COMPARISON OF EXISTING EPS-BLOCK GEOFOAM CREEP MODELS WITH FIELD MEASUREMENTS

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ABSTRACT

An estimate of the long-term vertical creep of EPS (expanded polystyrene)-block geofoam is required to predict the total vertical deformation that may occur in embankments and bridge approaches that utilize EPS-block geofoam as lightweight fill. This paper compares long-term vertical deformations from case histories with creep models that have been suggested for EPS blocks to investigate the accuracy of existing creep models. These comparisons show that current creep models do not provide reliable estimates of creep effects and are used to present other techniques for estimating the long-term creep strains of EPS-block geofoam in lightweight fill applications. Recommendations for future study of time-dependent stress-strain behavior of EPS block are also presented.

KEYWORDS: Creep, Deformation, Expanded Polystyrene, Lightweight Fill, Settlement, Strain

INTRODUCTON

Two time-dependent stress-strain (creep) models that have been suggested for predicting the vertical strain or deformation of EPS (expanded polystyrene) blocks that occurs under an applied stress include the general power-law equation and the Findley equation. An initial overview of the theory and application of both equations is presented. The total vertical strain predicted by these two equations consist of two components as shown below.

$$e = e_o + e_c \tag{1}$$

where ε = total strain after time t after application of the stress,
ε_o = immediate strain upon stress application, and
ε_c = time-dependent strain (creep) after time t after application of the stress.

Based on the assumption that ε_o is linear-elastic and based on empirical relationships established through laboratory creep-test data, the Laboratoire Ponts et Chaussess (LCPC) derived the following General Power-Law equation for the total strain of EPS blocks (Horvath 1998; Magnan and Serratrice 1989):

$$e = \left(\frac{s}{\mathrm{E_{ti}}}\right) + 0.00209\left(\frac{s}{s_{\mathrm{p}}}\right)^{2.47}\left(t^{\left\{-0.9\log_{10}\left[1-\left(\frac{s}{s_{\mathrm{p}}}\right)\right]\right\}}\right) \tag{2}$$

where ε = total strain at some time period t after stress application (in decimal form, not as a percent),
σ = applied stress in kPa,
σ_p = plastic stress of EPS in kPa, which is defined as the stress corresponding to the onset of yielding (Horvath 1995),
E_{ti} = initial tangent modulus in kPa, which is defined as the average slope of the compressive stress-strain relationship at a strain between 0 and 1%, and
t = time in hours after stress application.

The LCPC established the following two empirical relationships based on laboratory testing to facilitate use of Equation (2):

$$\sigma_p = 6.41\rho - 35.2 \tag{3}$$

$$E_{ti} = 479\rho - 2875 \quad (4)$$

where σ_p = plastic stress in kPa,
E_{ti} = initial tangent modulus in kPa, and
ρ = EPS-block geofoam density in kg/m^3.

However, during this study it was found that Equation (4) yields values of initial tangent modulus that are higher than typically reported in the literature. The consequence of using Equation (4) to estimate the initial tangent modulus is discussed subsequently. The following relationship, based on averaging other published relationships by Horvath (1995) can also be used to estimate E_{ti} :

$$E_{ti} = 450\,\rho - 3000. \quad (5)$$

The Findley equation (Findley 1960; Findley and Khosla 1956) is also used to predict the total time-dependent vertical strain of geofoam. The Findley equation has been modified by (Horvath 1998) based on creep test results that extend for nearly 19000 hours (2.2 years) as shown below:

$$\varepsilon = 1.1\sinh\left(\frac{\sigma}{54.2}\right) + 0.0305\sinh\left(\frac{\sigma}{33.0}\right)(t)^{0.20} \quad (6)$$

where ε = total strain at some time t after a stress application (in percent),
σ = applied stress in kPa, and
t = time in hours after stress application.

Equation (6) is based on three tests performed on 50 mm cube-shaped EPS specimens with a density of 20 kg/m^3 at stresses of 30, 40, and 50 kPa. Therefore, the modified Findley equation, i.e., Equation (6), is applicable to EPS block with a density of 20 kg/m^3 subjected to stresses between 30 and 50 kPa. The applicability of Equation (6) at stress levels not between 30 and 50 kPa is investigated herein to determine the potential benefit of refining Equation (6) so that it can be used for other stress levels.

Both the general power-law and modified Findley equations will be compared with laboratory measured results on full-size EPS blocks to assess their accuracy.

LABORATORY CREEP TESTS

A review of published creep test results (Duskov 1998; Horvath 1998; Magnan and Serratrice 1989; Negussey and Jahanandish 1993; Public Works Research Institute 1992; Sun 1997; van Dorp 1988; Wu 1996; Zou and Leo 1998) for this study revealed a lack of a standard test method for geofoam. Therefore, a qualitative, not quantitative, comparison is made between published laboratory creep test results and the calculated strain values derived from the general power-law and modified Findley equations to assess the accuracy of these equations.

It is recommended that a standard test method be developed for performing creep tests on EPS-block geofoam so creep models can be developed and reliably evaluated. The primary variables that need to be considered for creep tests are: test specimen shape, test specimen dimensions, test specimen age at the start of testing, confinement of the test specimen, test duration, applied stress level, and ambient temperature in the laboratory where the test is performed (Stark et al. 2000). Specimen shapes that have been reported in the literature include a cube, right-circular cylindrical, and disc. Cube-shaped specimens are typically 50 mm cubes. Right-circular cylindrical specimens with heights of 38, 50, 200, and 300 mm and diameters of 76, 50, 100, and 150 mm, respectively, have been utilized. Disc-shaped specimens typically replicate the dimensions of oedometer (one-dimensional consolidation) test specimens of soil (i.e. 25 mm thick and 65 mm ± in diameter). Figure 1 shows creep test results from three different specimen sizes with a density of 20 kg/m^3 tested at stresses of 20 kPa. These results as well as comparisons made from specimens tested at stresses of 30 and 50 kPa indicate that disc shaped specimens may yield higher creep strains than cylindrical specimens.

Figures 1 and 2 provide a qualitative comparison between various size EPS specimens with a density of 20 kg/m^3 at stresses of 20 kPa and 70 kPa and the calculated results based on the general power-law and the modified Findley equations. The laboratory test results shown in these figures are limited to specimens with a density of 20 kg/m^3 and to stress levels of 20 kPa and 70 kPa because this is the density and stress range of EPS blocks that are used in the full-size block and full-scale model tests. Laboratory test data utilized in deriving the general power-law and modified Findley equations are not shown to provide non-bias comparisons. At the lower stress level of 20 kPa, both equations predict strains that are in agreement with the measured values from cylindrical EPS specimens. However, the modified Findley equation predicts slightly larger strains than the general power-law equation. Neither equation predicts strains near the measured values obtained on a disc-shaped specimen. A disc-shaped specimen is usually used when creep testing is performed with an oedometer, which is typically used to simulate one-dimensional compression of soils in the laboratory. At the higher stress level of 70 kPa (Figure 2), the power-law equation predicts and the modified Findley equation predicts larger and smaller total strains, respectively, than the measured values.

The general power-law equation indicates a relationship between the time-dependent behavior of EPS and the plastic stress and initial tangent modulus, see Equation (2). Therefore, it is recommended that compressive strength tests be performed on similar specimens that will be used for creep testing so values of plastic stress and initial tangent modulus can be obtained from the same test sample. It is also recommended that the elastic-limit stress be determined from compressive strength tests because, as will be discussed later, the elastic-limit stress may be a useful guide for estimating the onset of significant creep effects (Horvath 1995). The elastic-limit stress is defined as the measured compressive normal stress at a compressive normal strain of 1% (Horvath 1995). It is also recommended that axial strain data be obtained immediately upon stress application and frequently for the first hour after load application to better estimate the immediate strain, ε_o, (Horvath 1998). A good estimate of ε_o is critical to estimating the total strain because ε_o contributes more to the total strain than the creep-induced strain, ε_c.

FULL-SIZE EPS BLOCK CREEP TEST

A full-size block with a density of 20 kg/m^3 and dimensions of 1.5 m by 1 m by 0.5 m was loaded under a stress of 71 kPa for 61 days (Aabøe 1993). A stress of 27 kPa was initially applied for four days. An additional stress of 19 kPa (total stress equal to 46 kPa) was applied for seven days and an additional stress of 25 kPa (total stress equal to 71 kPa) was applied for 50 days. The stress at the bottom of the block was measured using seven pressure cells and an average pressure of 34, 55, and 79 kPa was measured in the pressure cells for days 1 through 5, 5 through 12, and 12 through 62, respectively. These average stresses are used in calculating the vertical strains using the power-law and modified Findley equations.

Figure 3 shows a comparison between the calculated and measured total strains for compressive stresses of 34, 55, and 79 kPa. At the initial stress levels of 34 and 55 kPa, both the general power-law and modified Findley equations predict total strains that are in agreement with the measured strains. At the largest stress of 79 kPa, the power-law equation significantly overestimates the measured strains and the modified Findley equation underestimates the measured strains. However, the modified Findley equation provides the best agreement with the measured values especially as the time, t, increases.

FULL-SCALE MODEL CREEP TEST

A full-scale model creep test was performed at the Norwegian Road Research Laboratory (Aabøe 1993; Aabøe 2000) to investigate the time-dependent performance of EPS-block geofoam. The test fill had a height of 2 m and measured 4 m by 4m in plan at the bottom of the fill decreasing in area with height approximately at a ratio of 2 (horizontal) to 1 (vertical) to about 2 m by 2 m at the top of the fill. A load of 105 kN was applied through a 2 m by 1 m plate at the top of the fill resulting in an applied stress of 52.5 kPa. The fill consisted of four layers of full-size EPS blocks with dimensions 1.5 m by 1 m by 0.5 m and densities of 20 kg/m^3.

The stress at the bottom of the fill was measured using four pressure cells. An average pressure of 7.8 kPa was measured in the pressure cells during the 1270 day test. Based on this average pressure measured at the bottom of the test fill and the stress of 52.5 kPa applied at the top of the fill, the stress distribution within the EPS fill was approximately 1 (horizontal) to 1.8 (vertical). This is in agreement with a stress distribution of 1 (horizontal) to 2 (vertical), which is typically assumed in design calculations incorporating EPS-block geofoam structures. The measured stress distribution is slightly wider but still in agreement with 1 (horizontal) to 2 (vertical). Thus, the measured stress with depth is slightly less than the typically assumed stress distribution, which results in a slightly conservative design. Therefore, it is recommended that the assumed 1 (horizontal) to 2 (vertical) stress distribution be utilized in design calculations for EPS-block geofoam embankments.

Figure 4 shows a comparison of the total strain measured in the EPS blocks of the full-scale test fill and the calculated total strains based on the power-law and modified Findley equations. In calculating the total strains, the fill was divided into the same number of horizontal layers as EPS block layers used, four. The total strain of each layer was determined based on the average stress calculated at the middle of each block using the measured 1 (horizontal) to 1.8 (vertical) stress distribution. Thus, the stress used for each layer from top to bottom was 36.2, 20.4, 13.1, and 9.1 kPa. As indicated in Figure 4, both the general power-law and modified Findley equations underestimate the strains measured in the full-scale test fill. The power-law predictions are lower than the modified Findley predictions and thus the Findley equation provides the best agreement.

FULL-SCALE FIELD MONITORING

A field monitoring program was implemented as part of the Løkkeberg bridge project built in Norway in 1989 (Aabøe 1993; Aabøe 2000). EPS blocks were used to construct a bridge approach embankment and to support the bridge foundation. Pressure cells were installed at various locations within the embankment and settlement monitoring rods were installed at four locations to measure the total settlement of the embankment and the vertical strains at various depths in the embankment. The height of the embankment is 4.5 m. EPS blocks with an unconfined compressive strength of 240, 180, and 100 kPa, were used in the top 1.2 m, middle, and bottom 2.1 m of the embankment, respectively. A 10 cm concrete slab was placed between the 180 and 100 kPa blocks to further distribute the stresses within the 100 kPa blocks.

Figure 5 shows the total vertical strain measured in the lowest block layer. The density of the bottom row of EPS blocks is 20 kg/m^3 and the original thickness of the EPS blocks is 0.6 m. Three pressure cells were installed below the first row of blocks. An average pressure of 67 kPa was recorded in the three pressure cells during the period that the vertical strain was being obtained from the settlement rods. As shown in Figure 5, the power-law and modified Findley equations significantly overestimate and underestimate the measured total strains, respectively. However, the total strains predicted by the modified Findley equation are again in better agreement with the measured values than the power-law equation.

SUMMARY OF COMPARISON OF MEASURED AND CALCULATED VALUES OF TOTAL STRAIN

For stresses between 10 and 55 kPa, both the power-law and modified Findley equations yield total strain values similar to or less than the measured values obtained on the full-size block and full-scale creep test fills. In general, the power-law equation predicts total strains smaller than the modified Findley equation for compressive stresses between 10 and 55 kPa. A similar observation was made by Horvath (Horvath 1998). Horvath (Horvath 1998) suggests that the power-law equation predicts smaller total strains than laboratory measured values, especially for short time durations, because the test specimens used by the LCPC to derive the power-law equation yield larger values of initial tangent modulus than for other test specimens reported in the literature. This is apparent by comparing Equations (4) and (5). Horvath (Horvath 1998) suggests that the values of E_{ti} obtained from the LCPC relationship in Equation (4) are approximately 40 % larger than the values from Equation (5), which is based on averaging other published relationships. In summary, the modified Findley equation is recommended to predict total vertical strains for compressive stresses between 10 and 55 kPa. Further refinement of the modified Findley equation for stresses outside the 30 to 50 kPa stress range that was used in developing the equation may result in better predictions.

At larger compressive stresses of 67, 70, and 79 kPa, the total strains determined by the power-law equation and the modified Findley equation significantly overestimate and underestimate the measured full-size block and full-scale test fill values. The modified Findley equation provides better agreement than the power-law equation, especially as the elapsed time increases. Further refinement of the modified Findley equation for stresses outside 30 to 50 kPa stress range that was used in developing the equation may result in better predictions. As noted by Horvath (Horvath 1998), the power-law equation may provide unusually high strain values at large compressive stresses, especially at longer durations of applied stress, because the power-law equation was developed from creep tests of insufficient duration. This results in greater strains because the total strains decrease with increasing elapsed time as shown in Figures 1-5.

The time-dependent behavior obtained on one layer of blocks in the full-scale field test is similar to the behavior obtained during the full-size block test. After a time equal to 1440 hours (60 days), the difference in total strain measured was approximately 3.2%, with the full-size block test producing the larger total strain because the average total measured stress in the full-size block test was 79 kPa compared to 67 kPa for the full-scale field test. Therefore, it appears that creep tests based on a full-size EPS block may provide reasonable predictions of total vertical strain with time for projects utilizing EPS-block geofoam as lightweight fill. This reduces the need for constructing full-scale model test fills to develop time-dependent data. Therefore, a standard test method could be developed either using a full-size block or comparing the results from smaller specimens with the results of full-size blocks.

SUMMARY

At present general power-law and modified Findley equations do not provide a reliable estimate of the time-dependent total strains. Further research is required to either refine these expressions or develop new expressions based on other creep models. In particular, the power-law equation should be refined to include results from specimens with lower values of E_{ti} and tests of longer duration. The modified Findley equation should be refined to include test results from compressive stresses outside the 30 to 50 kPa stress range that was used to develop the relationship.

The results of the full-scale model test conducted at the Norwegian Road Research Laboratory indicates that the typically assumed 1 (horizontal) to 2 (vertical) distribution of compressive stresses through a geofoam embankment is reasonable, albeit slightly conservative because the measured stress showed a stress distribution of 1 (horizontal) to 1.8 (vertical), for design calculations. A comparison made during this study indicates that the measured total strains obtained on one layer of blocks in the full-scale field test fill is similar to the strains obtained from the full-size block test. Therefore, creep tests based on a full-size block may provide reasonable predictions of total vertical strain with time for projects utilizing EPS-block geofoam as lightweight fill. Currently, there is a lack of comparable test data on small laboratory specimens and full-size blocks. It is recommended that creep tests be performed on both full-size blocks and small specimens cut from similar full-size blocks to establish a correlation between these two specimen sizes. If a correlation is established, future creep testing can be performed on small laboratory specimens instead of full-size blocks.

Published test results are not sufficient to refine the existing creep models or to develop new models because testing procedures are not standardized and sufficient information about the testing procedures are not available. It is recommended that creep testing be standardized so the necessary information for refining creep models becomes available. Recommendations on standardizing creep testing procedures are provided herein. In addition to using traditional creep testing procedures, consideration should be given to using time-temperature superposition procedures or a combination of both conventional testing procedures and time-temperature superposition procedures (stepped isothermal methods) to measure creep behavior. These alternate methods have been used to study creep behavior of other geosynthetic materials (Sandri et al. 1999) and can accelerate acquisition of meaningful creep data. The resulting creep data could be used to develop a stress-strain-time-temperature mathematical model for EPS block. Such a model would enable better predictions of creep strains at temperatures other than the conventional laboratory ambient conditions.

The current state of practice for considering creep strains in the design of EPS block embankments and bridge approaches is to base the design on laboratory creep tests on small specimens cut from the same type of EPS block that will be used in construction or to base the design on published observations of the creep behavior of EPS, such as:

- If the applied stress produces an immediate strain of 0.5% or less, the creep strains, ε_c, will be negligible even when projected for 50 years or more. The stress level at 0.5% strain corresponds to approximately 25% of the compressive strength at a compressive normal strain of 1% or 33% of the yield stress.
- If the applied stress produces an immediate strain between 0.5% and 1%, the geofoam creep strains will be tolerable (less than 1%) in lightweight fill applications even when projected for 50 years or more. The stress level at 1% strain corresponds to approximately 50% of the compressive strength or 67% of the yield stress.
- If the applied stress produces an immediate strain greater than 1%, creep strains can rapidly increase and become excessive for lightweight fill geofoam applications. The stress level for significant creep strain corresponds to the yield stress which is approximately 75% of the compressive strength.

In summary, the compressive stress at a vertical strain of 1%, i.e., the elastic-limit stress, appears to correspond to a threshold stress level for the development of significant creep effects and the field applied stresses should not exceed the elastic-limit stress until more reliable creep models are developed (Horvath 1995). Based on these observations, it is concluded that creep strains within the EPS mass under sustained loads are expected to be within acceptable limits (0.5% to 1% strain over 50 to 100 years) if the applied stress is such that it produces an immediate strain between 0.5% and 1% (Horvath 1995; Stark et al. 2000).

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FIGURES

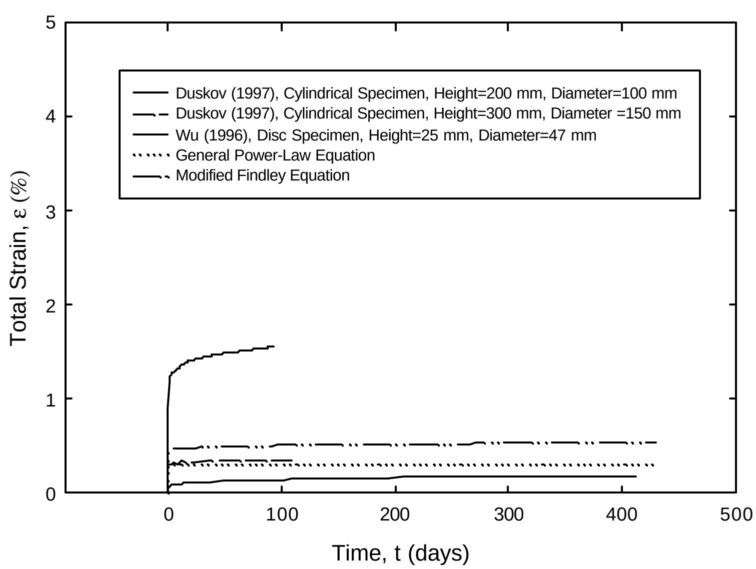

Figure 1. Comparison of Laboratory Compression Creep Test Data for an EPS Density of 20 kg/m^3 and Applied Stress of 20 kPa and Calculated Values.

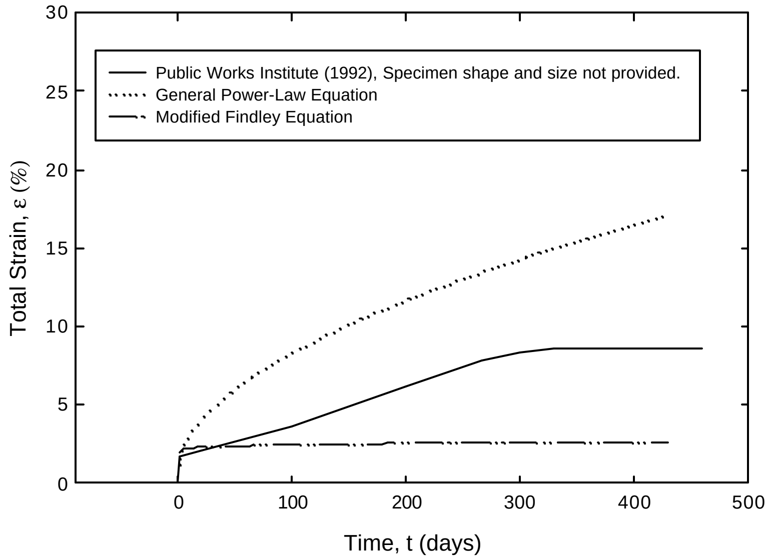

Figure 2. Comparison of Laboratory Compression Creep Test Data for an EPS Density of 20 kg/m^3 and Applied Stress of 70 kPa and Calculated Values.

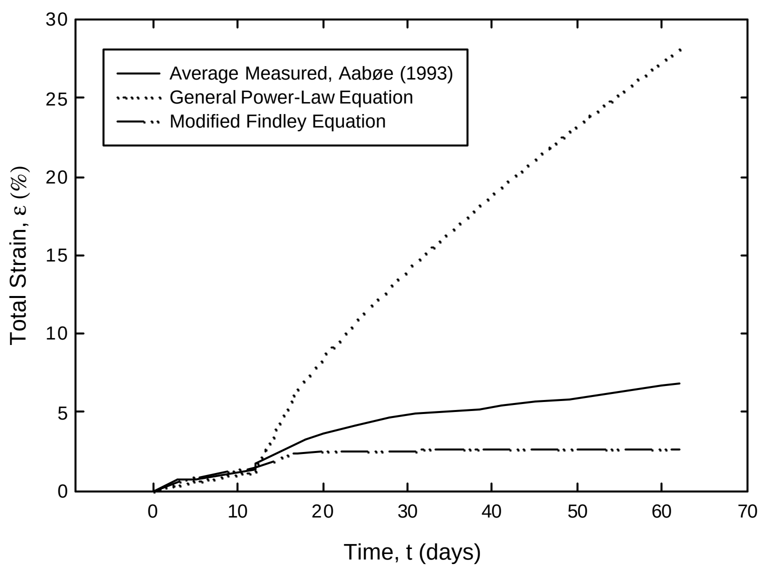

Figure 3. Comparison of Full-Size EPS Block Creep Test Data and the Creep Equations for an EPS Density of 20 kg/m^3 and an Applied Stress of 34 kPa for Days 1-5, 55 kPa for Days 5-12, and 79 kPa for Days 12-62.

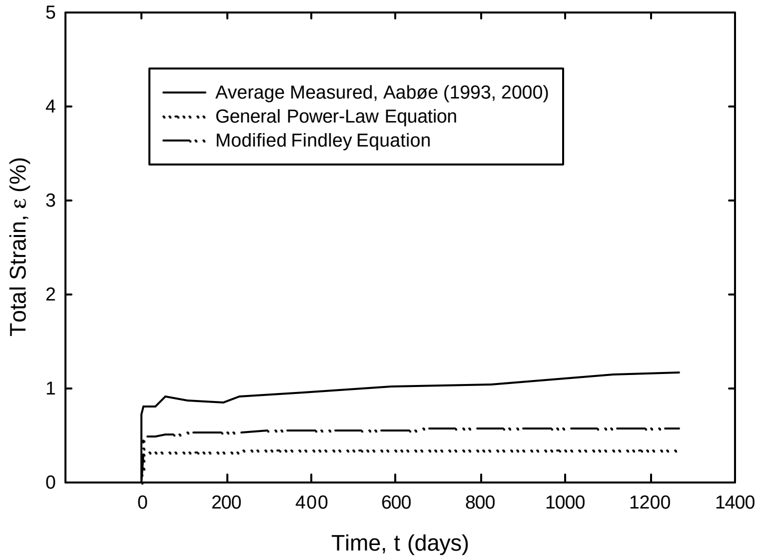

Figure 4. Comparison of Full-Scale Model Creep Test Data and the Creep Equations for an EPS Density of 20 kg/m^3.

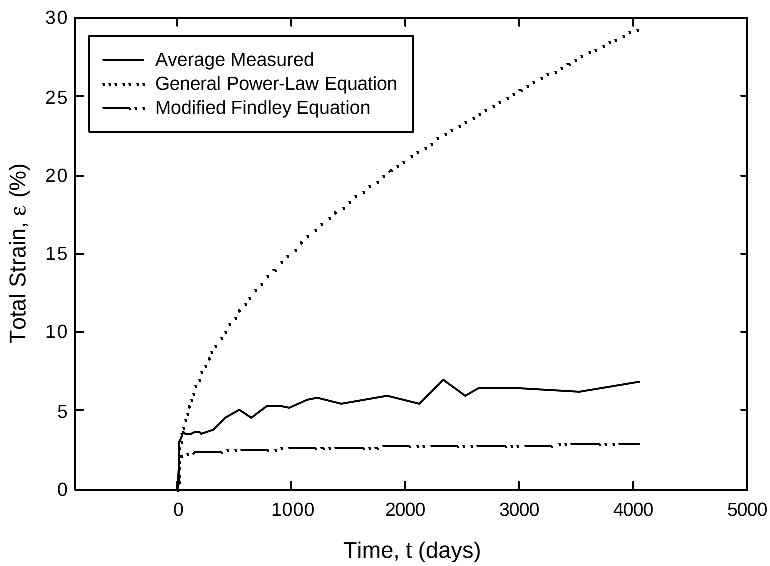

Figure 5. Comparison of Total Vertical Strain Measured in the Lowest EPS Block Layer of the Field Test Fill and the General Power-Law and Modified Findley Equations.