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Lifetime modeling of polypropylene absorber materials for overheating protected hot water collectors

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Abstract

For the utilization of polymeric materials in high-demanding applications like solar thermal systems it is of utmost importance to define the performance requirements and to investigate the applicability of components for defined systems under service relevant conditions. This paper deals with the lifetime estimation of black-pigmented polypropylene (PP) absorber grades for overheating protected solar thermal collector systems for hot water preparation in five representative climate zones. Based on experimental aging data in hot air and heat carrier fluid at elevated temperatures (95 °C, 115 °C and 135 °C) and climatic input data, as well as deduced loading conditions and absorber temperature distributions, the lifetime was calculated using a theoretical and an empirical extrapolation approach and assuming cumulating damages in service relevant temperature intervals. Depending on the PP grade, the extrapolation method and the location, endurance limits ranging from 8 to 50 years were obtained. The PP grade with ß-spherulithic structures and less carbon black exhibited a superior performance (factor 2) compared to a well-established grade which is currently widely used for swimming pool absorbers.

Keywords: Polypropylene; Solarthermal collector; Absorber; Lifetime

1. Introduction

The combination of research in the fields of polymer engineering and solar energy science offers a high potential for further developments in solar thermal technologies regarding costs, processing and collector design (Wallner and Lang, 2005; Lang et al., 2013). For polymeric solar thermal absorber materials a long-term stability in hot heat carrier fluid or hot air environment is of prime importance (Kahlen et al., 2010a,b). Aging and degradation of polymeric materials decisively influence the physical performance properties and subsequently the lifetime (Celina, 2013). According to Köhl et al. (2005) for solar thermal collectors a service lifetime of 20 years is required. For the currently market-dominating, cost-efficient thermo-siphon hot water systems also shorter lifetimes ranging from 5 to 20 years are quoted by manufactures (Meyer, 2009; Sessler, 2014).

To assess the lifetime of pressurized polymeric components (e.g. pipes) internal pressure tests (EN ISO 9080) at elevated temperatures are carried out (Lang et al., 1997). By performing long-term tests on pipes at different pressure levels, creep rupture curves are generated, showing three different failure regions. When large defects are absent ductile failures are obtained at high hoop stresses (Region I). At lower stresses (Region II) mechanical phenomena (slow

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crack growth) and chemical degradation (thermo-oxidative aging) compete, resulting in quasi-brittle failures. The end of lifetime in Region III has been reached when extreme brittleness occurs and the lifetime is nearly independent on the hoop stress (Leijström and Ifwarson, 1998; Lang et al., 1997, 2005).

Solar collectors are commonly used in pressurized pumped or non-pumped systems. For polymeric materials based absorbers special attention has to be given to the control of the pressure level, but also the maximum stagnation temperature. Within the collaborative research projects *SolPol-1/2* (Solar thermal systems based on polymeric materials) an overheating controlled (OHC) glazed plastic collector has been developed, which is operated at a maximum pressure level of 1.5 bar (Lang et al., 2013). For functional model collectors it was shown that it is possible to limit the maximum stagnation temperature by back-cooling on the backside of the collector to 95 °C (Thuer et al., 2013). At elevated temperatures some polyolefin pipe grades (e.g. polypropylene) do not exhibit the stress dependent Region II characterized by quasi-brittle failure (Ifwarson and Leijström, 1992). Hence, it is of utmost importance to investigate and characterize primarily the Region III of large scale aging and brittle failure.

The absorber of a solar thermal collector is exposed to varying temperature levels depending on the application (domestic hot water preparation or space heating in single- or multi-family houses), the plant types (pumped systems or thermo-siphon systems) and the climate zone. Kaiser et al. (2013) carried out a comprehensive theoretical study on the loading conditions for collector components used in various solar thermal system types. Five climatic conditions representing different climate zones were considered. The derived loading conditions on the absorber level were used to perform comprehensive aging investigations on two black-pigmented, commercially available polypropylene grades for solar thermal absorbers (Povacz, 2014). The main purpose of this paper is to assess the lifetime for PP based absorbers of overheating protected glazed flat plate collectors for hot water preparation. Therefore the theoretically determined loading profiles (Kaiser et al., 2013) and the experimental aging data on specimen level (Povacz, 2014) were combined assuming cumulating damages at various temperature levels. This approach is commonly termed Miner's rule and is also used for the lifetime assessment of hot water pipes (Leijström and Ifwarson, 1998).

2. Methodology and procedure

2.1. Modeling of service relevant loading conditions

Based on the study by Kaiser et al. (2013) and prevalent market potentials, five different climatic conditions (continental (Graz/Austria), Mediterranean (Athens/Greece), hot and dry (Pretoria/South Africa), hot and humid (Fortaleza/Brazil), moderate climate (Beijing/China)) were taken into account for this work regarding the requirements for polymeric materials in solar thermal absorbers. Based on Meteonorm-data, relevant climatic parameters (e.g. air temperature, relative humidity, global radiation) were established on an annual basis. In a further step for all five climate zones market-based polymeric overheating controlled collectors for hot water preparation in multi-family houses were defined and evaluated. By theoretical modeling, annual time/temperature distributions for the absorber were obtained, which were significantly dependent on the location and the associated climatic conditions.

2.2. Aging characterization of black-pigmented PP grades and time/temperature extrapolation

Since the thickness dependency of the aging behavior of the investigated black-pigmented PP grades is limited (Povacz, 2014), results of the aging behavior of 100 μm thick micro-sized specimens (MSS) were selected as database for lifetime predictions. Based on compression molded 2 mm thick plates of two black-pigmented PP grades PP-B1 and PP-B2, 0.1 mm thick micro-sized specimens (MSS) were automatically manufactured using an adapted CNC-milling technique (Wallner et al., 2013). While the grade PP-B1 is established and widely used for unglazed swimming pool absorbers, PP-B2 is a novel grade characterized extensively in the collaborative research project *SolPol-1/2*. Both grades are black-pigmented polypropylene block copolymers. PP-B1 is an extrusion grade with 2.0 m% carbon black and a melt flow rate of 0.3 g/10 min (230 °C/2.16 kg) manufactured by LyondellBasell, Houston, USA. The stabilizer package of PP-B1 is based on 0.2 m% tri-functional primary antioxidants, 0.2 m% tetra-functional primary antioxidants and 0.1 m% secondary antioxidants (Beissmann et al., 2013). The grade PP-B2, provided by Borealis Polyolefine GmbH, Linz, Austria, is a ß-nucleated, heterophasic copolymer grade developed especially for hot-water compression fittings with a carbon black content of 0.8 m% and a melt flow rate of 0.3 g/10 min (230 °C/2.16 kg). PP-B2 contains an antioxidant mixture of 0.25 m% tetra-functional primary antioxidants and 0.05 m% secondary antioxidants (Beissmann et al., 2013).

After predefined aging times in hot air and hot heat carrier fluid at 95 °C, 115 °C and 135 °C at least 3 specimens were removed and characterized. As most relevant aging indicators describing the end of induction period and ultimate failure the associated carbonyl index and the strain-at-break values were evaluated.

To determine the carbonyl index FT-IR spectroscopy in transmittance mode was performed. The carbonyl index (C.I.) was calculated by the ratio of the absorbance peaks at 1715 cm^{-1} (carbonyl-peak) to 974 cm^{-1} (Horrocks et al., 1999). C.I. change of more than 0.1 indicated a significant carbonyl build-up at the end of the aging induction period of polyolefins (Schwarzenbach et al., 2009).

To obtain strain-at-break values tensile tests were carried out at 23 °C using a screw-driven universal testing machine. The test speed was 10 mm/min. The specimen were classified as embrittled when the strain-at-break values dropped below the strain-at-yield value ($\varepsilon_B < \varepsilon_Y$). A minimum of three specimens were tested for each state of aging.

2.3. Lifetime assessment using the cumulative damage approach

For lifetime assessment the experimental data gathered at elevated temperatures were extrapolated to service temperatures ranging from 40 °C to 95 °C. Using the extrapolated endurance limits the lifetime was deduced assuming cumulating damages in the various temperature intervals (in 5 K intervals) of the location specific time/temperature stress distribution. The commonly used approach is termed Miner's rule. In the following the extrapolation techniques and the Miner's rule approach are described.

2.3.1. Extrapolation to service temperatures

Endurance time extrapolation of both investigated PP impact copolymer grades was carried out using a theoretical Arrhenius approach and an empirical extrapolation approach. The Arrhenius approach which is also established and used in ISO 2578 is based on the assumption that as long as the degradation mechanisms in a given temperature range remain constant it can be used for lifetime predictions (Kahlen et al., 2010a,b).

However, polymeric materials can exhibit various aging processes and changes of degradation mechanisms, defined as crossover temperatures. Several authors determined the crossover temperature of PP in the temperature range between 70 °C and 83 °C along with activation energies of 101 kJ/mol and 72 kJ/mol below and above this temperature (Celina et al., 2005; Hoàng and Lowe, 2008; Kahlen et al., 2010a,b). Hence, besides the Arrhenius approach an empirical method considering crossover temperatures based on sigmoidal aging curvatures (Gugumus, 1999) was used for the endurance time determination. Gugumus (1999) published experimental data for PP grades with different catalyst residues and antioxidant formulations up to 2000 days. The reported sigmoid curvature was attributed to the interaction of Ti catalyst residues and phenolic antioxidants (Gugumus, 1999).

As endurance time limits two aging indicators were selected. Carbonyl index (C.I.) changes of more than 0.1 were investigated by FT-IR spectroscopy and the time-to-embrittlement ($\varepsilon_B < \varepsilon_Y$) of the specimens were characterized by tensile testing. Although Gugumus (1999) and Celina et al. (2005) indicated that linear lifetime predictions for polymers used at low temperature, based on high temperature tests are not valid, due to changes in mechanism and activation energies, they are still used to assess the service lifetime. In this study the linear ISO 2578 based approach is utilized as optimistic upper bound method. To take into account the crossover temperature and the change in mechanism at low service temperatures, for temperatures below 63 °C (PP-B1) and 68 °C (PP-B2) a constant endurance time of 50 years was assumed, which is in agreement with investigations carried out by Leijström and Ifwarson (1998).

Based on an Arrhenius type relationship, the endurance time in terms of a projected failure time in the service temperature range between 75 °C and 95 °C is described by following equation:

$$\ln t_{\text{endurance}} = \ln A + 1/T * E_a$$

where $t_{\text{endurance}}$ represents the endurance time, A is a material constant, T is the absolute temperature in K, and E_a is the activation energy in J/mol (Kahlen et al., 2010a,b).

The second extrapolation method used in this study is based on the work of Gugumus (1999). On the basis of experimental aging data of 120 μm thick extruded PP films Gugumus (1999) derived characteristic S-shaped curves for the embrittlement values of investigated PP grades formulated with various phenolic stabilizers. Since the black-pigmented PP grades characterized for this work contained the same stabilizer packages with different concentrations, for the suggested modeling approach a rigorous similarity in the curvature was assumed and a vertical shift of the literature data at a fixed temperature of 115 °C was applied due to the different stabilizer contents. As depicted by Gugumus (1999), an higher concentration of antioxidants (0.05 vs. 0.10 m%) led to a vertical shift of the experimental aging curve with sigmoidal shape in an Arrhenius plot. While for PP-B1 mean values of Gugumus' data for PP with 0.05 m% of the tri-functional primary antioxidant and the grade with 0.05 m% tetra-functional primary antioxidant were used (from Fig. 6 in Gugumus, 1999) neglecting synergistic or antagonistic effects, the data for PP with 0.05 m% tetra-functional primary antioxidant were taken and shifted for PP-B2 (from Fig. 3 in Gugumus, 1999). Gugumus (1999) published aging data for more than 2000 days and gave an indication for an extrapolation at temperatures below 60 °C (s. Fig. 3 in Gugumus, 1999), which was not clearly stated by Gugumus (1999), but due to a lack of data also considered in this study. By vertical shifting of the literature data at a fixed temperature of 115 °C a good agreement with experimental embrittlement data of PP-B1 and PP-B2 at 135 and 95 °C was obtained. For PP-B1 the deviation was less than 10% for the data point at 135 °C (experiment: 104 days; shift: 94 days) and >25% for the point at 95 °C (experiment: >670 days; shift: 525 days), at which no embrittlement was reached so far. For PP-B2 deviations of 30% (experiment: 145 days; shift: 190 days) and >0% (experiment: >980 days; shift: 975 days) were obtained at 135 and 95 °C, respectively. Interestingly, for both grades PP-B1 and PP-B2 the shifted data at 95 °C are predicting lower embrittlement times than the measured data, for which no embrittlement was achieved so far. Since experimental literature data regarding the aging behavior at low temperature (0–40 °C) are scarce or not existing constant endurance times of 50 years were assumed for temperatures below 40 °C (PP-B1) and 45 °C (PP-B2).

To investigate the validity of this approach hot air aging studies at 60 °C are also carried out and ongoing revealing no embrittlement within a period of 4 years.

2.3.2. Cumulation of damages and lifetime assessment

Solar thermal absorbers are exposed to varying temperature and pressure loads. As described by Kaiser et al. (2013) polymeric solar thermal absorbers in distinct systems (with overheating protection ensured by back-cooling) are affected by location dependent, varying climatic parameters (e.g. air temperature, relative humidity, global radiation) and have to withstand a absorber temperature distribution during operation. Consequently models for static loads are not a convenient method to predict the lifetime of this high-demanding component. Hence, in this study a calculation method for cumulative damages at varying temperatures is applied, which is called Miner's rule and which is established in ISO 13760.

According to Leijström and Ifwarson (1998) it is assumed that each damage (caused by a constant service condition) is proportional to the duration of the attack ("proportionality rule"). The damage from different service conditions "*i*" is cumulatively added ("additively rule") according to the following equation:

$$1/t_f = \sum_{i=1}^{i=n} \left[(t_i/t_{tot})/t_{fi}(T_i, \sigma_i) \right]$$

t_f	Lifetime at specific temperature loading conditions
$t_{fi}(T_i, \sigma_i)$	Endurance time for condition "*i*"
n	Number of service conditions
t_i	Exposure time at condition "*i*"
t_{tot}	Total exposure time

Based on a cumulative damage approach, first information as to the temperature profile and temperature frequencies (hours per year) occurring in different climate zones for an overheating protected collector for hot water preparation were transferred in 5 K steps to a diagram. In a second step the ratios of the exposure times at the varying conditions (t_i) to the total exposure time (t_{tot}) were determined. Afterward failure times (predicted endurance times) t_{fi} based on the two modeling approaches (linear and S-shaped) were evaluated for the various temperature steps (5 °C) and according to Miner's rule, lifetimes for PP-B1 and PP-B2 were predicted (s. Fig. 1). While the Miner's rule is currently primarily used for polyolefin pipe grades, a further developed cumulative material damage concept, the wear-out approach, was implemented by Gillen and Celina (2001) and validated for elastomeric materials (e.g., EPR, EPDM or NBR) (Gillen et al., 2006). The wear-out approach was applied to deduce the remaining lifetime of a pre-aged polymeric material at ambient use temperature by subsequently aging at higher temperatures. No wear-out studies are available with focus on PP grades with different formulations. Hence, the wear-out approach was not considered for this work.

3. Results and discussion

3.1. Service relevant loading conditions

Fig. 2 illustrates the simulated time frequencies of the absorber temperatures in the polymeric overheating controlled collector system for hot water preparation in multi-family houses at five climatic locations. Due to the back-cooling system used in the investigated overheating controlled collectors with gross areas of 22–50 m^2 for the locations Fortaleza and Beijing, respectively, the maximum temperature occurring is limited to 95 °C for all climate zones. Nevertheless differences in the time frequencies can be observed for the various locations. While for the continental and moderate locations Graz and Beijing the lower limit of the temperature profile is below 0 °C, all other locations do usually not encounter freezing problems. What is common to all locations, is the frequency maxima in a range between 10 °C and 30 °C. Especially in the hot and humid climate of the location Fortaleza the time frequency maxima is quite distinct in the range between 25 °C and 30 °C. While for the hot climatic locations Athens and Fortaleza the maximum temperature of 95 °C occurs up to 70 h a year in the colder locations Graz and Beijing similar frequencies occur 10 °C lower.

3.2. Aging behavior at elevated temperatures and extrapolated endurance times

Figs. 3 and 4 illustrate the experimental data of the investigated grades PP-B1, and PP-B2 after in hot air at 95 °C, 115 °C and 135 °C. In the diagrams ultimate values of the two investigated aging indicators (e.g. time to change of C.I. more than 0.1 and time-to-embrittlement (strain-at-break values below strain-at-yield) are depicted. While for PP-B1 (Fig. 3) due to the hot air aging at 135 °C and 115 °C embrittlement was observed after about 2500 h (104 days) and 8500 h (354 days), respectively, embrittlement of PP-B2 (Fig. 4) occurred after about 3500 h (146 days) and 13,500 h (562 days). The time-to-embrittlement data of both grades were in good agreement with the onset of an increase in the carbonyl index. Hence, solely the time-to-embrittlement data were used for lifetime assessment.

The significant differences in the long-term thermal stability of PP-B1 and PP-B2 are attributable to the polymer structure (impact copolymers), the crystalline morphology, the varying carbon black content (2.0 vs. 0.8 m%) and the different stabilizer formulations (Povacz, 2014).

According to ISO 2578, the aging time causing a predefined change of property is proposed to define endurance limits and to establish so-called time/temperature limits. Fig. 3 illustrates the derived endurance limits as Arrhenius plots over the reciprocal temperature (K^{-1}). While filled

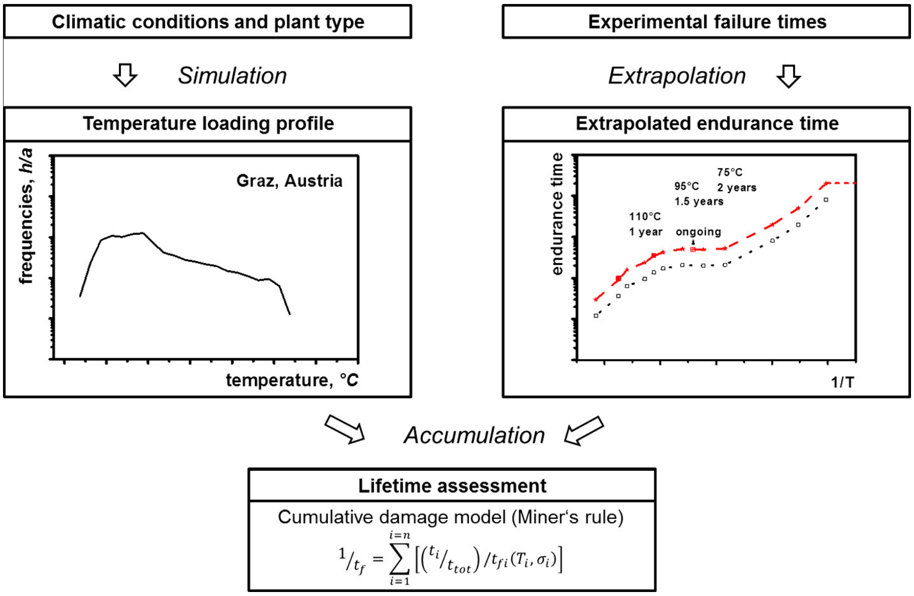

Fig. 1. Methodological lifetime assessment approach, based on the simulation of temperature loading profiles for solar thermal absorbers, the extrapolation of experimental aging data from elevated temperatures to service temperatures and the cumulation of the damages in the temperature intervals.

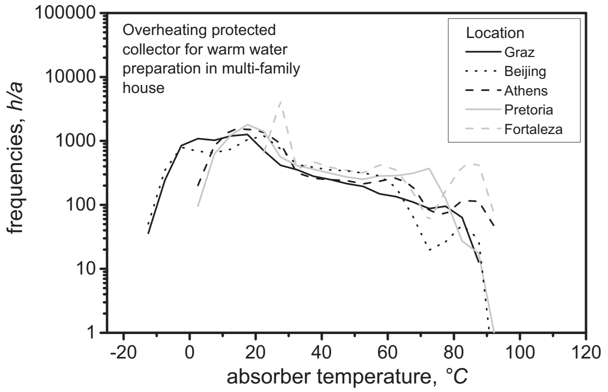

Fig. 2. Time frequencies (*h*/*a*) of the absorber temperatures in polymeric solar thermal collectors with overheating protection based on a back-cooling system for the hot water preparation in multi-family houses (MFH) at different climatic locations.

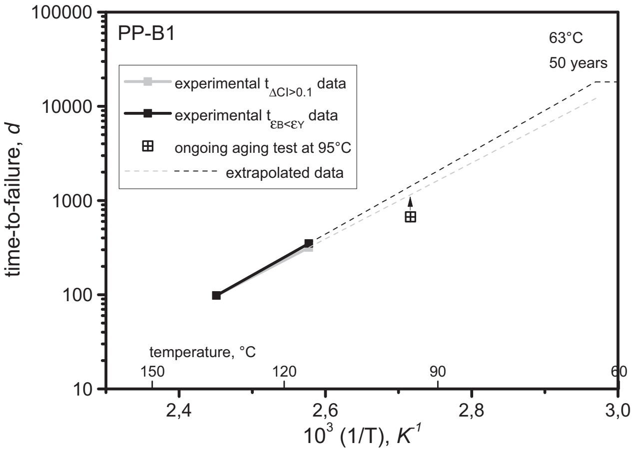

Fig. 3. Experimental failure times for PP-B1 (filled symbols; black – strain-at-break; gray – carbonyl index) and extrapolated endurance times at lower temperatures using the Arrhenius relationship.

rectangular symbols represent experimental data for 100 μm thin micro-sized specimens, the dashed curves depict predicted data based on a linear Arrhenius fit. The open symbols with a cross correspond to ongoing aging tests at 95 °C. For time-to-embrittlement of PP-B1 the linear Arrhenius lifetime extrapolation resulted in an endurance limit of about 4 years (1420 days) at 95 °C and about 19 years (6840 days) at 75 °C (s. Fig. 3). At 95 °C no embrittlement was obtained after close to 2 years of aging (670 days) for PP-B1. Regarding PP-B2 the values for time-to-embrittlement and the carbonyl index are significantly higher. By linear Arrhenius extrapolation endurance times of about 7 years (2575 days) at 95 °C and about 40 years (14,260 days) at 75 °C were obtained, which is a factor of about 2 times higher than for PP-B1. For temperatures below ∼70 °C an endurance time of 50 years was assumed. The aging experiments for PP-B2 are still ongoing. No embrittlement was obtained after 980 days (2.7 years).

In addition to the linear Arrhenius extrapolation also the empirical S-shaped method based on Gugumus (1999) was used. The experimental time-to-embrittlement data (Figs. 5 and 6) of the black-pigmented micro-sized specimens (filled symbols) were extrapolated using empirical literature data (open rectangular and triangular symbols) derived by Gugumus (1999). The stabilizer packages used in the experiments of this study were similar to the stabilizers used by Gugumus (1999) except deviations in the concentration and the formulation of tri- and

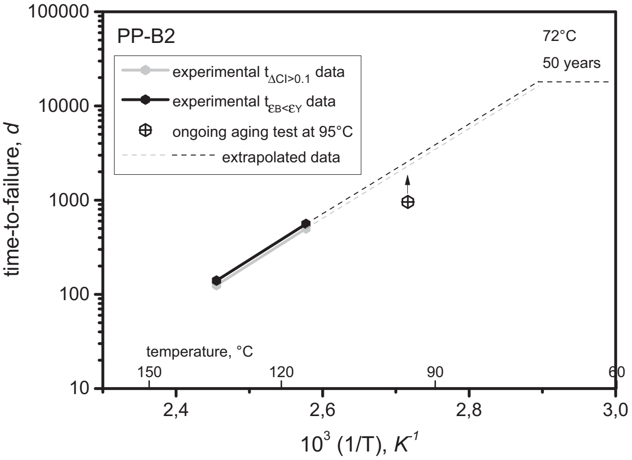

Fig. 4. Experimental failure times for PP-B2 (filled symbols; black – strain-at-break; gray – carbonyl index) and extrapolated endurance times at lower temperatures using the Arrhenius relationship.

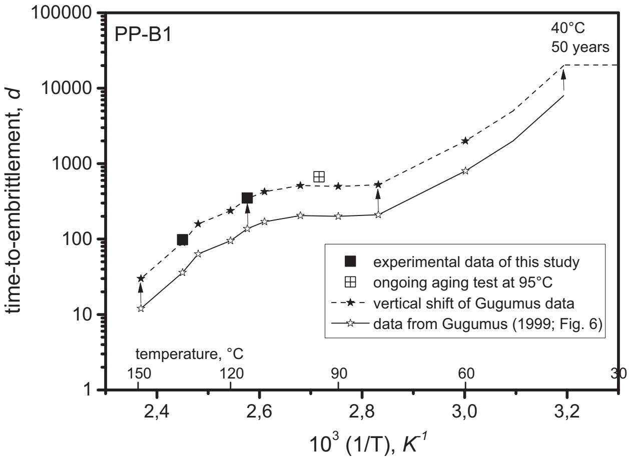

Fig. 5. S-shaped endurance time extrapolation diagram for PP-B1 for hot air aging using time-to-embrittlement as endurance limit.

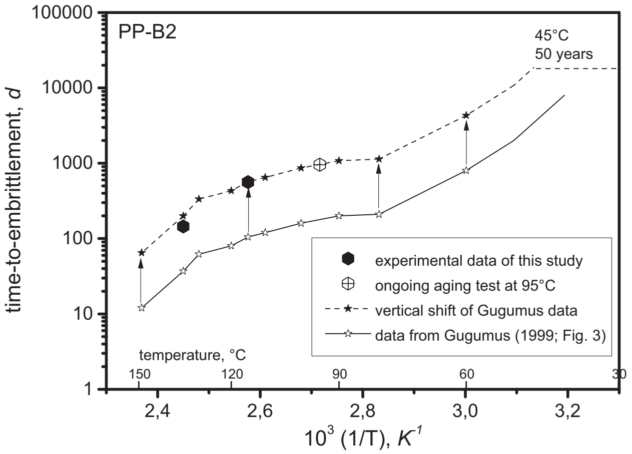

Fig. 6. S-shaped endurance time extrapolation diagram for PP-B2 for hot air aging using time-to-embrittlement as endurance limit.

tetra-functional primary antioxidants. For the investigated grades the amount of primary phenolic antioxidants was a factor of 5 (PP-B2) to 8 (PP-B1) higher.

The empirical endurance times established by Gugumus are characterized by a sigmoidal shape of the curvature, which is related to the varying aging mechanisms in the temperature range between 70 °C and 83 °C, described in the literature (Glass and Valange, 1988; Celina et al., 2005; Hoàng and Lowe, 2008; Kahlen et al., 2010a,b). To extrapolate the empirical data of PP-B1 or PP-B2 to lower temperatures, the data from Gugumus (1999) were vertically shifted at a fixed temperature of 115 °C. This approximation method revealed some uncertainties, like different polymer morphologies compared to the study of Gugumus (1999), different stabilizer concentrations and pigmentation influencing the aging behavior (Povacz, 2014).

In Fig. 5 the fit according to Gugumus is presented for PP-B1. First a sigmoidal fit was generated combining the literature data for 0.05% of AO-1 (tetra-functional primary antioxidants) and 0.05% AO-4 (tri-functional primary antioxidants). In a second step this fit was vertically shifted with a constant factor to fit the experimental data of this study (starlike symbols). Due to the S-shaped curvature of the values for time-to-embrittlement endurance limits for PP-B1 of about 1.5 years (525 days) at 95 °C (ongoing experiments after more than 670 days) and of about 2 years (810 days) at 75 °C were obtained for this empirical approach. For temperatures below 40 °C a constant endurance time of 50 years minimum was assumed.

Fig. 6 depicts the extrapolation fit according to Gugumus (1999) for the black-pigmented polypropylene grade PP-B2. Following the procedure applied for PP-B1 a sigmoidal fit was generated for the literature data of PP grades formulated with 0.05% of AO-1 and with 0.01% AO-1. Shifting this S-curve with a constant factor allows fitting the experimental embrittlement data derived for PP-B2. Due to the elevated level of the predicted data for PP-B2 in comparison to PP-B1, higher endurance times at 95 °C (about 2.5 years (960 days)) and 75 °C (about 4.5 years (1610 days)) are derived. For temperatures below 45 °C a constant endurance time of 50 years was assumed.

3.3. Estimated lifetimes for the absorber materials

For the benchmark material PP-B1 already widely used for swimming pool absorbers various optimistic upper bound scenarios (linear Arrhenius approach) were calculated for different locations. Table 1 shows that the estimated lifetime for PP-B1 is in the range of 31 years (Fortaleza) to 47 years (Beijing) depending on the climate conditions. While in the hot and humid climate of Fortaleza, Brazil the estimated lifetime is reduced due to harsher climate conditions than in the other investigated locations, especially the assessed lifetimes in the continental and moderate climate zones are affected by the assumption of a constant endurance time of 50 years below 70 °C.

Table 1
Estimated lifetimes for PP-B1 applied in solar thermal absorbers with overheating protection (95 °C) in five different climate zones for hot water preparation of multi-family house according to an optimistic linear Arrhenius approach and a conservative S-shaped Gugumus model.

Climate zone	PP-B1 Estimated lifetimes in years	
Location	Linear	S-shaped
Beijing	47	23
Graz	46	21
Pretoria	45	14
Athens	41	15
Fortaleza	31	8

Table 2
Estimated lifetimes for PP-B2 applied in solar thermal absorbers with overheating protection (95 °C) in five different climate zones for hot water preparation of multi-family house according to an optimistic linear Arrhenius approach and a conservative S-shaped Gugumus model.

Climate zone	PP-B2 Predicted lifetimes (time-to-embrittlement) in years	
Location	Linear	S-shaped
Beijing	49	34
Graz	49	32
Pretoria	49	24
Athens	46	25
Fortaleza	40	15

Due to the S-shaped curves of the empirical Gugumus (1999) based cumulative damages approach, estimated lifetimes for PP-B1 are significantly lower, ranging from 8 years (Fortaleza) to 23 years (Beijing).

For PP-B2 higher lifetime values were deduced for both approaches, the Arrhenius fit and the shift of S-shaped data from Gugumus (1999). While for the linear cumulative damages approach lifetimes in the range of 40 years (Fortaleza) to 49 years (Graz, Pretoria, Beijing) were calculated, the S-shaped cumulative damage approach estimates lifetimes from 15 years (Fortaleza) to 34 years (Beijing) (see Table 2).

4. Summary and conclusions

To assess the lifetime of two black-pigmented PP grades for overheating protected solar thermal collectors in five representative climatic zones, absorber loading profiles (temperature/time distribution) were established based on climatic input data. Using experimental failure data at elevated temperatures, endurance times at service relevant temperatures ranging from 40 °C to 95 °C were extrapolated. Extrapolation was based, on the one hand, on a linear fit (theoretical Arrhenius approach) as well as a shift of empirical S-shaped failure curves (Gugumus approach), on the other. Subsequently a model of cumulative damages, termed Miner's rule was applied to assess lifetimes for an established black-pigmented PP (PP-B1) and a novel PP grade (PP-B2) for absorbers in overheating protected collector systems for domestic hot water preparation in different climate zones. Results of lifetime estimation based on a linear cumulative damages approach were ranging from 31 years (PP-B1; Fortaleza, Brazil) to 49 years (PP-B2; Beijing, China). However, the calculated lifetimes were significantly affected by the constant endurance time of 50 years that was assumed for the temperature range below ~70 °C or ~40 °C (depending on the applied method) for which information on the aging behavior of polymeric materials is scarce.

For lifetime assessment on the empirical cumulative damages approach, estimated lifetimes for the harshest climatic conditions in Fortaleza were 8 years for PP-B1 and 15 years for PP-B2. Hence, due to the enhanced long term thermal stability of PP-B2, it was possible to increase the estimated lifetime by a factor of approximately 2. Further aging tests at lower temperatures, as well as field experiments on a component level are necessary to verify the estimated lifetime results and subsequently adjust the safety factors and model parameters. Finally, it is of utmost importance to also consider pressure distributions in the collector systems as well as variations of the water pressure in water supply lines.

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