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MEASUREMENT OF CREEP IN THE DYNAMIC STIFFNESS OF RESILIENT MATERIALS

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Abstract

ISO 9052-1, currently under revision, defines the test method for determining the dynamic stiffness of resilient materials used under floating floors, a key parameter for assessing acoustic performance. However, it does not account for the evolution of this property over time. Material ageing leads to a gradual increase in dynamic stiffness, resulting in a decrease in impact sound insulation, which may reach 1 dB after one year and up to 4 dB after ten years.

In this context, the present study investigates a method for evaluating the long-term creep of dynamic stiffness, based on an adaptation of EN ISO 16534, originally developed for compressive creep. To this end, a long-term experimental campaign, initiated in March 2021, monitored the evolution of dynamic stiffness for several floating screed underlays over a five-year period. The results are analysed to assess the relevance of this methodology for characterising and extrapolating the creep behaviour of dynamic stiffness.

Keywords: *dynamic stiffness, creep, resilient material*

1. Introduction

The acoustic performance of floating floors depends strongly on the dynamic stiffness of the resilient underlay. Under a permanent load, the mechanical properties of the underlays change gradually due to phenomena such as settlement, compaction, viscoelastic relaxation or material ageing. This change leads to a gradual increase in dynamic stiffness, which results in an increase in the resonance frequency of the mass-spring system comprising the finishing screed and the acoustic underlay. It is important to take dynamic stiffness creep into account because it enables the changes in the acoustic performance (ΔL_w) of a floating floor to be assessed over its service life. In fact, several studies have been carried out on this subject [1, 2, 3].

The aim of this study is therefore to propose an experimental method for assessing the creep of the apparent dynamic stiffness of samples of resilient underlays intended for floating floors. The method, inspired by EN ISO 16534 [4], is based on monitoring the resonance frequency—measured in accordance with ISO 9052-1 [5]—over a short period, followed by the fitting of a mathematical model to extrapolate the observed behaviour over several years.

The validity of this approach is assessed on the basis of a long-term experimental programme involving eight acoustic underlays representative of different families of materials.

2. Methodology for Estimating the Long-Term Creep of the Apparent Dynamic Stiffness

The long-term creep of the apparent dynamic stiffness, $s'_t(t)$, is determined by monitoring the resonance frequency, $f_0(t)$, of the mass–spring system formed by an 8 kg steel loading plate placed on the resilient specimen, in accordance with ISO 9052-1. The apparent dynamic stiffness is calculated from the measured resonance frequency using Eq. (1).

$$s'_t(t) = 4\pi^2 f_0^2(t) m' \text{ [N/m}^3\text{]} \tag{1}$$

where,

m' is the surface mass of the steel loading plate [kg/m²];

f₀(t) is the resonance frequency of the mass–spring system as a function of time [Hz].

More specifically, creep is assessed from the increase in resonance frequency, $\Delta f_{0,t}$, relative to the initial value measured two hours after loading (Fig. 1).

While Annex A of ISO 16534 describes the compressive creep of thermal insulation materials using a power-law function, the evolution of the resonance frequency over

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time follows a logarithmic relationship of the form:

$$\Delta f_{0,t} = a\ ln(t) + b \tag{2}$$

where a and b are material-specific constants obtained by fitting the first 50 days of experimental data.

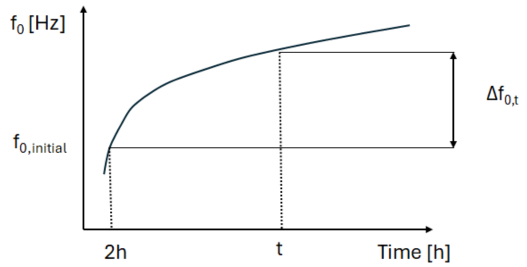


Figure 1. Plot showing the change in resonance frequency over time, $f_{0,t}$, and the increase in resonance frequency, $\Delta f_{0,t}$

This formulation reflects a physically consistent behaviour, characterized by a rapid increase in the resonance frequency immediately after the load is applied, followed by a gradual decrease in the rate of stiffening over time.

Eq. (2) can be linearised by setting x = ln(t), thereby reducing the problem to a standard linear regression. Once the constants are determined, the resonance frequency—and consequently the apparent dynamic stiffness—can be extrapolated for up to 30 times the test duration, provided the fit has a correlation coefficient $r^2 > 0.9$ as specified in the standard.

3. Experimental validation

3.1 The test campaign

Validation involves verifying that the extrapolation obtained from the first 50 days of measurement accurately reproduces the actual behaviour observed over the long term. This study therefore directly compares the extrapolated values with the experimental measurements taken over a five-year period on eight materials (Table 1).

The resonance frequency was measured periodically using an impact hammer in accordance with ISO 9052-1 [5]. The value shown in the graph corresponds to the average of six measurements, without extrapolation to 0 N, while the associated standard deviation is represented by the error bars.

It was decided not to apply a plaster layer to the specimen in order to capture the very early stages of creep.

The samples were stored in a room where the temperature remained relatively stable throughout the test period. However, relative humidity and atmospheric pressure were not recorded continuously. This lack of monitoring constitutes a limitation of the study, as some of the variations observed may be attributable to these environmental conditions.

3.2 Statistical validation of the model

The validation of the extrapolation model is based on two complementary criteria.

The first involves verifying that measurements taken several years after loading remain within the 95 per cent prediction interval calculated from the logarithmic regression performed solely on data acquired during the first fifty days.

The prediction standard deviation for a linear regression is calculated using the following formula:

$$s_{pred} = s\sqrt{1 + \frac{1}{n} + \frac{\left(\ln(t_0) - \overline{\ln(t)}\right)^2}{\sum\left(\ln(t_i) - \overline{\ln(t)}\right)^2}} \tag{3}$$

where:

s is the residual standard deviation of the regression;

n is the number of measurements (over the 50 days);

t_i are the measurement times.

The 95% prediction interval is therefore:

$$\hat{f}(t_0) \pm t_{n-2,\,0.975}\, s_{\text{pred}} \tag{4}$$

where $t_{n-2,\,0.975}$is the 97.5th percentile of the Student's t-distribution with $n-2$degrees of freedom.

The prediction intervals are shown in the figures as dotted lines in order to directly visualise the consistency between the long-term measurements and the extrapolated values.

The second criterion is based on the analysis of the normalised residuals from the last 9 measurements:

$$z_j = \frac{f_j - \hat{f}_j}{\sigma_{\text{pred,j}}} \tag{5}$$

where:

f_j is the measured value;

$\hat{f}_j$ is the predicted value;

$\sigma_{pred,j}$ is the corresponding prediction uncertainty.

When the model is statistically valid, the normalised residuals should have a mean close to zero; a standard deviation close to one; and approximately 95 per cent of the values falling within the interval [-2; +2].

3.3 Proposed creep indicators

In addition to validating the model, several indicators have been defined to facilitate the interpretation of the results and to highlight the practical consequences of dynamic stiffness creep.

The first indicator (D1) corresponds to the predicted increase in the resonance frequency after twenty-eight days of loading compared with the initial frequency. This increase is expressed both in Hertz and as a percentage of the initial frequency.

The second indicator (D2) represents the predicted increase in the resonance frequency after five years of loading.

Based on these frequencies, indicators (D3) and (D4) reflect the increase in apparent dynamic stiffness after twenty-eight days and after five years, respectively.

The 28-day creep is particularly relevant when comparing ΔL_w values measured in the laboratory,

after the minimum three-week screed curing period, with those predicted according to EN ISO 12354-2.
The creep behaviour after 5 years is of particular interest to manufacturers wishing to characterise the mechanical ageing of their products.
The indicator (D5) estimates the potential loss of acoustic performance of the floating floor. This value is obtained by calculating the difference between the predicted impact sound improvement indices ΔL_w after twenty-eight days and after five years, using the calculation model set out in EN ISO 12354-2 [6]. This indicator is particularly useful for specifiers. However, this estimate is based on the apparent dynamic stiffness (s'_t) of the test specimen rather than the product's dynamic stiffness (s'). Therefore, ΔL_w values should be interpreted with caution, while differences in predicted performance over time provide a more reliable indication of the expected evolution of acoustic performance.
Finally, a further indicator (D6) corresponds to the time required for the instantaneous rate of increase in the resonance frequency to fall below 1 per cent per hour. This parameter provides useful information for any revision of the standardised procedure for measuring dynamic stiffness, as it enables a justified and objective period to be identified before proceeding with the tests.

3.4 Results

To ensure a concise presentation, the graphical results are shown only for three representative samples. For each sample, two graphs are provided: the first illustrates the fit of the logarithmic model to the measurements of the increase in resonance frequency taken during the first fifty-three days of loading, while the second graph shows the extrapolation of this regression to five years of loading. The extrapolated values of this increase are added to the initial value, $f_{initial,2h}$, and subsequently compared with the experimental values of the resonance frequency, $f_0(t)$, obtained over the same period. The 95% prediction intervals are also shown in order to assess the validity of the extrapolation. The values of the six performance indicators are summarized in Table 1 for all eight samples analyzed. The samples are ranked in ascending order of the floating screed's performance loss.

3.4.1 Cross-linked polyolefin foam with a corrugated surface

This sample of closed-cell, cross-linked polyolefin foam with a corrugated surface is between 4 and 5 mm thick and has a density of 28 kg/m³ (Sample 4 in Table 1). The initial resonance frequency measured is 93.9 Hz, corresponding to an apparent dynamic stiffness of 69.7 MN/m³.
The coefficient of determination obtained from the regression is close to 0.90, which also allows for extrapolation over several years (Fig 2).
If we look at the 5-year extrapolation curve, at certain points in time, significant discrepancies are observed between the measured and predicted data (Fig 3). Three of the last nine measurements fall within the prediction interval (Fig 3).
The normalised residuals have a mean of -1.39; a standard deviation of 0.88; and approximately 67 per cent of the values falling within the interval [-2; +2].

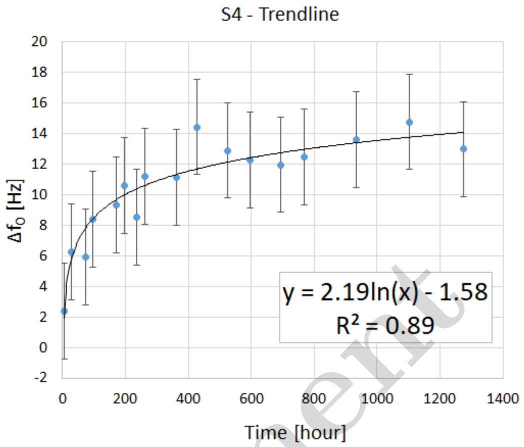


Figure 2. Logarithmic function fitted to the first 53 days of creep measurement data for the polyethylene sample with corrugated surface. Measurements (blue dots), trendline (black line)

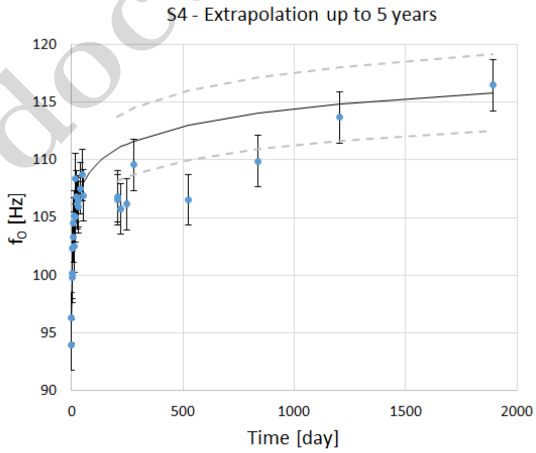


Figure 3. Extrapolated resonance frequency creep over 5 years for the polyethylene sample with corrugated surface, compared with long-term measurements. Measurements (blue dots), extrapolation (black line), and 95% prediction interval (grey dotted lines).

In his study, Caniato [3] demonstrated that increases in dynamic stiffness may result from complex material-dependent mechanisms, such as binder effects, phase separation, or microstructural changes. However, these mechanisms are unlikely to account for the variations observed in the present study.
Indeed, the analysis of the temporal evolution of all the tested materials reveals that these variations occur synchronously. A comparison of Figures 3, 5 and 7 shows a pronounced decrease in the resonance frequency between days 205 and 248, followed by a brief recovery and then a second decrease between days 524 and 837, before the resonance frequency increases again. Although the magnitude of these fluctuations

depends on the material, their timing is consistent across all the tested samples. This common behavior suggests that the observed variations are more likely driven by an external environmental factor than by intrinsic material mechanisms. Possible contributing factors include changes in ambient humidity and/or atmospheric pressure.

The model predicts an increase in the resonance frequency of 13.6 per cent after twenty-eight days and 23.3 per cent after five years. The estimated loss in acoustic performance is in the region of 1.0 dB.

3.4.2 Closed-cell extruded polyethylene foam

This sample of closed-cell extruded polyethylene foam (Sample 5 in Table 1) is 6 mm thick and has a density of 32 kg/m³. The initial resonance frequency measured two hours after loading is 55.5 Hz, corresponding to an initial apparent dynamic stiffness of 24.3 MN/m³.

The regression analysis based on measurements taken during the first fifty-three days shows a coefficient of determination greater than 0.90 (Fig. 4). This value meets the criterion set for allowing extrapolation to just over four years.

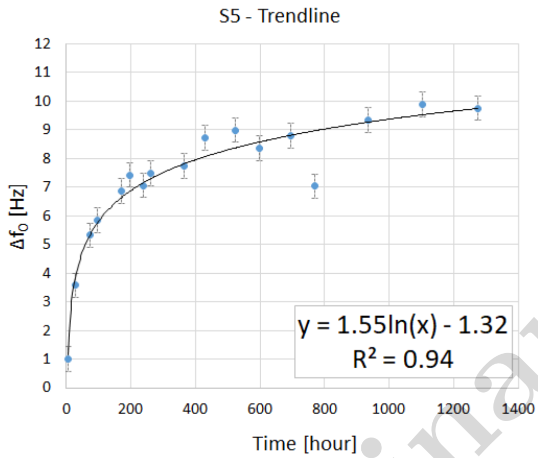


Figure 4. Logarithmic function fitted to the first 53 days of creep measurement data for the extruded polyethylene sample. Measurements (blue dots), trendline (black line)

The sample was kept under load for more than five years in order to experimentally verify the validity of the long-term extrapolation (Fig. 5).

The last nine measurements all fall within the 95 per cent prediction interval. The normalised residuals are correctly centred around zero and exhibit a dispersion consistent with the model's assumptions. These results confirm the excellent predictive ability of the logarithmic model for this sample.

The resonance frequency increases by 15.9 per cent after twenty-eight days of loading compared with the initial value. After five years, this increase reaches 27.6 per cent. This change corresponds to an estimated reduction in impact sound insulation of approximately 1.2 dB.

3.4.3 Rubber-based underlay

Sample 8 is a 5 mm thick rubber underlay with a density of 507 kg/m³. Its initial resonance frequency measured is 70.2 Hz, corresponding to an apparent dynamic stiffness of 38.9 MN/m³.

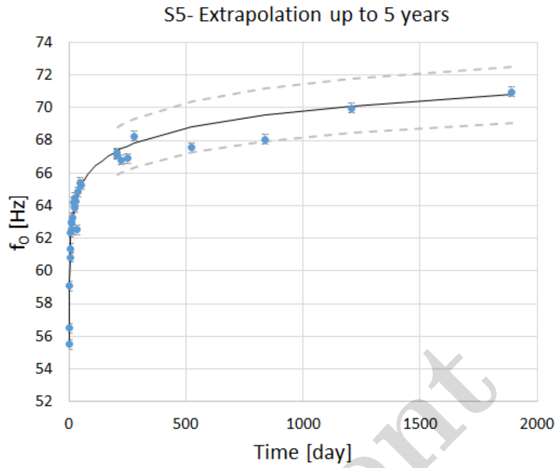


Figure 5. Extrapolated resonance frequency creep over 5 years for the extruded polyethylene sample, compared with long-term measurements. Measurements (blue dots), extrapolation (black line), and 95% prediction interval (grey dotted lines).

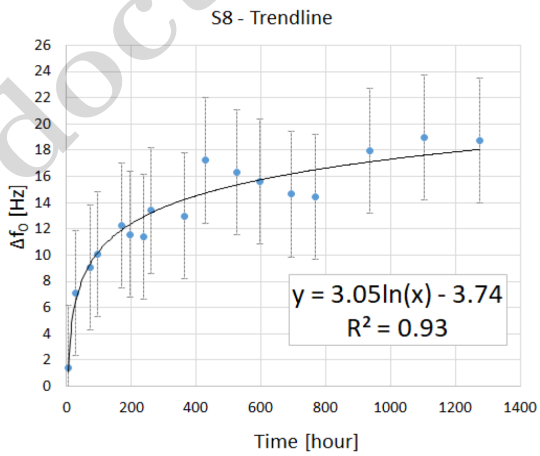


Figure 6. Logarithmic function fitted to the first 53 days of creep measurement data for the rubber sample. Measurements (blue dots), trendline (black line)

The logarithmic fit also yields a coefficient of determination greater than 0.90 (Fig. 6). However, unlike the previous material, experimental validation reveals a much greater variation in the long-term measurements. Only one of the last nine measurements falls within the prediction interval (Fig. 7). Although the standardised residuals remain broadly centred around zero, their dispersion is significantly greater than expected and could be explained by changing environmental conditions. Consequently, the statistical criteria used to validate the extrapolation are not fully met.

As a guide, the model predicts an increase in the resonance frequency of 23.1 per cent after twenty-eight days and 41.2 per cent after five years. The associated loss of acoustic improvement is estimated at approximately 1.7 dB. However, given the discrepanies observed between the predictions and the experimental measurements, these values should be interpreted with caution.

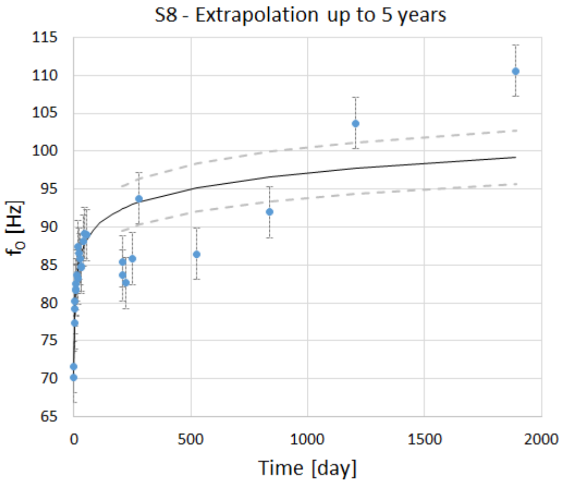


Figure 7. Extrapolated resonance frequency creep over 5 years for the rubber sample, compared with long-term measurements. Measurements (blue dots), extrapolation (black line), and 95% prediction interval (grey dotted lines).

3.4.4 Summary for other resilient underlay

Table 1 summarises the results of the 5-year extrapolation for the eight products tested. Please note that the trendline for three of these products (recycled PU foam, mineral wool and textile fibre) has a low correlation coefficient. The creep indicators should therefore be interpreted with caution.

4. Discussion

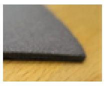
4.1 Creep of a product (rather than a specimen)

Initially, the validity of extrapolating creep over a five-year period was demonstrated on the basis of measurements carried out on a single sample. The next question is how to estimate the creep of the resonance frequency of a product, or a batch of products, over this period. To obtain a representative estimate, the trend curve must be plotted using creep measurements taken from at least three samples representative of the product or batch. When the standard deviation between the samples, $stdev_{sample}$, is of the same order of magnitude as the measurement uncertainty, $stdev_{measure}$, the average of the three sets of measurements may be used to determine a representative trendline (Fig. 8). However, when the variability between samples significantly exceeds the measurement uncertainty the samples must be regarded as exhibiting distinct creep behaviours. In this case, a single trend curve is no longer representative, and a specific trend curve must be determined for each of the samples (Fig. 9).

4.2 Cases requiring a layer of plaster

Where ISO 9052-1 requires the application of a layer of plaster, the initial resonance frequency ($f_{0,initial}$) may be measured after 24 hours rather than after 2 hours. However, for this test campaign, the trend curves derived from an initial frequency measured at 24 hours show a slightly poorer agreement between the experimental measurements and the five-year predictions than those obtained using an initial frequency measured after two hours.

Table 1. Creep indicators for eight samples

				
	S1	**S2**	**S3**	**S4**
Material	Recycled PU foam	Mineral wool	Textile fibre	PE with corrugated surface
e [mm]	10	20	12	4-5
ρ [kg/m^3]	90	99	134	28
$f_{initial,2h}$ [Hz]	35.9	24.4	44	93.9
R^2 trendline	0.8	0.3	0.6	0.89
D1 [Hz]	1.9 (5.2%)	2.2 (9.0%)	4.6 (10.4%)	12.7 (13.6%)
D2 [Hz]	3.5 (9.7%)	3.7 (15.1%)	7.6 (17.3%)	21.8 (23.3%)
D3 [MN/m^3]	1.1 (10.6%)	0.9 (8.7%)	3.4 (21.9%)	20.2 (28.9%)
D4 [MN/m^3]	2.1 (20.4%)	1.5 (32.6%)	5.8 (37.7%)	36.2 (52%)
D5 [dB]	0.5	0.7	0.8	1
D6 [h:min]	1h15m	1h30	1h45m	2h50m

(continued)

				
	S5	**S6**	**S7**	**S8**
Material	Extruded PE	PE + polyester felt	PE	Rubber
e [mm]	6	9	5	5
ρ [kg/m^3]	33	46	20	507
$f_{initial,2h}$ [Hz]	55.5	35.1	101.7	70.2
R^2 trendline	0.94	0.9	0.91	0.93
D1 [Hz]	8.8 (15.9%)	4.0 (11.5%)	22.9 (22.5%)	16.2 (23.1%)
D2 [Hz]	15.3 (27.6%)	8.4 (23.9%)	38.3 (37.6%)	28.9 (41.2%)
D3 [MN/m^3]	8.4 (34.3%)	2.4 (24.2%)	38.8 (46.2%)	20.0 (51.5%)
D4 [MN/m^3]	15.3 (62.7%)	5.2 (53.4%)	70.9 (84.6%)	38.7 (99.4%)
D5 [dB]	1.2	1.3	1.4	1.7
D6 [h:min]	3h	3h20	4h10m	4h40m

4.3 Effect of the applied load

The creep rate naturally depends on the load applied to the product. For example, long-term tests were carried out on a recycled polyurethane foam product (S1) subjected to two load levels: 8 kg and 16 kg. After five years, the apparent dynamic stiffness of the product loaded with 16 kg increased by 44.9 per cent, compared with 20.4 per cent for the one loaded with 8 kg. This increase in stiffness results in a reduction in impact noise reduction of 1 dB for the product under the higher load, compared with 0.5 dB for the one under the lower load. Furthermore, the time required for the rate of increase in the resonance frequency to fall below 1 per cent per hour is also longer when the applied load is higher.

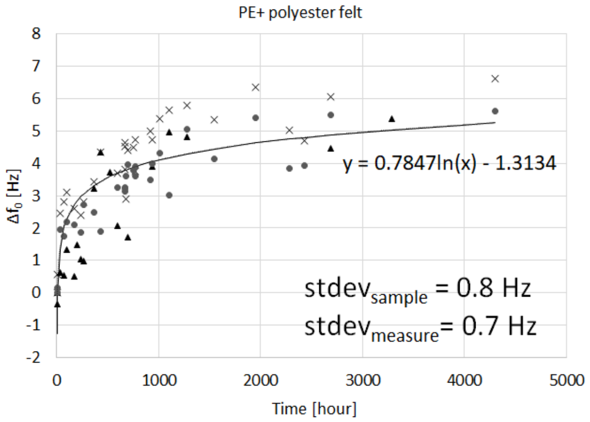


Figure 8. Logarithmic function fitted to the mean of the three sets of measurements

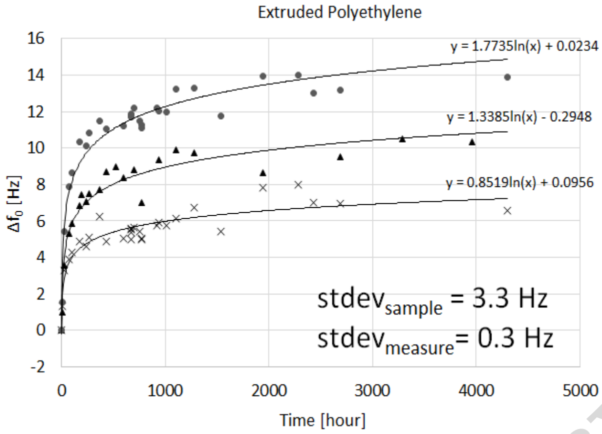


Figure 9. A logarithmic function specifically fitted to each sample

4.4 Effect of air flow resistance

The creep tests were carried out on 20 × 20 cm samples. Under these conditions, the measurements do not take into account the effect of air that may become trapped within the product in real-world conditions.

In practice, the product is generally applied over a large area and covered with a floating floor. Air escape is then limited and depends in particular on the material's resistance to air flow (or porosity). This phenomenon can alter the product's deformation and therefore its creep behavior.

4.5 Rate of creep

ISO 9052-1 is currently under revision. Although the standard specifies the test method for determining the dynamic stiffness of resilient underlays used under floating screeds, it does not define the loading duration before measurement. Since these materials exhibit time-dependent creep, specifying a standardized loading duration would improve the reproducibility and comparability of test results.

The D6 indicator could provide a basis for defining this duration, either by specifying a common loading time for all products that ensures a creep rate below 1% per hour, or by defining a product-specific loading time corresponding to the point at which the creep rate falls below this threshold.

5. Conclusion

This study proposes an experimental method to estimate the long-term creep of the apparent dynamic stiffness of resilient underlays for floating floors. The method monitors the resonance frequency of a mass–spring system for about fifty days (ISO 9052-1) and applies a logarithmic model to predict behaviour over several years. The approach was validated using eight acoustic underlays monitored for more than five years. Although the measurements were affected by uncontrolled environmental factors, the model accurately reproduced the long-term behaviour of most materials when the logarithmic fit was satisfactory. Statistical criteria were used to assess the reliability of the extrapolation, which generally slightly underestimated the actual creep. Finally, creep indicators are proposed to quantify changes in resonance frequency, apparent dynamic stiffness, and floating-floor acoustic performance.

6. Acknowledgments

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