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Effect of service temperature on the shear creep response of rigid polyurethane foam used in composite sandwich floor panels

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HIGHLIGHTS

- Experimental characterisation of creep in a rigid PUR foam.
- High influence of temperature on creep for a typical indoor temperature range.
- Modelling using Findley's power law modified with the Arrhenius equation.
- Good agreement between the proposed model and TTSSP and TSSP predictions.
- Practical creep design equations are presented.

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ABSTRACT

This paper presents an experimental and analytical study about the effect of temperature on the shear creep response of a rigid polyurethane (PUR) foam within the scope of sandwich panel application in building floors. Shear creep tests were carried out on a foam (87.4 kg/m^3) subjected to shear stress levels of 11%, 22% and 44% of its shear strength at temperatures of 20 °C, 24 °C and 28 °C – a range likely to be found in the envisaged application – for more than 1300 h. The results obtained show that the foam's creep response increases with both stress level and temperature. Findley's power law, extended to include Arrhenius equations describing the temperature dependency of its viscoelastic parameters, was fitted to the experimental creep curves, thus allowing to model the time-temperature-stress dependent shear creep behaviour of the PUR foam. The proposed model provided a good fit to the experimental creep curves within the linear viscoelastic range. Practical design equations were also derived for the time-temperature dependent (i) shear modulus, (ii) creep coefficient, and (iii) shear modulus reduction factor. Finally, the time-temperature-stress superposition principle (TTSSP) and the time-stress superposition principle (TSSP) were used to yield "master curves" that compared well with the proposed model's predictions.

1. Introduction

Various industries are increasingly adopting sandwich construction for structural applications, including the civil engineering construction and rehabilitation sectors [1–6], owing to the advantageous characteristics of this structural system. These include high strength-to-weight and stiffness-to-weight ratios, and also the versatility offered by the vast choice of geometrical options and materials available. This versatility allows for the integration of non-structural functions into structural sandwich panels, helping meet various criteria that may be required for different applications [7,8].

In the civil engineering domain, sandwich panels present high potential for application in building floors [9]. However, unlike other industries, sandwich panels used in such structural members often support significant permanent loads. This means that it is important to account for their creep deformability, especially considering that the service life required for civil engineering works (building structures, bridges, and other civil engineering structures) is usually equal to or higher than 50 years [10]. In fact, sandwich panels frequently comprise viscoelastic materials, such as polymeric adhesives, resins, foams, honeycombs and engineered wood, which typically show significant creep under permanent loads [7,8,11].

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Rigid polyurethane (PUR) foam is one of the most commonly used core materials in sandwich panels for civil engineering applications owing to aspects such as its relatively low cost, low thermal conductivity, and relatively easy processing and free-form shaping. Such foams have a strongly temperature dependent viscoelastic behaviour, furthermore being highly prone to creep even at room temperature [12,13]. However, experimental data regarding the influence of temperature on the creep response of rigid PUR foams is scarce. In addition, practical design methodologies need to be developed to account for the effects of temperature on the creep behaviour of such foams.

This paper aims to address these issues, by experimentally investigating the shear creep behaviour of a rigid PUR foam exposed to different in-service temperatures (20–28 °C, likely to be found in building floors) and shear stress levels (11–44% of the foam's shear strength). The creep tests were carried out for periods ranging between 1300 h and 2100 h. The adopted temperatures correspond to a reasonable service temperature range found indoors in air-conditioned (or otherwise temperature controlled) residential and office buildings. The stress levels and test durations were selected taking into consideration the respective ranges found in other relevant creep studies (as per the literature review presented in Section 2). A modelling approach is proposed based on Findley's power law formulation [14]. This formulation was adapted to include an Arrhenius law temperature dependence for the power law parameters that define the creep rate. The generalised equation obtained was used (i) to model the foam's time-dependent shear deformations as a function of the shear stress level and in-service temperature, and (ii) to derive expressions for the time-dependent shear moduli and shear creep coefficients, thus providing a practical tool for the design of sandwich structures comprising a rigid PUR foam core. The final part of the paper compares the long-term creep predictions provided by the proposed model with results obtained from the application of the time-temperature superposition principle (TTSSP) [15] to the experimental data, allowing to assess the consistency and agreement between the two approaches.

2. Literature review

While several studies addressed the creep behaviour of polymer foams, few data exist on the influence of temperature on the creep of rigid PUR foams. Moreland et al. [16] and Briody et al. [17] have studied the influence of temperature on the compressive creep behaviour of flexible PUR foams typically used for cushioning and packaging applications. Such foams differ significantly (in chemical composition and with regards to mechanical behaviour) from the rigid type used for sandwich construction, and are typically subjected to much higher strains (a range of 10–60% is common). These differences make buckling of the cell walls the main deformation mechanism. However, it is interesting to note that the findings of the two works are not in agreement. On one hand, Moreland et al. [16] reported an overall reduction in the creep rates of such foams (the authors did not specify the density of the investigated foams) for the range of 30 °C to 125 °C. On the other hand, the results of Briody et al. [17] highlighted significant increases in creep rate as a function of temperature, with increasing temperatures causing the acceleration of the foam's creep (the authors investigated a foam with a density of 85 kg/m^3).

Rigid open cell polymer foams were studied by Huang and Gibson [13], who adapted Findley's power law formulation [14] to model the creep of such foams. This adaptation was made considering the creep of the solid polymer used in the foaming process and the ratio between the elasticity moduli of the produced foam and that of the source solid polymer, according to the micromechanics model of Gibson and Ashby [18]. To experimentally validate the model, the authors carried out shear creep tests on PUR foams with densities ranging between 32 kg/m^3 and 96 kg/m^3 and shear stresses between 10% and 40% of the foam's yield stress, for durations of 1200 h. The authors found that the PUR foam was linear viscoelastic for stress levels lower than half of its yield strength, and that creep response was higher in lower density foams. However, the influence of temperature on the foams' creep response was not considered.

Davies and Craveur [19] performed shear creep tests on closed cell poly(vinyl chloride) (PVC) foams, for shear stresses ranging from 0.24 MPa to 0.56 MPa (approximately 50% of the foam's shear strength at the highest stress level) and temperatures of 20 °C and 50 °C. Test durations ranged from ~2000 h to ~10,000 h. Acceleration of the creep response of such foams was found to occur with increasing temperature and/or stress level. However, the authors did not provide a quantified description of the influence of these factors on the viscoelastic response.

Andrews et al. [20] proposed expressions for the prediction of the steady-state creep rate of cellular solids when subjected to high temperatures, following the general approach of Gibson and Ashby [18], extending it to time-dependent deformations and incorporating an Arrhenius law dependency of temperature. The authors carried out a set of compression creep experiments on an open-cell aluminium foam, for temperatures between 275 and 350 °C and stress levels between 14% and 49% of the foam's yield stress (test durations ranged from 0.03 h to 80 h). They found out that the proposed steady-state creep model provided good predictions of the experimental results for such a metallic foam.

As several previous studies have shown [12–14], the creep response of rigid PUR foams in the linear viscoelastic range is very well explained by a power law dependency of time. Power law (of time) creep developments contrast with steady-state approaches by not considering a constant creep rate at any point in time, but rather an exponentially decreasing one. Owing to its successful application in polymers, and polymer foams in particular, Findley's power law formulation [14] was used in the present study. This formulation was extended to include an Arrhenius law temperature dependence, as detailed in the following section.

3. Theoretical formulation

3.1. Findley's power law

Eq. (1a) describes the basic expression for Findley's power law formulation [14], adapted for shear strains and stresses, where γ is the total shear strain, τ is the applied shear stress, t is the time elapsed after load application, t_0 is the time unit considered (to normalise the time parameter, thus guaranteeing the dimensional consistency of the equation), m is the creep amplitude, and n is the time exponent. This equation separates the time-dependent shear strain in two components: (i) the elastic strain (γ_0) and (ii) the viscoelastic strain (mt^n). These two components are considered to follow a hyperbolic sine dependency of the applied shear stress, as per Eq. (1b). In this equation, γ'_e is the reference instantaneous shear strain, τ_e is reference stress level associated with γ'_e, m' is the reference creep amplitude and τ_m is the reference stress level associated with m'.

$$\gamma(\tau,t) = \gamma_0 + m\left(\frac{t}{t_0}\right)^n \tag{1a}$$

$$\gamma(\tau,t) = \gamma'_e \sin\mathrm{h}\left(\frac{\tau}{\tau_e}\right) + m' \sin\mathrm{h}\left(\frac{\tau}{\tau_m}\right)\left(\frac{t}{t_0}\right)^n \tag{1b}$$

The creep amplitude (m) is typically proportional to stress, while the time exponent (n) is stress-independent and may be taken as a material constant for a given hygrothermal condition