogrid C2, which are representative of all the HDPE geogrid isochrones, are shown in Figure 14. The shape of these curves differs from that of the PET geogrids. Unlike the PET isochrones, the HDPE isochrones are initially nearly straight. In addition, the HDPE isochrones are not in such close proximity as those for the PET geogrids. This is explained by the fact that, unlike the PET geogrids, the HDPE grids exhibit rather large creep strains. In addition, the HDPE geogrids exhibit distinct primary, secondary and tertiary phases of creep response; the tertiary phase was essentially absent from the response of the PET grids. In the case of the HDPE specimens tested at 30 and 40 percent of ultimate strength, secondary creep is dominant. Consequently, the associated isochrones are rather closely spaced, much like the PET isochrones shown in Figure 13. However, at 60 and 80 percent of ultimate, the HDPE specimens exhibit not only secondary, but also prominent tertiary creep response. The latter particularly causes the isochrones to be more spread out as compared to the PET isochrones. Similar characteristics for isochrones associated with PE specimens can be seen in Greenwood (1990).

Finally, the isochrones associated with PP geogrid D2, which are representative of all the PP Geogrid isochrones, are shown in Figure 15. They are relatively similar in shape to the curves associated with the HDPE geogrids. This is explained by the fact that, like the HDPE geogrids, the PP grids exhibit rather large strains during creep. Similar characteristics for isochrones associated with PP specimens can be seen in Greenwood (1990).

4 ASSESSMENT OF RELAXATION RESULTS PREDICTED FROM ISOCHRONES

Having constructed the isochrones for each of the eleven geogrids tested, it is now possible to predict the stress relaxation response from these curves. For a given value of strain, a vertical line intersecting the isochrone for a given time yields the corresponding value of force. The relaxation response so predicted will then be compared to that measured experimentally.

The predicted stress relaxation response obtained from creep isochrones is represented by broken lines in Figures 16 to 26. In the same figures, solid lines represent the experimentally measured relaxation response.

The predicted and measured relaxation response of the PET Geogrids A1, A2 and A3 is shown in Figures 16 to 18, respectively. From these figures, it is evident that the agreement between predicted and measured response becomes progressively worse as the initial load level is increased. In particular, as the initial load level is increased, the experimentally measured relaxation is increasingly under predicted. This phenomenon is explained by the previously noted close proximity of the isochrones associated with the PET Geogrids (Figure 13). Consequently, for a given value of strain, the associated reduction in force will not be large.

The predicted and measured relaxation response of the PET Geogrids B1, B2 and B3 is shown in Figures 19 to 21, respectively. The agreement between predicted and measured relaxation is better than for the A1, A2 and A3 geogrids. Nonetheless, similar to the results for these geogrids, the agreement between predicted and measured response becomes progressively worse as the load level is increased. This is not surprising, as the A1, A2 and A3 and B1, B2 and B3 geogrids are made of polyester, all exhibit relatively little strain during creep, and all posses isochrones that are in rather close proximity to one another. With the exception of the B1 geogrid tested at 40 percent of ultimate (Figure 19), the predicted relaxation is less than that measured experimentally.

The predicted and measured relaxation response of the HDPE Geogrids C1, C2 and C3 is shown in Figures 22 to 24, respectively. Overall, the agreement between predicted and measured relaxation for the HDPE geogrids is better than for the PET geogrids. Nonetheless, as the initial load level is increased, the agreement between predicted and measured relaxation worsens. With the exception of the C1 geogrid tested at 60 percent of ultimate (Figure 22), the experimentally measured relaxation is again under predicted.

The predicted and measured relaxation response of the PP Geogrids D1 and D2 is shown in Figures 25 and 26, respectively. Similar to the HDPE specimens, the overall agreement between predicted and measured relaxation for the PP geogrids is somewhat better than for the PET geogrids. Compared to the results for the HDPE geogrids, the agreement between predicted and measured relaxation for the PP geogrids is somewhat better. With the exception of the D2 geogrid tested at 30 percent of ultimate (Figure 26), the experimentally measured relaxation is again under predicted.

5 CONCLUSIONS

The validity and limitations of using creep isochronous curves to predict relaxation response of geogrids has been investigated. The experimental data against which such predictions were compared was obtained from in-isolation creep and relaxation tests performed on eleven different geogrids from three manufacturers. For the geogrids tested, it appears that *overall* accurate relaxation response cannot be predicted from isochronous curves constructed using creep data. Acceptable agreement (+/- 20%) between predicted and experimental relaxation response was rather limited, being observed for specimens tested at low initial load levels and for materials such as HDPE and PP that exhibit relatively large creep strains. With minor exceptions, the experimentally measured force relaxation was under predicted by using the isochrone approach. Consequently, in the sense that the predicted level of force in the geogrids is higher than the actual value, such underpredictions are conservative.

The acceptable agreement at low load levels is consistent with the aforementioned conclusions of Greenwood (1990), and with the observation that the isochrone concept is, strictly speaking, applicable only in the linear viscoelastic range of geosynthetic response; i.e., for relatively small strains. Clearly, for higher initial load levels the response ceases to be viscoelastic (indeed, it is viscoplastic). Not surprisingly, the agreement between predicted and experimental results becomes progressively worse as the load level is increased.

In order to extend it to the non-linear regime, the isochrone concept for predicting relaxation response would have to be modified. Such modifications would likely be complicated and, as evident from the present results, would have to be a function of both load level and polymer type.

Finally, although the present results imply a lack of uniqueness of the load-strain-time relation embodied by isochronous curves, it is important to note that such curves are nonetheless useful in understanding the time dependent response of geosynthetics. In particular, isochronous curves are a good way in which to visualize the decrease in stiffness of the material with time under load. The proper analytical description of such material “softening” could facilitate the development of constitutive models that are able to realistically account for both creep and relaxation of geosynthetics.

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NOTATION

Basic SI units are given in parentheses.

I_{SC} = Isochronous stiffness (kN/m)