Determination of Long-Term Mechanical Properties for Thermal Insulation under Foundations

Holger Merkel, Ph.D.

ABSTRACT

Thermal insulation is widely used in applications under sustained loading, such as insulated foundations of buildings. In this application, the impact of thermal insulation is twofold—frost protection and energy saving. In order to maintain the thermal protection of foundations over the lifetime of a building, it is absolutely necessary to predict the long-term mechanical performance of thermal insulation materials. Accordingly, requirements have been defined in the new harmonized European standards for factory-made insulation product.

This paper discusses the impact of these requirements on determination and design of properties for thermal insulation products, such as extruded polystyrene foam (XPS), typically used in this application. The key physical phenomena, which determine the long-term mechanical behavior, are described as well as a mathematical model for prediction of long-term performance.Based on experimental results and findings, conclusions are drawn for the design of thermal insulation layers under foundations.

INTRODUCTION

Thermal insulation materials are used under sustained heavy loading in many civil engineering applications, such as road and railway insulation. The use of thermal insulation under heavy loading in buildings for higher energy savings has grown rapidly during the past 10 to 15 years.

Plastic foams, especially extruded polystyrene foam (XPS), are widely used as thermal insulation below grade (perimeter insulation). Building physicists and architects are increasingly specifying thermal insulation for foundations as well as heavy-loaded industrial floors or parking decks. Recognizing this development, the new harmonized European Standards (hEN) define requirements for factory-made thermal insulation products used in applications subjected to heavy long-term loading.

SHORT-TERM AND LONG-TERM MECHANICAL BEHAVIOR OF CELLULAR PLASTIC FOAM

The short-term mechanical behavior of cellular plastic foam (Figure 1), such as XPS, deviates significantly from the long-term behavior. The stress-strain curve under short-term load follows approximately the Hookean law up to the peak of stress, which is known as yield (Figure 1). This peak occurs due to a strong irreversible deformation of one or more cell layers, although the structure is not broken. Such behavior is completely different from that of materials with brittle structures, such as cellular glass or concrete.

If no peak occurs in the stress-strain curve, the material deforms continuously. In such a situation, therefore, the failure criterion must be defined. This criterion was set as the stress at 10% deformation (Figure 1).

The long-term behavior under constant and sustained loading will be discussed in the following section. For the design of buildings, this long-term deformation and failure is of topical interest. Therefore, it is appropriate to explain the mechanism affecting the deformation of cellular plastic foams.

COMPRESSIVE CREEP OF CELLULAR PLASTIC FOAM

Cellular plastic foams under constant load exhibit time-dependent behavior. When the material is exposed to a load,

Holger Merkel is Technical Service and Development Leader Europe, DOW Deutschland GmbH&Co. OHG.

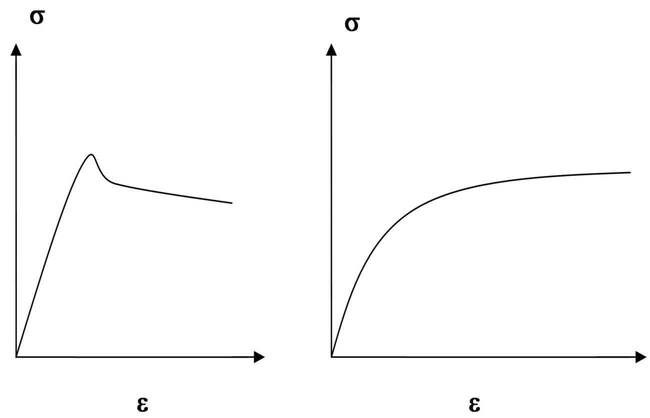

Figure 1 *Stress-strain behavior under short-term load: left graph, compressive strength at yield; right graph, compressive stress at 10%.*

the initial strain can be described approximately by the linear stress-strain curve. If the stress applied is below yield, a slowly continuing deformation process occurs. The strain induced is then a function of time.

This deformation with time under constant load is called *creep*. The creep mechanism can be divided into three stages (Krollmann et al. 1998). The primary stage is the early stage of loading when the creep rate decreases rapidly. In this range there is no disruption to the cell structure. Only polymer flow processes (cold flow) are thought to occur. The secondary stage is characterized by a nearly constant creep rate. After this stage the creep rate increases again until yield has been reached. The tertiary creep only occurs at very high stress levels.

The way the cells will be deformed under load is shown schematically in Figure 2. Initially the load causes bending of the cell walls. While the load is increasing, the cell walls tend to buckle, and finally, under very high loads, the walls will touch each other.

Figure 3 shows the deformation model for XPS. The model combines Hookean springs and Newtonian dashpots. The spring models the elastic response, while the dashpot models the viscous response to the applied load.

Primary creep can be described by an equation of the form

$$\varepsilon = \varepsilon_0 + a \cdot t^b \qquad (1)$$

where

a,b = material parameters,

t = time,

ε_0 = initial deformation,

and the second term characterizes the time-dependent deformation. For the design of building applications, only primary creep is considered, which occurs up to about 10% of deformation for XPS.

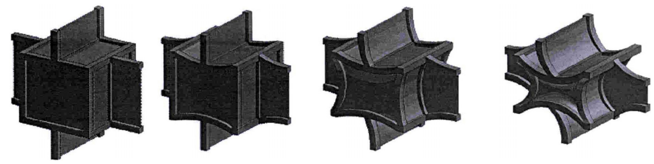

Figure 2 *Deformation of cells in cellular polystyrene foam under load (Krollmann et al. 1998).*

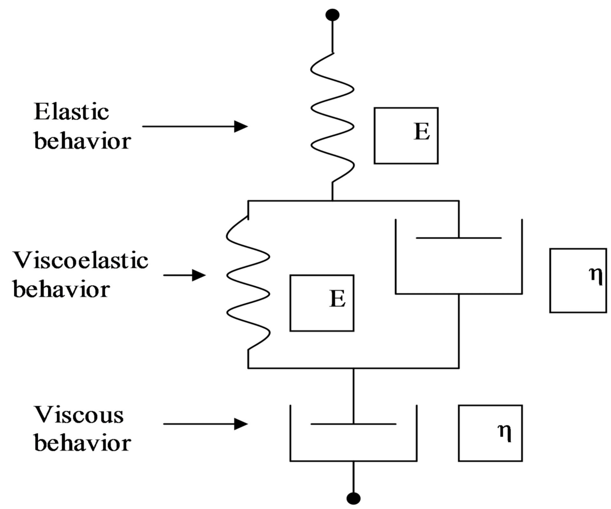

Figure 3 *Schematic diagram of combined deformation model for XPS:* E = *elastic modulus,* η = *viscosity (Krollmann et al. 1998).*

TEST METHOD FOR DETERMINING COMPRESSIVE CREEP

The test method as well as the calculation method for determination of compressive creep is specified in the European *Standard EN 1606:1996* (CEN 1996). The size of the samples can vary between 50 mm × 50 mm and 300 mm × 300 mm depending on the thickness of the insulation board. The measurements shall be carried out at 23°C and 50% relative humidity. The levels of load shall be determined as a percentage of the short-term compressive strength, e.g., 0.35 · σ. The strain ε_t at time t can be expressed by Equation 2:

$$\varepsilon_t = (X_t / d_s) \cdot 100 \qquad (2)$$

where

X_t = deformation at time t (mm) and

d_s = thickness of sample (mm).

In order to determine the creep deformation at time t the measured values can be extrapolated using a well-established method known as the FINDLEY method. This method describes the viscoelastic behavior of cellular plastic foam and

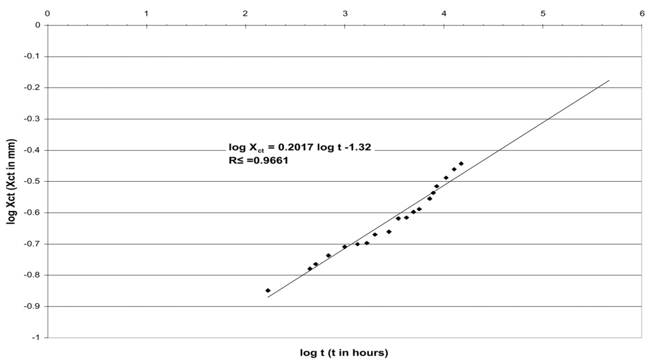

Figure 4 *Typical regression curve to determine the FINDLEY parameters* m *and* b.

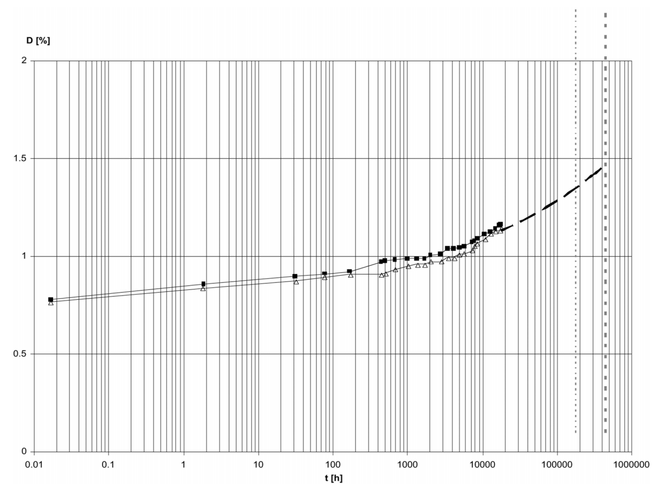

Figure 5 *Creep deformation* D *(*D = ε_t*) in %—measured and extrapolated values as function of the logarithm of time (Graph: DOW Europe Creep Lab).*

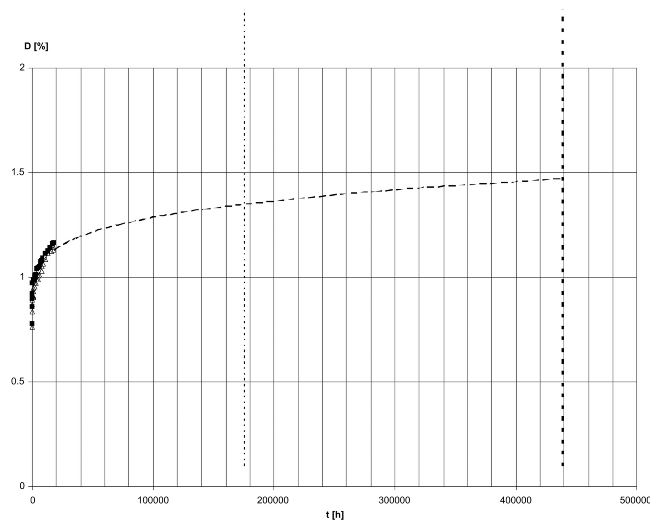

Figure 6 *Creep deformation* D *of XPS foam—measured and extrapolated values as function of time.*

has been validated widely. The total deformation of the sample under steady load can be expressed as

$$X_t = X_0 + m(\sigma) \cdot t^{b(\sigma)}. \tag{3}$$

The creep part of Equation 3 can be expressed as

$$X_{ct} = X_t - X_0 = m(\sigma) \cdot t^{b(\sigma)}, \tag{4}$$

where

X_0 = initial deformation 60 s after the load has been applied,

X_{ct} = creep deformation at time t, and

m, b = material parameters (FINDLEY parameters).

This equation is known as the Findley equation. The material parameters m and b are stress-dependent. Equation 4 can also be expressed in a linear form by introducing logarithmic terms:

$$\log (X_t - X_0) = \log m(\sigma) + b(\sigma) \cdot \log t. \tag{5}$$

The parameters m and n can be obtained from a linear regression curve, which is based on the measured values starting 168 hours after initial measurement. From Equation 5 it follows that parameter b is the slope of the curve and log m the intercept of the ordinate.

Figure 4 shows such a typical linear regression fit for the new generation of CO_2 blown XPS to determine m and b. The details of this procedure are described in detail in *EN 1606*. An extrapolation 30 times the testing time is permitted when R^2. Taking the given example, the FINDLEY parameters are determined to be: b = 0.2017 and m = 0.048.

Equation 3 leads to a creep deformation after 50 years (= 438000 hours) of about 0.66% of initial thickness. The total deformation behavior of the insulation can be obtained from Equation 2, whereas X_t follows from Equation 3.

Figure 5 shows a form of the creep curve that is commonly used to express the results. Note that this logarithmic form changes the shape of the curve, stretching out the short-term part and compressing the long-term part. This can cause some difficulties in interpreting the creep deformation. Therefore, the same curve is plotted against time in Figure 6. It shows that after a short period of initial response to the load, the remaining creep part of the deformation is pretty small, as was calculated above. The dashed perpendicular lines are at 20 years and 50 years. Between 20 years and 50 years of service, the creep deformation is approximately negligible.

TECHNICAL SPECIFICATION REQUIREMENTS FOR HIGH-LOADED THERMAL INSULATION

Compressive creep of thermal insulation products has been specified in the new harmonized European Standards

Table 1. Typical Range of Compressive Strength/Stress Values for Cellular Plastic Foam, EPS (Expanded Polystyrene Foam), and PU (Polyurethane Foam)

Product	Nominal Compr. Strength σ_N in kPa	Long-Term Compr. Stress σ_c in kPa
XPS	300 …… 800	110 …. 280
EPS	200 …… 350	40……110
PU	100 …… 300	20…… 100

(hEN) for factory-made insulation products. According to *EN 13164:2001* (CEN 2001) compressive creep ε_{ct} and total thickness reduction ε_t shall be determined after at least 120 days of testing at a declared compressive stress σ_c and the results extrapolated 30 times corresponding to 10 years.

For building applications such as thermal insulation of foundations, a total thickness reduction of ≤2% of thickness and an extrapolation time of 50 years are generally required. Conclusively, thermal insulation products have to be tested for 608 days at a stress level that will finally result in deformations less than 2%.

The results for compressive creep shall be declared in levels as well as the total thickness reduction at a declared stress. For example, the designation code CC(2/1.5/50)180 indicates a value not exceeding 1.5% for compressive creep and 2% for total thickness reduction after an extrapolation time of 50 years at a stress level of 180 kPa.

RESULTS AND FINDINGS OF LONG-TERM BEHAVIOR UNDER CONSTANT LOAD

The limitation of deformation to 2% considers the following requirements:

- keep the creep deformation within the primary stage, applying a reasonable safety factor, and
- ensure the long-term thermal performance of the insulation.

Table 1 shows the range of compressive stress that does not lead to higher than 2% deformation after 50 years for various insulation products made of cellular plastic foam.

For most of the massive buildings, even multistory buildings, the design load for the foundation slab is, from experience of the author, between 100 kPa and 250 kPa. Within this range, an example for the long-term behavior of an XPS foam with a nominal compressive strength of 700 kPa is given in Figure 7. The required deformation limit of 2% maximum has not been reached under the load applied. For such a product the deformation with time after applying the initial load, e.g., the foundation slab, is negligible. Even when the performance of a large number of types of soil is considered, this statement remains valid.

Comparing the creep results of the former HCFC blown XPS and the results for the new generation of CO_2 blown XPS

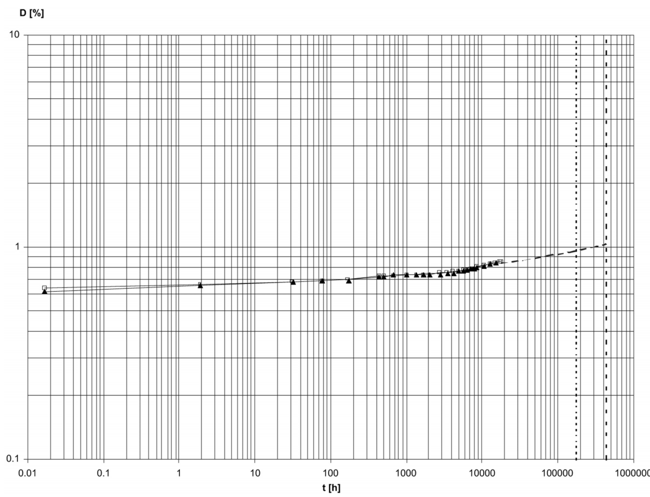

Figure 7 *Long-term deformation of a CO_2 blown XPS under constant load of 260 kPa (Graph: DOW Europe Creep Lab).*

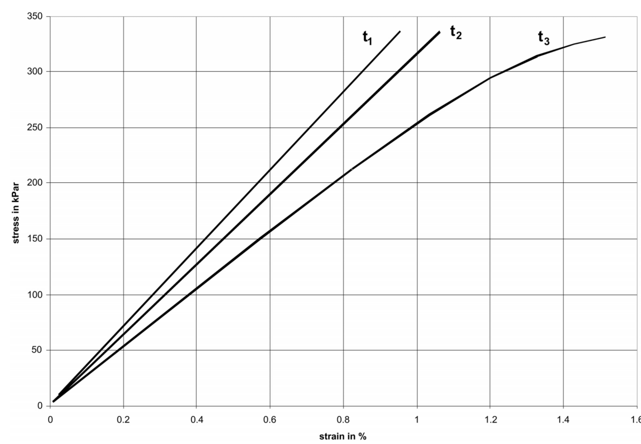

Figure 8 *Stress-strain curves at constant time for a 700 kPa XPS-type foam,* $t_1 = 1000$ *h,* $t_2 = 10000$ *h,* $t_3 = 438000$ *h (50 y).*

(Figure 7) the latter shows an improved performance, meaning the curves are more flat and the creep deformation is smaller in general.

The size of the load that can be applied on a specific product varies with the blowing agent or cell gas, the foam structure (XPS/expanded polystyrene foam EPS), and the polymer that forms the cell walls (polystyrene foam/polyurethane foam), respectively.

In order to determine the creep modulus, the stress can be plotted against the strain calculated from Equation 3 at different times (Figure 8). The curves are then called isochrones. Depending on the compressive strength of the foam and the size of the load, the curves show an approximately linear relation between stress and strain at different times. For higher

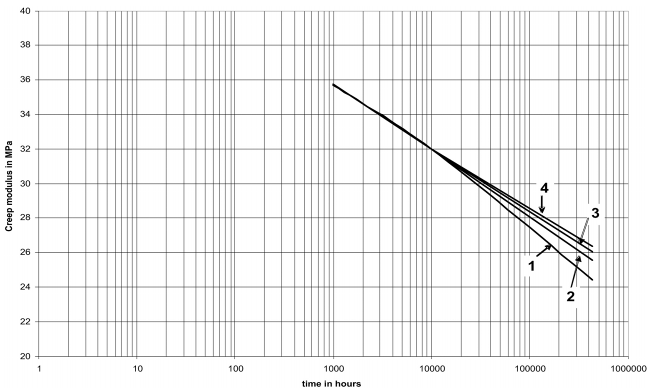

Figure 9 *Time-dependent creep modulus for a 700 kPa XPS-type foam for different stresses applied, 1 = 300 kPa, 2 = 250 kPa, 3 = 200 kPa, 4 = 150 kPa.*

loads and longer time, the stress-strain relation becomes nonlinear.

The creep modulus E_c determined from Equation 6 shows a time-dependent behavior (Figure 9).

$$E_c(t_i) = \sigma / \varepsilon (t_i) \tag{6}$$

where

$E_c(t_i)$ = creep modulus at time t_i,

$\varepsilon (t_i)$ = strain at time t_i,

σ = applied stress.

It decreases with time. This has an influence on the design E-modulus of the foam, which will be discussed later.

Taking into account the application environment of the insulation below grade, it should be mentioned at this point, for the sake of completeness, that water absorption requirements also have to be fulfilled. For applications outside the waterproofing (perimeter) layer, usually XPS and EPS are being used (Merkel 2002). The significantly lower water absorption capacity of XPS is due to the closed cell structure of the foam (Table 2).

How can we characterize the influence of the water absorption properties on mechanical properties? For both XPS and EPS, a limit for the reduction of compressive strength after water absorption by freeze-thaw processes is required in the corresponding European product standards. This is being set as 10% of the initial compressive strength or stress. Although it is obvious that freeze-thaw processes don't take place under all application conditions below grade, this property gives at least an indication of the coupled moisture and mechanical performance of the foam. To the author's knowledge, no specific results for EPS have been reported, but for XPS results are available. These results were obtained by performing the diffusion test according to EN 12088 and also the freeze-thaw test according to EN 12091.

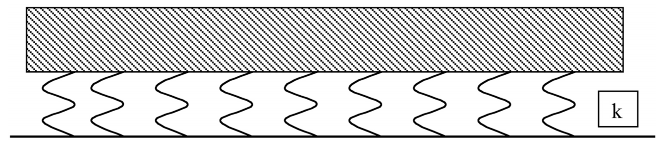

Figure 10 *Foundation slab resting on thermal insulation, simulated by a number of springs (schematically).*

Table 2. Water Absorption (WA) Properties for XPS and EPS (Properties Vary by Product)

Property	Unit	XPS	EPS
WA by diffusion	Vol-%	3.0	12.0
WA by immersion	Vol-%	0.5	5.0
WA after freeze/thaw	Vol-%	1.0	20.0

After the freeze-thaw test, XPS foam samples show either a slightly increasing or an approximately constant compressive strength, while the stress-strain curve remains nearly unchanged. From samples taken from existing buildings—not from foundation insulation but from parking decks with long-term dynamic loads—it is known that the compressive strength of XPS in a humid environment does not change significantly after more than ten years of service (Oswald 1998).

APPLICATION OF RESULTS TO THE DESIGN OF THERMAL INSULATION OF FOUNDATIONS

Besides the thermal design of the insulation, which has been discussed extensively on the basis of EN ISO 13370 (Dahlem 2003), the design for the static load is also a matter of critical interest. This not only influences the structural stability of the building but the long-term performance of the insulation as well.

From an energy savings standpoint, it is sometimes questionable to insulate the entire area of a foundation slab. Specific calculations of heat transfer through a foundation might show that it is sufficient to insulate just a strip along the edges of the slab, but there is another view that takes the static behavior of the building into account. Different underlayments of the foundation slab may cause differential settlement of the slab and, therefore, different stresses that might reduce the structural stability of the foundation.

For simplicity a spring model can be used to simulate a foundation slab resting on a thermal insulation layer as shown in Figure 10. All springs are assumed to have the same spring constant k. Therefore, the insulation layer can be characterized by a value of k that is equal at each point of the layer. For thin insulation (120 mm) the spring constant k of the thermal insulation layer can be expressed by Equation 7 (Merkel 2002):

$$k = E_{cr} / d_{ins} \tag{7}$$

Table 3. k-values for XPS Products at 2% Deformation after 50 Years for Various Design Loads and Insulation Thicknesses

Insulation Thickness (mm)	k (MN/m³) for Design Load 0.13 N/mm²	k (MN/m³) for Design Load 0.18 N/mm²	k (MN/m³) for Design Load 0.25 N/mm²
60	108	150	208
80	81	112	156
100	65	90	125
120	54	75	104

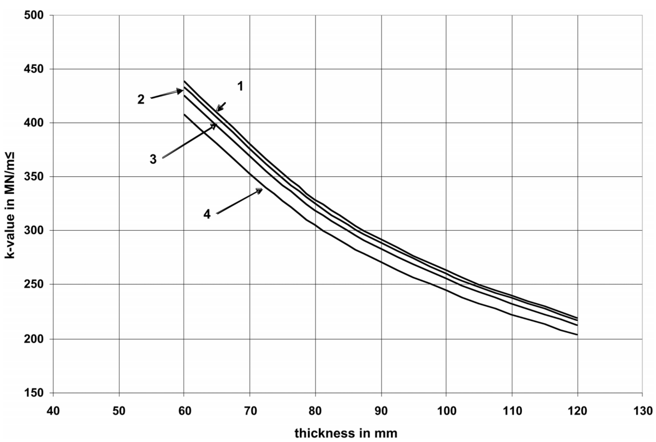

Figure 11 *The k-values (spring constant) for thermal insulation (see Figure 9) dependent on thickness and load: 1 = 150 kPa, 2 = 200 kPa, 3 = 250 kPa, 4 = 300 kPa.*

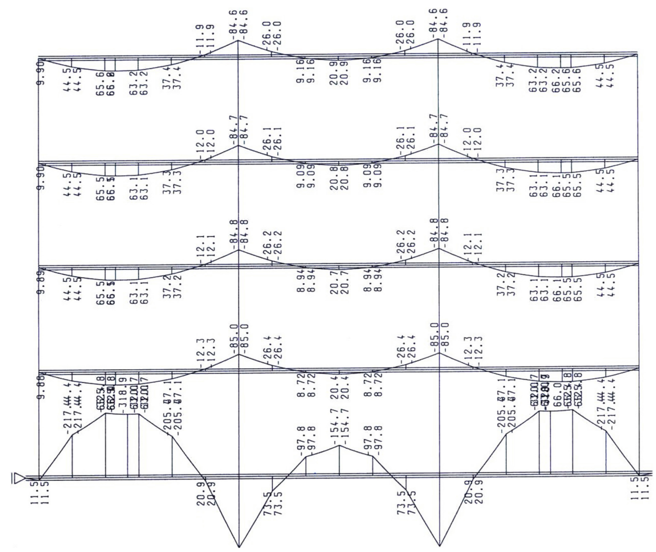

Figure 12 *Bending moments (kNm/m) of deck slabs and foundation slab for a multistory building with thermal insulated foundation slab (Steiner et al. 2001).*

where

E_{cr} = creep modulus (MPa or MN/m^2) and

d_{ins} = thickness of the insulation (m).

Using the values shown in Figure 9 for the creep modulus, k-values can be obtained. Note that these values are product dependent; therefore, the specific values cannot be extrapolated to all XPS products in general. But the example in Figure 9 shows how to determine design values that can be used for realistic calculations. Table 3 shows typical k-values for various design loads and different thicknesses of the insulation layer. (*Note:* For static calculations, the unit N/mm^2 instead of kPa is commonly used.)

In Figure 12 a typical example is shown with the results depicting the bending moments of deck slabs and foundation slab in a multistory building while the foundation slab is resting on 70 mm XPS foam thermal insulation with nominal compressive strength of 700 kPa. The foundation slab is assumed to be 80 cm thick. The deformation of the foam is about 1.0 mm maximum, which is less than 2% of the thickness. In the case of XPS, the bending moments in the foundation slab are impacted by the stiffness of the soil rather than stiffness of the insulation layer.

SUMMARY AND CONCLUSION

The creep deformation of CO_2 blown XPS can be properly determined by applying EN 1606 (CEN 1996). For applications of thermal insulation products under foundations, a lifetime of 50 years is required in the European Construction Products Directive (CPD). Therefore, the creep deformation for a minimum extrapolation time of 50 years has to be determined.

It was shown in this paper that deformation behavior under short-term loading differs significantly from creep behavior under sustained loading. Conclusively, the short-term mechanical characteristics of a thermal insulation product are not sufficient to calculate the response of a foundation slab under static loading. The creep curves for the XPS products tested are relatively flat with time, and the measured values follow the curve predicted by the FINDLEY method. For static calculations, knowledge of the creep modulus is a prerequisite.

Using the stress-strain equation for viscoelastic materials and determining the FINDLEY parameters, the creep modulus can be determined for various loads at different times.

The mechanical behavior of the insulation layer can be approximately simulated by a spring model with a spring constant equal at each point of the layer. This constant has been determined for various design loads and thicknesses of the insulation. It can be directly used for static calculations of foundation slabs resting on an XPS insulation layer.

As shown in this paper, even the foundation slab of a multistory building can be thermally insulated when it is necessary. The method and the results presented enable the building physicist as well as the civil engineer to properly design a thermally insulated foundation, taking into account the mechanical properties of the insulation material. This closes the gap between building physics and mechanical design.

REFERENCES

CEN. 1996. *EN 1606, Thermal insulating products for building applications—Determination of compressive creep.*

CEN. 2001. *EN 13164, Thermal insulation products for buildings—Factory made products of extruded polystyrene*.

Dahlem, K.-H. 2003. Wärmeübertragung erdreichberührter Bauteile; Bauphysik Kalender 2003. Berlin, Verlag Ernst&Sohn.

Krollmann, N., et al. 1998. Verhalten von Polystyrol-Extruderschaumstoff unter Langzeit-Druckbeanspruchung, Technical Report FPX (Fachvereinigung Polystyrol-Extruderschaumstoff) Nr. 5/1998, Ludwigshafen, Frankfurt.

Merkel, H. 2002. Wärmeschutz erdberührter Bauteile (Perimeterdämmung)—Dämmstoffe, Beanspruchungen, Konstruktionen, Bauphysik Kalender 2002, Berlin, Verlag Ernst&Sohn.

Oswald, R. 1998. Langzeitverhalten von Parkdecks mit Umkehrdach-Wärmedämmung—Floormate; Report, Aachen.

Steiner, J., et al. 2001. Zur Berechnung von Bodenplatten auf extrudergeschäumten Polystyrol-Hartschaumplatten. Report not published, Mannheim.