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Analysis of Time-Dependent Deformation of Expanded Polystyrene (EPS) Geofoam as a Flexible Pavement Subgrade Material

연성포장의 노반재료로써의 EPS 지오폼의 시간의존적 변형 분석

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ABSTRACT

The main objective of this study is to investigate the time-dependent deformation of EPS blocks under repeated loading conditions which is the one of the flexible pavement structure. The study comprised of both the experimental work and analytical modeling in order to understand the behavior of EPS blocks under repeated loading. The analytical modeling included the selection of a suitable model for describing the deformation behavior observed under repeated loading conditions, investigating the relationship among the unit weight, deformation and applied stress, analyzing the effect of repeated load on deformation. The test results were compared with the Findley's theory and model analysis with the results of this research under repeated loading conditions. Both Modified Findley's model and the proposed model can be adopted to illustrate the deformation behavior of EPS blocks under repeated loads.

요 지

본 연구의 주된 목적은 반복적인 하중조건하에서 연성포장체의노반재료로써, EPS블럭의 시간의존적 변형을 연구하는데 있다. 반복하중 조건에서의 EPS블럭의 거동을 이해하기 위해서 본 연구에서는 실험적 방법 및 수치모형을 제시하였다. 이 수치모델링을 위해서 반복하중 조건하에서 관찰된 변형거동과 단위중량, 변형 그리고 적용된 하중과의 상관관계의 조사가 행해졌다. 실험결과는 핀들레이 이론과 반복하중 조건에서의 연구결과의 모델 분석등과 비교되었고, 보완된 핀들레이 모델과 본 연구에서 제시한 모델은 반복하중에서의 EPS블럭의 변형거동을 나타내는데 이용될 수 있는 것으로 기대된다.

Keywords : EPS blocks, Time-dependent, Findley's equation, Effect of density, Repeated loading

1. Introduction

The use of expanded polystyrene (EPS) geofoam for subgrade in road construction is an alternative method to support loads induced by traffic vehicles for weak, poor, and compressible subgrade soils such as soft clay deposits and peat bogs, characterized as low bearing capacity.

Since first used in 1960s for road frost protection purposes in Norway, EPS geofoam has been utilized in many civil engineering construction applications for backfill against retaining structures (such as bridge abutments), fill for embankments on soft grounds, material for slope stabilization, and natural subgrade soils substitute (Frydenlund, 1987). There exist many conventional methods to reduce many types of pressures caused by natural soil and civil structures in-situ. But this innovative construction

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material, EPS geofoam, may potentially replace almost currently available conventional lightweight fill materials for a typical reason, i.e., lightweight material with a certain amount of strength withstanding external load to some extent.

Super-light EPS geofoam is a new construction material for multi-purposes but there are no standard testing methods by AASHTO (American Association of State Highway and Transportation Officials) within geotechnical engineering practice and there exist only few recommended guidelines in limited areas without universal standard. This is due to a comparatively short history of EPS geofoam applications in geotechnical engineering practice. Nevertheless, there has been much effort to adopt EPS geofoam's unique characteristic, that is, a super-lightweight as naturally heavy soil substitute material. Consequently, investigations of geotechnically relevant characteristics of EPS geofoam such as compressive strength, resilient modulus, and Poisson's ratio have been conducted and many applications have been made based on the experimental test result analysis.

In this study, the relationship of the stress-strain on EPS is developed as a function of applied loads so that we could suggest proper EPS density and replacement area in the field applications.

2. Material Properties of Expanded Polystyrene Foam

2.1 Design Strength

Strength of the EPS geofoam is very much a function of the manufacturing process and plastic content. Expanded Polystyrene foam can generally be divided into four basic types with each type having different strength characteristics that reflect the difference in cell structure and plastic content. The four types of EPS geofoam and their properties are illustrated in Table 1(James, 1984).

2.2 Density

The main advantage of EPS blocks is its low-density characteristics to be used for engineering applications extensively. When compared with other available lightweight materials in Table 2, EPS geofoam is from about 25 to over 100 times lighter than conventional fill materials (Yue, 1996). It can be used on sites where the conditions are unsuitable for ordinary lightweight materials.

3. Experimental Setup

The long-term deformation behavior of EPS blocks under the repeated loading conditions were analyzed by

Table 1. Typical Properties of Expanded Polystyrene Foam

Property	Requirement				Test Method
	Type 1	Type 2	Type 3	Type 4	
Compressive Strength, Min, kPa	55	110	170	210	ASTM D 1621
Tensile Strength, Min, kPa	140	210	250	250	ASTM D 1623
Flexural Strength, Min, kPa, Machine direction Cross Machine Direction	 170 170	 240 240	 350 350	 600 375	ASTM C 203
Shear Strength, Min, kPa	120	170	200	200	ASTM 203
Thermal Resistance, Min, m^2.℃/W Initial Aged	 0.65 –	 0.70 –	 0.74 –	 0.85 0.85	
Water Vapor Permeance, Max., ng/Pa.s. m^2	250	160	60	60	
Dimensional Stability, Max., % linear change	0.5	0.5	0.5	0.5	
Water absorption, Max., % by volume	6	4	2	0.7	ASTM D 2842

Table 2. Unit Weights of Some Light Fill Materials

Name of Material	Density	
	(pcf)	Kg/m^3
EPS block	1.25	20
Wood Chip	53.1	850
Light expanded clay (Leca)	50–62.4	800–1000
Cellular concrete waste	62.4	1000
Saw dust	62.4–68.7	1000–1100
Lytag	97.3	1500
Volcanic Ash	100	1600
Sand	106.2	1700
Clay	125.00	2000

conducting tests in the laboratory at South Dakota School of Mines & Technology (SDSM&T) geotechnical engineering laboratory. For performing the experiments, 12 samples of EPS blocks with different densities were used. Each sample was tested for a period of one-month duration under the application of varying stresses. In this section, the description of the EPS samples used for the tests, the set up of the consolidation unit for repeated loading conditions, and the procedure of carrying out the tests will be discussed.

3.1 EPS Sample

Benchmark Foam Inc., of Watertown, South Dakota, provided the required samples for performing the tests in the laboratory. The samples provided are cylindrical in shape with diameter of 100 mm (3.9 in) and height of 50 mm (1.9 in), made as per as specified for testing in the consolidation unit. Usually, the samples are made into required shapes by using a universal trimmer with a thermoelectric line as a cutting tool. The EPS blocks with different densities used in this research are: 1.0 pcf (16 kg/m^3), 1.5 pcf (24 kg/m^3), 2.0 pcf (32 kg/m^3), 3.0 pcf (48 kg/m^3) and 4.0 pcf (64 kg/m^3) (English Units are presented first as these represent the commercial description of the material). Fig. 1 shows the samples used in the experiments.

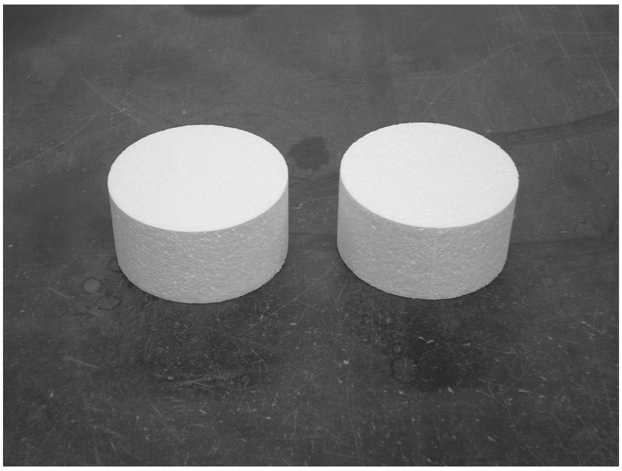

Fig. 1. Shapes of Samples Used in the Tests

To carry out the experiments, the applied stresses on the samples were derived based on the diameter and area of the samples. This led to the simplification of experimental steps and the loading procedures. Based on the applied stress calculation, stresses were applied on the samples at 30 kN/m^2, 60 kN/m^2 and 90 kN/m^2. Therefore, the experimental results can be compared with the analytical results with ease.

3.2 Compression Device

Fig. 2 shows the main compression device, which is mainly composed of a base plate, the sample cabinet and the dial gauge placed on the measuring bridge (not shown). The sample cabinet was designed in a way that the preferred EPS samples could be placed in that cabinet without lateral displacement within the cabinet while loading. The sample was placed under a porous stone inside the cabinet. The porous stone, which is of same diameter as the sample, was used in order to raise the sample in the

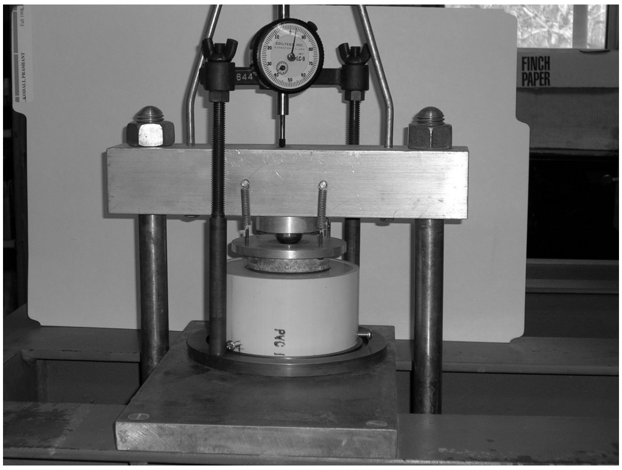

Fig. 2. Set- Up of Compression Device During Testing

Fig. 3. Loading Section Based on Leverage Mechanism

Table 3. Calculations of Needed Loads on the Samples During Testing

Stress on Sample (kPa)	Diameter of Sample Used (in)	Area (m^2)	Force applied on the Samples (N)
30	3.9	0.00785	235.5
60	3.9	0.00785	471
90	3.9	0.00785	706.5

set-up, but not for any drainage purposes. A thin aluminum disk with a diameter slightly less than the sample cabinet was place on top of the sample, to provide a uniform load distribution on the sample. A vertical dial gauge was placed on top of the loading beam for the measurement of vertical deformation of the sample during the tests.

3.3 Loading

The loading device used in the consolidation unit is shown in Fig. 3. The loading device uses a leverage mechanism to provide a vertical loading on the samples. The leverage ratio used is approximately 1:10. Table 3 shows the calculation of the load to provide different stresses on the sample namely 30 kPa, 60 kPa and 90 kPa respectively.

3.4 Repeated Loading Cam

Manual load application was not possible because of the high number of load cycles necessary to determine the deformation behavior of EPS sample under repeated loading for a period of one-month testing. A rotating mechanical device applying three cycles per minute was designed in order to provide a gentle impact of traffic loading on the samples. The cams were mounted on the shaft, each with three peaks and were placed under the center of the load lever. A roller was supported on the load lever to reduce the friction and binding between the lever and the cam. The weight of the cam and its mounting device was calibrated out of the equipment. The cam was designed such that the load would be on the sample for only three seconds during an interval of one cycle. The shape of the cam controlled the loading rate. In this research, a rounded cam was chosen, so that the angular cam did not create an impact load, which in turn could cause the load to bounce on the sample.

3.5 Experimental Parameters

The repeated loading tests were performed under different vertical loading to study the long-term deformation versus time behavior. Since the consolidation unit consisted of only three cams, only 3 samples were tested at once. The samples were exposed to three load cycles per minute for a period of approximately one month and tested at three different stress levels (30 kN/m^2, 60 kN/m^2 and 90 kN/m^2), exposing the samples to a total of between 90,000 to 115,000 repeated loads. A total of 12 samples were tested spanning over a period of approximately 5 1/2 months.

4. TEST RESULTS

4.1 Effect of Density

The time-dependent behavior of EPS blocks versus density under repeated loading can be correlated by comparing five samples with different density (sample #1, sample # 1 ½, sample #2, sample #3, sample #4). The results taken at 0, 1, 10, 15, 20, 25 and 30 days, are plotted in Figs. 4 through 7. As can be seen in the figures, the 1.0 pcf has the maximum magnitude of deformation and the 4.0 pcf sample has the minimum magnitude. However, the 1.5 pcf samples underwent less deformation than the 2.0 pcf samples. After 24 hours, the deformation for the 3.0 pcf and 4.0 pcf samples are only about 30 % of the deformation obtained for the 1.0 pcf sample at a load of 30 kPa. As observed in the plots, the deformation of the sample after 24 hours testing for each density EPS material generally exceeds 70 percent of the total deformation at 30 testing days, and the 10 day deformation is over 90 percent of the final deformation. Figs. 4 through 7 include the information of densities, sample numbers, and applied stress just as (1, 1 – 30 kPa) means (pcf, sample number – applied stress).

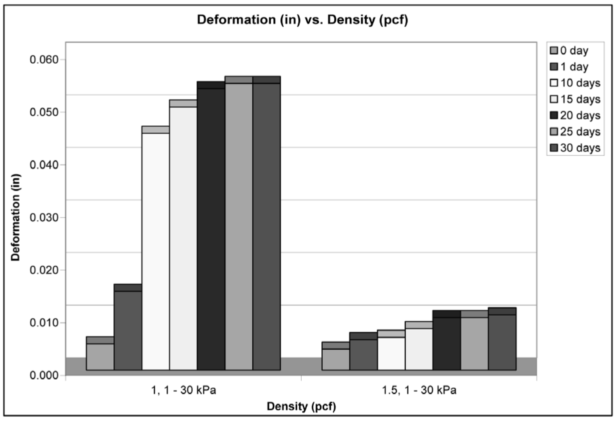

Fig. 4. Deformation versus Time and EPS Densities of 1.0 and 1.5 pcf Samples

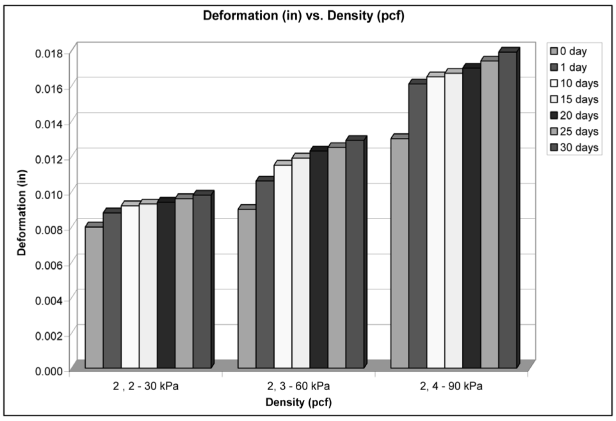

Fig. 5. Deformation versus Time and EPS Density of 2.0 pcf Samples

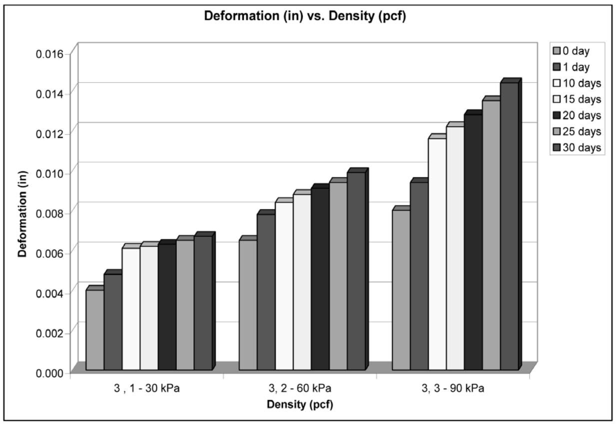

Fig. 6. Deformation versus Time and EPS Density of 3.0 pcf Samples

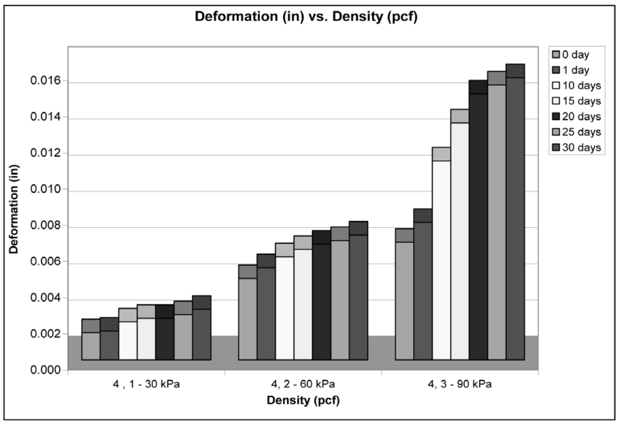

Fig. 7. Deformation versus Time and EPS Density of 4.0 pcf Samples

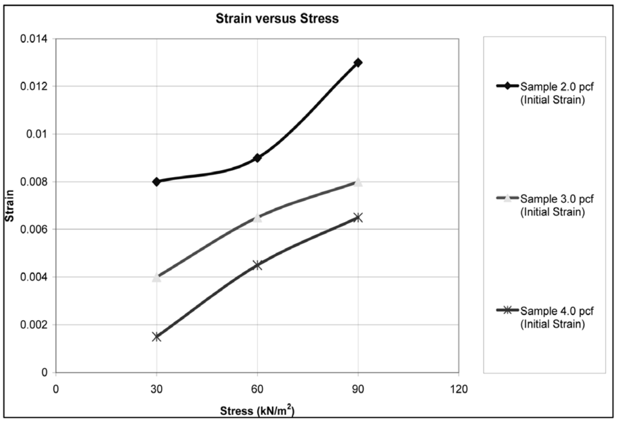

Fig. 8. Relation between Applied Stress and Strain for 2.0, 3.0 and 4.0 pcf Samples

As shown in Fig. 8, high-density samples show very less deformation difference in the initial stage than the low-density samples under the applied stresses. Thus, lesser the density, higher will be the strains obtained.

5. ANALYTICAL APPROACH

The time-dependent mechanical (stress-strain) behavior of polymeric geosynthetics has been a topic of significant interest for many years. Time-dependent mechanical behavior can be considered in practice using either an empirical or deterministic approach.

The parametric analysis approach included the evaluation of parameters describing the behavior of EPS material deformation with respect to the time under repeated loading conditions. As part of this thesis, the test results were compared with the behavior as described by the Findley model (Horvath, 1998). An attempt was also made to refine this model. The parametric approach estimates the change in deformation of EPS blocks under working condition. The effect on the deformation of EPS blocks by material density may indicate the type and the method of utilization of EPS blocks in design and construction. The mechanical behavior of the material can be determined by obtaining the relationship between stress and the strain. The deformation under repeated loading conditions can therefore assess the possible magnitude of the deformation of EPS lightweight material as in flexible pavement subgrade applications.

The primary time-dependent behavioral mode of interest for all geosynthetics is the creep, so it is logical to focus on models derived initially for that purpose. With few exceptions, the basic constitutive equation for all creep models has the following qualitative form:

$$\varepsilon = \varepsilon_0 + \varepsilon_c \tag{1}$$

where,

ε = total strain at some time t after the stress application,

ε_c = the time-dependent (creep) component of strain at some time t after the stress application, and

ε_0 = the immediate strain upon the stress application.

With regard to the creep component, ε_c, as summarized in Findley and Koshla (1956) and Findley (1960), researchers have used a variety of relatively simple arithmetic functions of time (linear, logarithm, exponential, power law), either alone or in combination, to define the basic behavior of this aspect. These functions can:

- Be an arbitrary mathematical assumption that appears to fit some set of data,
- Have an arbitrary physical basis, i.e., the mathematical result of using a relatively simple, abstract physical model composed of various combinations of mechanical elements such as springs and dashpots or
- Have a rigorous physical basis deriving from some assumed rheological behavior of a specific material.

5.1 Findley Equation

In developing an equation that was used initially to define the creep behavior of polymeric materials in tension, Findley and Koshla (1956) used the basic form of Eq. (1) with the assumption that

$$\varepsilon = \varepsilon_0 + \varepsilon_1 * (t/t_1)^m \tag{2}$$

where,

ε_0 = the immediate strain upon the stress application

ε_1 = the time dependent component of strain at some time after the stress application.

m = constant, independent of stress and its mode,

t_1 = unit time for a total of 3 cycles in minutes.

t = total time in minutes.

or, in terms of number of load cycles:

$$\varepsilon = \varepsilon_0 + \varepsilon_1 * (N / N_1)^m \tag{3}$$

where,

N = Total number of cycles,

N_1 = Number of cycles at certain time intervals.

Findley and Koshla (1956) pointed out that this relationship fits well for the creep of polymers tested in simple tension, compression and torsion, or in combination, and it was successfully used to extrapolate the creep strain of polyvinyl chloride and polyethylene, measured from 2000 hours, up to 132,000 hours. The value of the exponent m equals 0.09 to 0.21 for various plastics, 0.22 for wood and 0.2 to 0.45 for different metals.

5.2 Modified Findley Equation

It is of some interest to modify the Findley equation to match with the experimental results for all the EPS samples tested under repeated loading.

The standard form of the Findley equation is

$$\varepsilon = \varepsilon_0 + \varepsilon_1 * (N / N_1)^m \tag{4}$$

However, to be consistent with the variables used in Original Findley's Model, Eq. (4) is rewritten here as

$$\varepsilon = \varepsilon_0 + \varepsilon_1 * N^m \tag{5}$$

where,

ε_0 = initial strain obtained

ε_1 = time dependent strain and can be obtained from the following equation

$$\varepsilon_1 = \frac{(\varepsilon_N - \varepsilon_0)}{N^m} \tag{6}$$

m = Constant, independent of stress and its mode,

N = Total number of Cycles.

The Modified Findley's model was applied for the long term repeated loading tests. The results are shown in Figs. 9 through 11 which are the typical ones from the testing. As can be seen from the analysis, different values of m were obtained for different sample densities. For the 1.0 and 1.5 pcf samples, the exponent value m calculated was

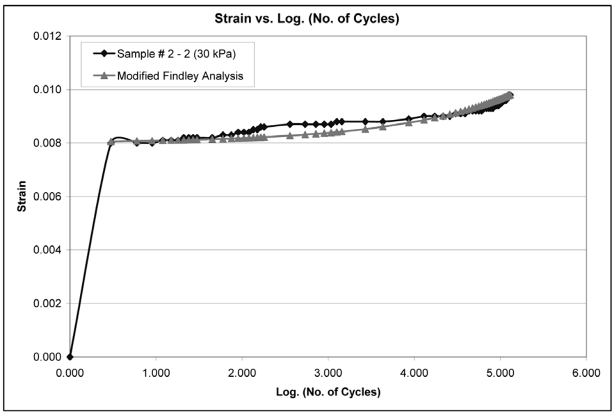

Fig. 9. Comparison of Modified Findley's Model with Testing Curves for Sample # 2 - 2 (30 kPa)

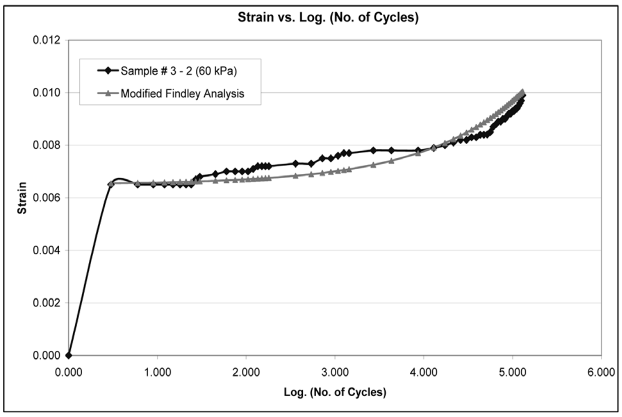

Fig. 10. Comparison of Modified Findley's Model with Testing Curves for Sample # 3 - 2 (60 kPa)

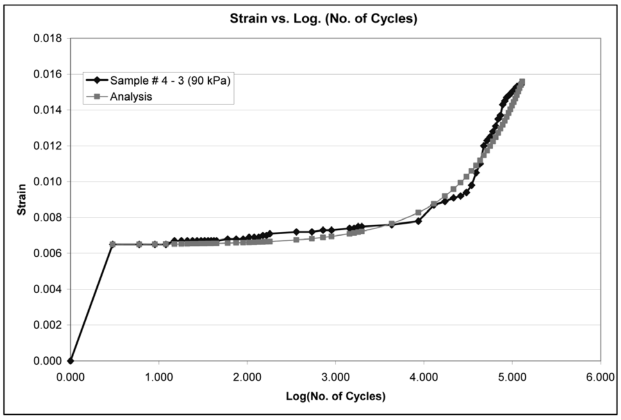

Fig. 11. Comparison of Modified Findley's Model with Testing Curves for Sample # 4 - 3 (90 kPa)

0.5 whereas for the 2.0 pcf samples, a value of approximately 0.3 was obtained. However, m values of 0.4 and 0.6 were obtained for 3.0 and 4.0 pcf samples respectively.

Figs. 9 to 11 show the typical comparison of Modified Findley's model with the test results obtained in the laboratory using the above m values. All plots are anchored to the strain after one cycle. From the plots, it can be seen that the model matches perfectly with the strains obtained for different EPS samples.

5.3 Proposed Model

This study suggests that a better model can be used to predict the behavior of EPS material. It is proposed that the strain can be suggested as

$$\varepsilon = \varepsilon_0 + \varepsilon_1 * \left(N^x - N_i^x\right) \tag{7}$$

where,

ε_0 = Initial strain obtained and

ε_1 = time dependent strain and can be obtained from the following equation

$$\varepsilon_1 = \frac{(\varepsilon_N - \varepsilon_0)}{N^x} \tag{8}$$

x = exponent value based on the weight of the EPS sample.

N = Total Number of Cycles

N_i = Corresponding number of cycles

The initial strain ε_0, based on the results of the tests done for this research, can be broken up into two parts, one based on EPS weight and the other based on applied stress, and expressed as

$$\varepsilon_0 = \varepsilon_{0\mathrm{w}} + \varepsilon_{0\sigma} \tag{9}$$

$$\varepsilon_{0\mathrm{w}} = \left(w^2 - 9w + 22\right) * 0.001 \tag{10}$$

$$\varepsilon_{0\sigma} = \left(\frac{\sigma - 30}{30}\right) * 0.002 \tag{11}$$

$$\varepsilon_0 = \left(\frac{w^2 - 9w + 22}{2} + \frac{\sigma - 30}{30}\right) * 0.002 \tag{12}$$

where,

$\varepsilon_{0\mathrm{w}}$= Initial strain based on EPS weight

$\varepsilon_{0\sigma}$ = Initial Strain based on applied stress

W = Weight of EPS samples in pcf.

σ = Applied Stress in kN/m^2.

For 1.0 and 1.5 pcf EPS samples, the value of the exponent x used in the model was 0.5; this value is constant for all the 1.0 and 1.5 pcf samples. For samples with weight 2.0 pcf and higher, the exponent is proposed to be expressed as

$$x = 0.2 * W - 0.2 \tag{13}$$

where,

W = Weight of EPS samples in pcf.

The proposed model is compared to the test results in Fig. 12, also shown is the Findley model, using ε_0 as determined by the analytical model.

As can be seen from the Fig. 12, the results obtained by the proposed models coincide with the test results for the EPS samples.

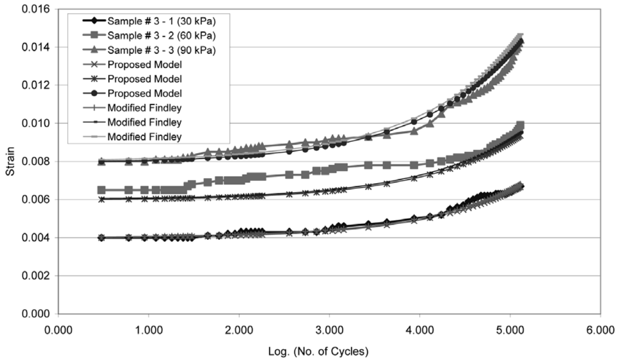

Fig. 12. Comparison of Modified Findley's Model and Proposed Model with the test results for 3.0 pcf Sample

6. Conclusions

Regardless of the magnitude of stresses, EPS samples with low densities deform much more than the higher density samples. Therefore, the lesser the density of EPS samples, the higher the deformations. From these tests, it can be drawn that the use of 1.0 pcf EPS samples should be restricted in its applications where the deformations are critical. Thus, the use of this lower density material may be limited to heat insulation purposes. It can be concluded that the Modified Findley's model matches well with the test results and gave an accurate model for the test results when compared to the original Findley model.

Finally, a model was proposed to predict the behavior of EPS material accurately under repeated loading with its properties and the conditions of applied stresses as shown in Eqs. (7) through (13).

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