Dependence of Properties of Expandable Polystyrene Particle Foam on Degree of Fusion

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ABSTRACT: Expandable polystyrene (EPS) particle foams were prepared in three major steps to investigate their mechanical, thermal, and fire behavior on their degree of fusion. Bending strength was found to increase progressively, whereas compressive stress was found to increase linearly with the degree of fusion of EPS particle foams. Although at low degree of fusion the flame heights, B2 was found to decrease, it remained constant at high degree of fusion. Optical microscopic method appeared to be more reliable than pneumatic method in the determination of degree of fusion over the whole range of EPS particle foams investigated.
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Key words: expandable polystyrene; foams; morphology; mechanical properties; thermal properties; fire behavior; degree of fusion

INTRODUCTION

Expandable polystyrene (EPS) is a suitable material for the production of particle foams by foam molding allowing the replica of very complicated shapes and structures. Such parts are useful, for example, as packaging materials protecting the packaged goods in storage locations and during transportation against mechanical or thermal damage. However, most of the EPS particle foam is used in the building and construction industry for the thermal insulation of walls, roofs, and ceilings as well as in impact sound insulation of buildings. Known over the past more than 50 years, EPS foams are the most widely used insulation material in the market after glass wools.[1,2]

In general, EPS particle foams are prepared in three major steps. The first step includes the prefoaming of the EPS raw material beads, the second step consists of a temporary storaging of the pre-expanded beads, and the third step involves the final foaming by a molding or block foaming process.[3] The final foaming process is one of the most important factors affecting the parameters and the application properties of the final EPS foam. In addition to technically adjustable machine parameters selected by EPS foam manufacturers,[4] the fusion of the pre-expanded EPS beads to a homogeneous foam plays a physical key role in the determination of the final foam properties.

In the case of EPS foam parts received by a molding process, first investigations on the effect of the fusion behavior on mechanical properties of the EPS foam have been performed.[5] The fusion behavior can be estimated by determining the degree of fusion, a quantity characterizing the autoadhesion (adhesion of the surfaces of different foamed EPS bead particles) and autofusion (partial fusion of the surfaces of different foamed EPS bead particles) of the initially discrete prefoamed bead particles within the EPS foam. It determines the perfection of the three-dimensional structure of the final EPS particle foam. Whereas the compressive stress was found to be almost independent of the degree of fusion of the expanded EPS beads in the mold, bending strength, and tensile strength are significantly increasing with an improved fusion of the foam.[5] The determination of the degree of fusion by a pneumatic method was found to display a high sensitivity and to be advantageous in comparison with a visual classification.[5]

However, these first investigations on the effect of the fusion behavior on mechanical properties of the EPS foam were solely performed on mold parts, usually showing inhomogeneities in the foam density because of the edges and complicated shapes and structures in the mold. Furthermore, they were only applied to a relatively narrow range of variation of the degree of fusion. Therefore, extended investigations on the dependence of mechanical properties on the degree of fusion were performed over a much broader range of particle fusion using homogeneous EPS foams prepared by a block

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foaming process of exactly the same EPS raw material. In addition, these measurements were expanded to other foam properties, such as, fire behavior and thermal conductivity, both essential properties of EPS foams for applications in the building and construction section. The applicability of the pneumatic method for the determination of the degree of fusion was also examined at first. However, because the results with this method were inadequate, a comprehensive investigation of the determination of the degree of fusion by optical microscopy was performed, allowing a successful application of this method and a discussion of the dependences of the foam properties over the whole range of the degrees of fusion investigated.

EXPERIMENTAL

Materials

The EPS raw material used for the preparation of the blocks of the EPS particle foam of fine-cell structure was Sconapor F 238 with a narrow EPS particle size from 1.0 to 1.4 mm (Dow Olefinverbund GmbH, Schkopau).

Preparation of EPS foam and test specimens

In a first step, the prefoaming of the EPS raw material beads was performed in a discontinuous pressurized prefoamer at a steam pressure of 0.12 bar and at a steam treatment time of 40 s resulting in a bulk density of about 14 kg/m^3. The temporary storaging of the pre-expanded beads as the second step carried out in hot air at 70°C for 21 h. The third step of final foaming by a block foaming process was realized in a small block mold of the size 500 mm × 250 mm × 250 mm by adjusting the steam pressure to values of 0.15, 0.25, 0.35, 0.45, 0.55, 0.65, and 0.75 bar.

The test specimens were prepared after a storage time of the blocks of 24 h in hot air at 70°C by cutting of the foam block in a cutting equipment with glowing wires into small specimens according to the dimensions required by the standards (EN 12667, EN 13163). Subsequently, the test specimens were stored for an additional time of 3 days in hot air at 70°C to exclude a possible effect of remaining pentane on the foam properties.

Measurements

The degree of fusion by a pneumatic method was determined as pressure drop of a gas jet upon passage through a needle into the EPS particle foam (degree of fusion: 100% at a closed needle, 0% at a totally open needle). The detailed equipment and procedures are described in Ref. 5. The determination of the degree of fusion by optical microscopy was performed with a Quantimet 550W equipment after cutting the foam samples to slices of 750 μm thickness by a rotating blade, resulting in a degree of fusion as the area percentage of the area of the foamed EPS beads in the foam and the whole area of the foam sample (including voids). Each degree of fusion determined is the average of photomicrographs (each of an area of the foam of 5.5 cm × 4.0 cm) of 10 different cross-sections taken from one specimen.

The compressive stress at 10% deformation and the bending strength were tested according to the European Standard EN 13163, the fire behavior was investigated using the fire test B2 of EN 13163, and the measurements of the thermal conductivity were performed according to European Standards EN 13163 and EN 12667.

RESULTS AND DISCUSSION

At first, a suitable method for the determination of the degree of fusion, characterizing the extent of the fusion of the outer particle walls of the prefoamed EPS beads by melt adhesion and the formation of interparticle space, for example, in the unfused corner gaps, to a more or less extent, was examined. Then, selected mechanical and thermal properties of the EPS foams as well as their fire behaviors were investigated in dependence on the degree of fusion.

Determination of the degree of fusion

The adjustment of the steam pressure in the final block foaming process to different values from 0.15 to 0.75 bar allowed the preparation of EPS foam blocks of different degrees of fusion in a broad range. In difference to Ref. 5 using test specimens of high foam densities of 21 and 30 g/L, a lower density of 15 g/L of the EPS foam was selected to achieve the broadest practicable variation in the degree of fusion.

At first, the determination of the degree of fusion by the pneumatic method has been investigated. The dependence of the degree of fusion of the EPS foam on the steam pressure is shown in Figure 1. The degree of fusion rapidly drops with decreasing steam pressure reaching a constant value below a pressure of about 0.6 bar. Because additional changes of the mechanical properties can be observed in dependence of the steam pressure also below a pressure of 0.6 bar, structural alterations within the particle foam based on the fusion of the prefoamed EPS beads are not detectable by this

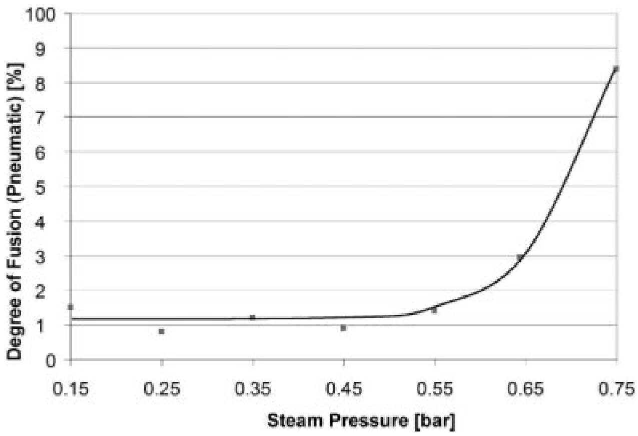

Figure 1 Dependence of the degree of fusion of EPS foam on steam pressure determined by the pneumatic method of the final block foaming process.

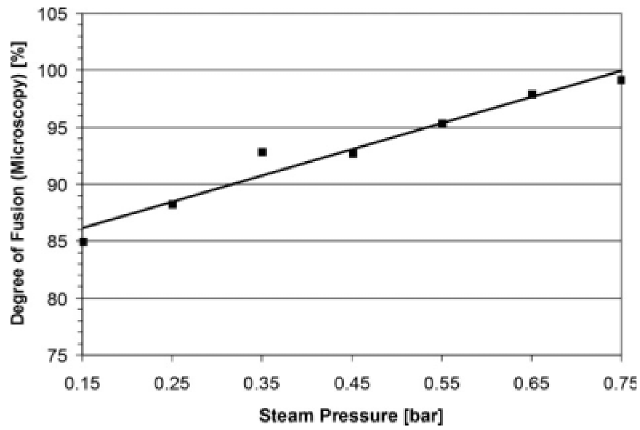

Figure 2 Dependence of the degree of fusion of EPS foam on steam pressure determined by optical microscopy of the final block foaming process.

method. Obviously, the pneumatic method for the detection of the degree of fusion of the EPS particle foam fails at a steam pressure below about 0.6 bar. A reason for this behavior might be the volume of the voids between the fused prefoamed EPS beads, reaching an extent so that the gas flow upon passage through the EPS foam does not experience a remarkable flow resistance, furthermore, and a significant difference in the pressure drop cannot be achieved as a result. Therefore, the pneumatic method is not suitable to reflect the degree of fusion over the whole range of the EPS foam samples prepared.

The results of the measurements of the degree of fusion by optical microscopy on foam samples stored at the same conditions in dependence on the steam pressure are shown in Figure 2 verifying a linear correlation between degree of fusion and steam pressure. This correlation can be given as

$$DF_M = 22.975 \times p_s + 82.711 \; (R^2 = 0.9559) \qquad (1)$$

with DF_M-degree of fusion by optical microscopy (%), p_s-steam pressure (bar), and R^2-correlation coefficient.

For comparison, some selected optical photomicrographs of the EPS foams received at steam pressures of 0.15, 0.45, and 0.75 bar are given in Figure 3 visually demonstrating the decrease in the gap volumes between the foamed EPS beads and the increase in the degree of fusion of the EPS particle foam. Therefore, the determination of the degree of fusion of the foam by optical microscopy is a reliable method over the whole range of the steam pressures adjusted in the final block foaming process, in contrast to the pneumatic method used.

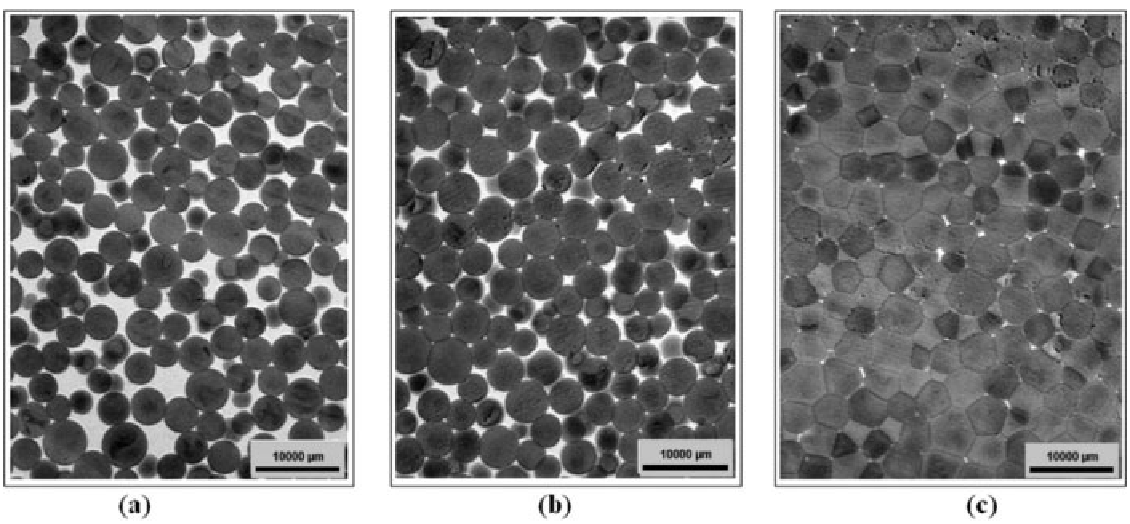

Figure 3 Optical photomicrographs of EPS foams received at steam pressures of 0.15 (a), 0.45 (b), and 0.75 bar (c) in the final block foaming process.

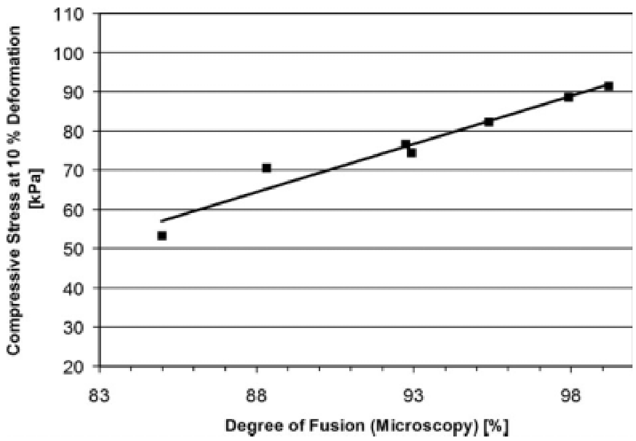

Figure 4 Dependence of compressive stress at 10% deformation on the degree of fusion determined by optical microscopy.

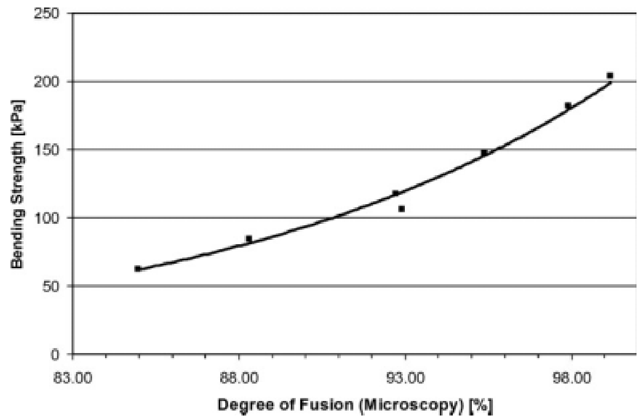

Figure 5 Dependence of bending strength on the degree of fusion determined by optical microscopy.

Mechanical properties

The dependence of the compressive stress at 10% deformation on the degree of fusion by optical microscopy is shown in Figure 4. The compressive stress increases linearly with an increase of the degree of fusion according to the following correlation

$$\sigma_{10} = 2.4487 \times \mathrm{DF}_M - 150.95 \; (R^2 = 0.9507) \quad (2)$$

with σ_{10}: compressive stress at 10% deformation (kPa).

In difference to Ref. 5 showing no correlation between compressive stress and degree of fusion by the pneumatic method, the investigations at an extended range of the degree of fusion allow to detect a correlation between both parameters as well. The decrease in compressive stress with lower degree of fusion can be explained by a higher compressibility of the foam, based on a relieved dislocation of the foamed EPS beads into the gap volumes between the foam beads, at lower degrees of fusion.

The correlation between bending strength and degree of fusion by optical microscopy is given in Figure 5. It can be seen that the bending strength does not increase linearly with the degree of fusion, however, increases slightly progressively according to the following equation

$$\sigma_b = 0.0577 \times \exp(0.0821 \times \mathrm{DF}_M) \; (R^2 = 0.9860) \quad (3)$$

with σ_b: bending strength (kPa).

Therefore, the linear or polynomic correlation between bending strength and degree of fusion observed in Ref. 5 might only be an approximation within a narrow range of the degrees of fusion.

In comparison with the dependence of the compressive stress at 10% deformation on the degree of fusion, the bending strength is much more affected by the degree of fusion than the compressive stress. This behavior is due to the function of the gap volumes as defect sites during the fracture process within the homogeneous foam, which can also be observed easily during the manual deformation of a piece of EPS particle foam with a high content of gap volumes. Especially under high load at a high strength, small defects in the foam structure immediately result in the fracture process, favored at higher degrees of fusion and leading to a progressive dependence of the bending strength on the degree of fusion.

Thus, the correlations given also allow a quantitative description and prediction of the dependences of the foam properties on the degree of fusion of the EPS foams.

Thermal properties and fire behavior

One of the most important thermal properties of EPS particle foam is the thermal conductivity. To

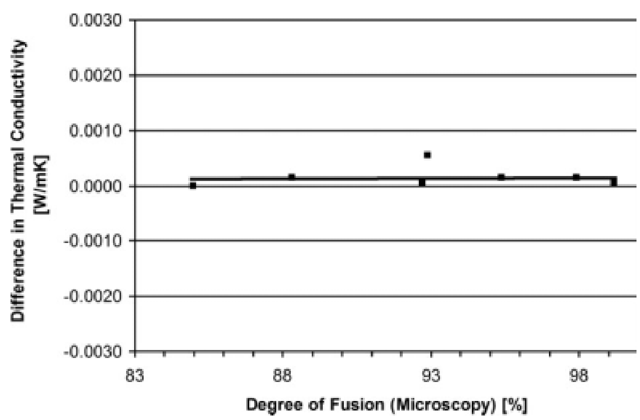

Figure 6 Dependence of the thermal conductivity (difference of the thermal conductivity according to the standard equation of EN 13163 and the observed value at exactly the same foam density) on degree of fusion determined by optical microscopy.

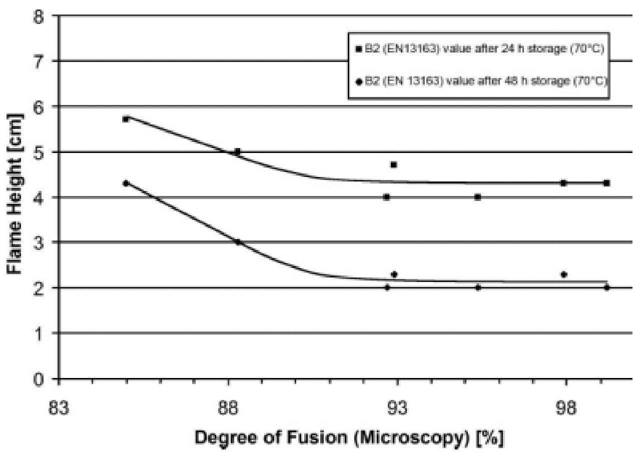

Figure 7 Dependence of fire behavior (investigated using the fire test B2 of EN 13163) on the degree of fusion determined by optical microscopy.

demonstrate a change in the thermal conductivity by the degree of fusion by optical microscopy, the differences of the thermal conductivity according to the standard equation of EN 13163 and the observed value at exactly the same foam density were plotted in Figure 6 in dependence on the degree of fusion. Despite the differences are positive in general indicating a lower thermal conductivity of the test specimens in comparison with the standard values, there is no correlation between thermal conductivity and degree of fusion over the whole broad range of this parameter investigated. Obviously, there is no negative effect of the gap volumes on the overall thermal conductivity of the whole EPS foam sample.

The fire behavior investigated using the fire test B2 in dependence on the degree of fusion by optical microscopy is summarized in Figure 7, at storage times of the foam samples of 24 and 48 h. At both storage times, the flame heights of the foam samples decrease with an increase of the degree of fusion. However, from values of about 91% to higher degrees of fusion, the flame heights remain constant at low values. In the case of low degrees of fusion, this behavior is due to the gap volumes filled with air and thus feeding oxygen to the burning flame resulting in a more intensively burning foam sample. At high degrees of fusion, the remaining gaps are very small and their effect on the burning behavior of the foam can be neglected.

In general, the flame heights at a storage time of 24 h are higher than those at a storage time of 48 h because of the higher residual content of pentane as the blowing agent remaining in the foam at a lower storage time.

CONCLUSIONS

This study has shown that in investigations of the dependence of mechanical and thermal properties as well as of fire behavior of EPS particle foams on the degree of fusion, as a quantity characterizing the perfection of the three-dimensional structure of the final EPS particle foam, the experimental determination of the degree of fusion has a significant importance. Although the pneumatic method in the detection of the degree of fusion failed at steam pressures below about 0.6 bar at the foam preparation, the optical microscopic method turned out to be a reliable method in the determination of the degree of fusion over the whole range of the EPS particle foams investigated. With regard to the properties, the bending strength was much more affected by the fusion of the EPS beads and was found to increase progressively, whereas compressive stress was found to increase linearly with the degree of fusion of EPS particle foams. Although at low degree of fusion the flame heights, B2 was found to decrease, it remained constant at high degree of fusion.

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