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Global Aging and Lifetime Prediction of Polymeric Materials for Solar Thermal Systems – Part 2: Polyamid 66 Glass-fiber Reinforced Absorbers for Integrated Storage Collectors

Michael K. Grabmann[1], Gernot M. Wallner[1], Thomas Ramschak[2], Georg Ziegler[3], Reinhold W. Lang[1]

[1] Institute of Polymeric Materials and Testing, University of Linz, Linz, Austria

[2] AEE Intec, Gleisdorf, Austria

[3] GREENoneTEC, St. Veit/Glan, Austria

Abstract

The paper deals with the lifetime estimation of black-pigmented, glass-fiber reinforced polyamide (PA-GF) absorber grades for absorber/storage tanks of pressurized, non-pumped hot water systems at different sites (Athens, Fortaleza, Pretoria). The annual absorber time/temperature distributions were simulated. Global aging data were gathered by exposure of specimens in hot water at elevated temperatures (115 and 135°C) and analytical and mechanical characterization after aging. Lifetime assessment for the absorber/storage-tank material was done by combining the time/temperature loading profiles, extrapolated endurance times from aging tests and assuming cumulative damages. Depending on the chosen aging indicator, glass fiber content and climate zone, the lifetimes varied between 35 and 47 years with lowest values for the hot-and-humid climate zone. The grade with 30 m% glass-fibers exhibited a slightly better long-term performance than the grade with 35 m%.

Keywords: *Polypropylene; Solar thermal collector; Absorber; Lifetime*

1. Introduction

Fiber-reinforced polymer composites represent an important material class for solar thermal systems (Wallner and Lang, 2005). Material properties like low weight, high mechanical strength, thermal, dimensional and chemical stability as well as mass production capability are of paramount importance for cost-efficient pressurized non-pumped systems based on integrated storage collectors (Celina et al., 2005; Kahlen et al., 2010). Today for solar thermal collectors a lifetime of up to 20 years or even more is mandatory (Köhl et al., 2005). In previous research the opportunities and limitations of injection moulding technologies for the production of absorbers of integrated storage collectors were evaluated (Brunold et al., 2012). It was shown that glass-fiber reinforced polyamides exhibit a high potential for such applications.

A main task of current research work is the lifetime assessment of these novel absorber materials for more cost-efficient and reliable collector systems. Hence, the main objective of the paper is to investigate the aging behavior and to assess the lifetime of various glass-fiber reinforced polyamide 66 grades for pressurized, non-pumped integrated storage collector systems. Therefore, temperature loading profiles were estimated for three different climate locations (Mediterranean (Athens, Greece), hot-and-humid (Fortaleza, Brazil) and hot-and-dry (Pretoria, South Africa)) with maximum temperatures up to 95°C. The technological parameter stress-at-break and the analytical parameter area crack density were determined for standardized specimens after exposure to hot water at elevated temperatures (115 and 135°C). Using an Arrhenius approach endurance times at service-relevant temperatures ranging from 5 to 95°C were calculated. For lifetime

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assessment a recently published approach based on calculated temperature loading profiles, extrapolated endurance times and cumulated damages was used (Wallner et al., 2016).

2. Methodological approach

2.1 Collector design and modelling of service relevant conditions

The investigated solar thermal integrated collector storage (ICS) (s. Fig. 1) combines the thermal absorber and the storage tank in one component. The system consists of cylindrical tubes with a diameter of about 150 mm and a thickness of 3 mm. These tubes are friction welded out of injection molded half shells and subsequently connected in series. Reinforced ribs and insulation are applied to fulfill mechanical and thermal properties. Under service conditions the tubes are permanently filled with drinking water under a given pressure, while the outside of the tubes remain dry. Consequential the tubes are loaded under permanent stress while recurring temperature changes lead to complex and superimposed conditions (Geretschläger, 2015).

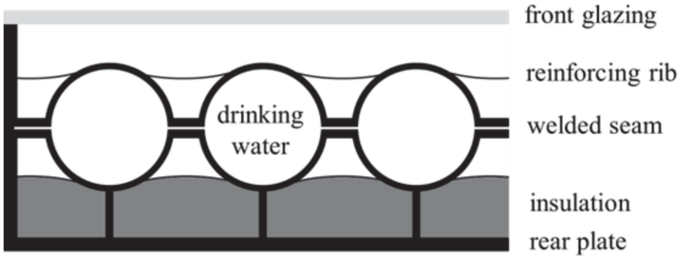

Fig. 1: Cross section of the ICS collector with injection molded absorber/storage tank made from half-shells [Geretschläger, 2015].

Based on the study by Kaiser et al. (2013) and prevalent market potentials, three different climatic conditions (Mediterranean (Athens, Greece), hot-and-humid (Fortaleza, Brazil) and hot-and-dry (Pretoria, South Africa)) are taken into account for this work. Based on Meteonorm-data, relevant climatic parameters (e.g. air temperature, relative humidity, global radiation) are established on an annual basis. In a further step for all three climate zones market-based polymeric collectors for hot water preparation in single family houses are defined and evaluated. By theoretical modeling using the software tool SHW (Streicher et al., 2004), annual time/temperature distributions for the absorber are obtained.

2.2 Materials, aging conditions and characterization

Based on established property requirements for materials of pressurized absorbers/storage-tanks aliphatic polyamide 66 grades with glass-fiber contents of 30 and 35 m% and carbon black pigmentation were selected for the investigations. The long term hydrolytic stability was characterized at elevated temperatures of 115 and 135°C. Therefore standardized dumbbell specimens were exposed in water filled pressure cooker autoclaves and withdrawn at defined intervals.

As global aging indicators, the technological parameter stress-at-break and the analytical parameter area crack density were monitored. Limit values of these aging parameters were defined on basis of maximum mechanical loads and material key-properties of an ICS. Tensile tests were carried out at 23°C using a screw-driven universal testing machine with a test speed of 50 mm/min. The lower limit as aging indicator for stress-at-break values was defined at 25 MPa. Microscopic investigations on surface defects were achieved by using a conventional microscope with a 5x-objective (2.0x2.8 mm^2). Area crack density was calculated by the ratio of single cracks on the surface relative to the size of the picture. The limit value for failure was the first appearance of cracks on the surface of the specimen. A similar methodological approach dealing with the aging characterization of glass-fiber reinforced polyamides in hot water and air was carried out successfully by Geretschläger and Wallner (2016).

2.3 Lifetime assessment

For lifetime estimation a cumulative damage approach was used established by Wallner et al. (2016) for black-pigmented PP solar absorber materials. The main elements of the approach are the simulation of temperature loading profiles, the extrapolation of aging data and the cumulation of damages of different temperature levels (Fatemi and Yang, 1998). The experimental global aging data gathered at elevated temperatures were extrapolated to service-relevant temperatures. Therefore, the log(t)/(1/T)-linear Arrhenius approach was applied assuming a specific degradation mechanism in the temperature range. Additionally, a constant endurance time of 50 years was assumed according to Leijström and Ifwarson (1998) to ensure not to overrate lower temperatures. The lifetime was deduced by weighting the temperature dependent endurance times with the loading profiles according to ISO 13760. This lifetime modelling approach neglects superimposed static and cyclic mechanical loads induced by temperature changes that are to be expected during operation of the ICS collector.

3. Results and discussion

3.1 Service relevant loading conditions

Fig. 2 illustrates the simulated absorber surface temperatures profiles for mediterranean (Athens), hot-and-humid (Fortaleza) and hot-and-dry (Pretoria) climate conditions. Two different situations (with hot water consumption and stagnation) are considered. The solid curve represents the stagnant condition whereby no water is used from the integrated storage collector. For the consumption condition, an assumed daily use of 110 litres at 45°C is taken into account. A maximum of hot water draw is assumed mainly in the morning (6am to 8am) and in the evening (7pm to 9pm) while a reduced water abstraction is given during day. Regarding the temperature loading profiles maximum temperatures of about 90°C are obtained for the collector system in Fortaleza. Slightly lower values are calculated for Pretoria and Athens. Also the maximum of the time/temperature distribution is significantly dependent on the installation site. The high temperature loads between 70 and 90°C are more pronounced for Fortaleza while minimum temperatures of about 30°C are obtained. Athens reveals lowest collector temperatures of about 5°C. In all locations the stagnant conditions lead to a slight shift of the profile curve towards higher temperatures. Hence, stagnant condition is selected to calculate a worst case scenario for lifetime modelling.

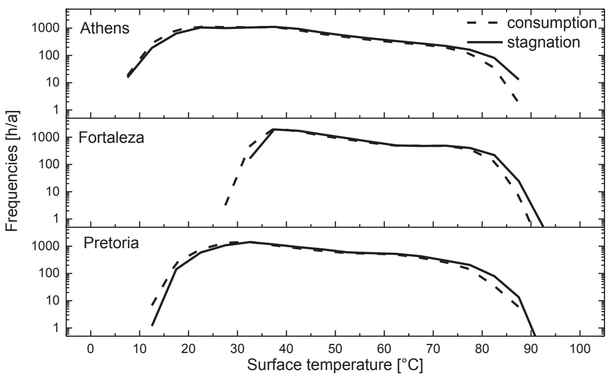

Fig. 2: Annual ICS absorber surface temperature profiles for three different climate zones with and without hot water consumption.

3.2 Aging behavior at elevated temperatures

Fig. 3 shows the stress-at-break values and the area crack density of the investigated GF-reinforced PA66 grades as a function of aging time in hot water at 115 and 135°C. Ultimate failure with stress-at-break values below 25 MPa are indicated with open symbols in the chart. The limit value for area crack density is the first visible appearance of cracks. Aging in hot water led to a steady decrease of stress-at-break values. Limit values of 25 MPa were obtained after about 750 h and 5000 h at 135 and 115°C, respectively. The aging behavior of the investigated grades was slightly differing. First cracks on the surface were detected within 350 h and about 2500 h at 135 and 115°C. Hence, this aging indicator was more sensitive and critical. The amount of cracks per area increased significantly for ongoing exposure. A higher tendency of crack formation was observed for PA66-GF35 and therefore a worse hydrolytic stability. Both materials exhibited a regular crack pattern primarily oriented perpendicular to the fiber direction i.e. line of injection (s. Fig. 4).

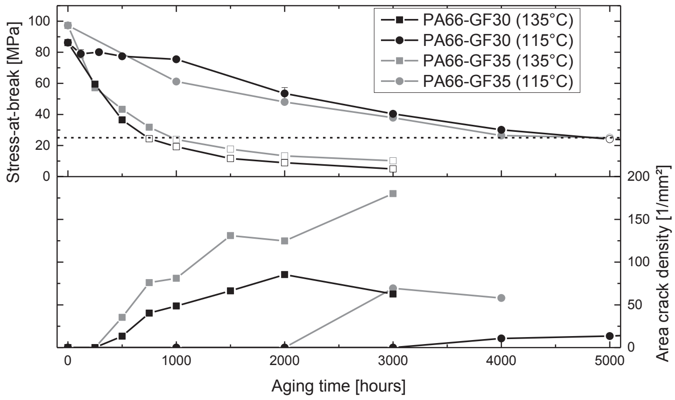

Fig. 3: Stress-at-break values (top layer) and area crack density (bottom layer) for glass-fiber reinforced PA66 specimens as a function of aging time exposed to hot water at 115 and 135°C.

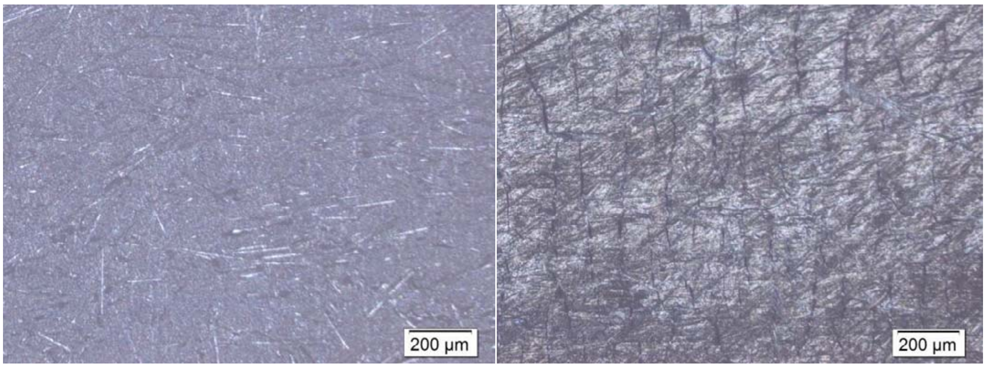

Fig. 4: Unaged (left) and degraded/cracked (right) surface of PA66-GF30 after exposure to hot water at 135°C for 750 h.

3.3 Extrapolated endurance times and estimated lifetimes for glass-fiber reinforced PA66 specimen

The derived Arrhenius plots for material endurance time estimation is presented in Fig. 5. The filled symbols represent the stress-at-break limit values while the open symbols depict crack formations on the surface of the samples for 115 and 135°C in hot water. The experimental data were fitted using an Arrhenius approach and extrapolated to service-relevant temperatures ranging from 5 to 95°C. A similar methodological approach dealing with the assessment of long-term mechanical performance of glass fibre reinforced polyester composites in aqueous environments was carried out by Carra and Carvelli (2015).

Due to the fact, that PA66-GF35 exhibited a slightly less drop of the strength at 135°C and a comparable aging behavior at 115°C, the extrapolated curves of both investigated grades intersect resulting in a worse aging behavior for PA66-GF35 below 115°C. To examine this phenomenon, additional exposure tests are ongoing at 125 and 105°C.

The shorter failure times for the aging indicator area crack density results in left shifted extrapolated curves with lower endurance times. The material with the higher glass-fiber content exhibited a more pronounced formation of cracks and therefore a worse aging behavior. For the assumed 50 years cut-off a temperature threshold of 74 and 68°C was deduced for PA66-GF30 and PA66-GF35, respectively.

Table 1 depicts the deduced lifetimes which are ranging from 35 years in the hot and humid climate of Fortaleza up to 47 years for the less critical mediterranean climate of Athens. Comparable maximal lifetimes of 47 years were deduced for the hot-and-dry climate condition of Pretoria. However, all results were significantly affected by the 50 years cut-off. Lower lifetime values were obtained for the grade with 35 m% glass fibers. This can be attributed to differences in the stabilization packages. For both materials the aging indicator area crack density exhibited slightly lower lifetimes (less than 10% deviation).

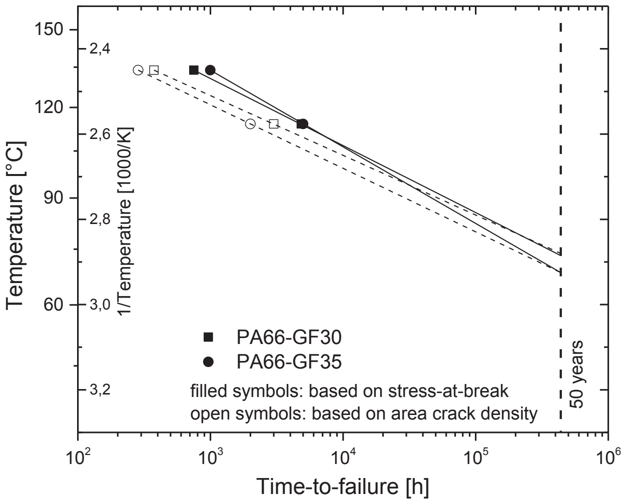

Fig. 5: Experimental failure times for glass-fiber reinforced PA66 based on stress-at-break and area crack density as limit values with extrapolated endurance times in the service relevant temperature range.

Tab. 1: Estimated lifetimes for the investigated glass-fiber reinforced PA66 grades for integrated storage collectors at the installation sites Athens, Fortaleza and Pretoria.

Aging indicator	Material	Predicted lifetimes in years		
		Athens mediterranean	**Fortaleza** hot and humid	**Pretoria** hot and dry
Stress-at-break	PA66-GF30	47	44	47
	PA66-GF35	44	38	43
Area crack density	PA66-GF30	47	43	47
	PA66-GF35	42	35	41

4. Summary and conclusion

Lifetime estimation was established for two black-pigmented glass-fiber reinforced PA66 grades used for integrated storage collectors for hot water preparation. Therefore, temperature loading profiles for three different climate zones were determined based on climatic input data. As experimental failure limits, the drop of stress-at-break below 25 MPa and the appearance of cracks on the surface of the specimen was defined. These aging indicators were observed for exposition in hot water at 115 and 135°C. Furthermore, endurance times at service relevant temperatures (5 to 95°C) were extrapolated using an Arrhenius approach. A model of cumulative damages (Miner's rule) was applied to assess lifetimes for the investigated materials.

Absorber temperature loading profiles ranging from 5 to 95°C were obtained. The profile was dependent on the installation site with longer exposure times at higher temperatures for Fortaleza. The stagnant condition led to a shift of the loading profile towards higher temperatures for all three locations. Thus, these temperature loading profiles were used for lifetime assessment.

Hot water exposure of the investigated grades at elevated temperatures resulted in a decrease of stress-at-break values with ultimate failure times of 750 and 5000 h at 135 and 115°C, respectively. Crack formation started after 350 h at 135°C and 2500 h at 115°C. Both materials showed a regular crack pattern primarily oriented perpendicular to the fiber direction with a higher tendency for crack formation for the PA66-GF35 grade.

The obtained lifetime values were ranging from 35 to 47 years. The Mediterranean climate in Athens and hot-and-dry climate in Pretoria exhibited highest calculated lifetimes, while the hot and humid climate in Fortaleza led to shorter lifetimes (4 to 7 years lower). PA66-GF35 exhibited lower lifetimes, which was attributed to differences in the stabilization package. To assure the extrapolated endurance times and the deduced lifetime values exposure tests at 125 and 105°C are carried out additionally.

5. Acknowledgment

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6. References

Carra, G., Carvelli, V., 2015. Long-term bending performance and service life prediction of pultruded Glass Fibre Reinforced Polymer composites, Composite Structures 127 (2015) 308–315.

Celina, M., Gillen, K.T., Assink, R.A., 2005. Accelerated aging and lifetime prediction: review of non-Arrhenius behavior due to two competing processes. Polymer Degradation and Stability 90 (3), 395–404.

EN ISO 13760, 1998. Plastics Pipes for the Conveyance of Fluids under Pressure –Miner’s Rule – Calculation Method for Cumulative Damage.

Fatemi, A., Yang, L., 1998. Cumulative fatigue damage and life prediction theories: a survey of the state of the art for homogeneous materials, International Journal of Fatigue 20 (1998) 9–34.

Geretschläger, K.J., 2015. Characterization of pigmented and reinforced polymeric materials for solar energy technologies, doctoral thesis, University of Linz, Austria.

Geretschläger, K.J., Wallner G.M., 2016. Aging characteristics of glass fiber-reinforced polyamide in hot water and air, Polymer Composites.

Kaiser, A., Fink, C., Hausner, R., Ramschak, T., Streicher, W., 2013. Leistungsanforderungen an Polymermaterialien in solarthermischen Systemen. Erneuerbare Energie 2013-1, 12–17.

Kahlen, S., Wallner, G.M., Lang, R.W., 2010. Aging behavior of polymeric solar absorber materials – Part 1: Engineering plastics. Solar Energy 84 (9), 1567–1576.

Köhl, M., Jorgensen, G., Brunold, S., Carlsson, B., Heck, M., Möller, K., 2005. Durability of polymeric glazing materials for solar applications, Solar Energy 79 (2005) 618–623.

Brunold, S., Papillon, P., Plaschkes, M., Rekstad, J., Wilhelms, C., 2012. Collectors and Heat Stores, in: Köhl, M., Meir, M.G., Papillon, P., Wallner, G.M., Saile, S., Polymeric Materials for Solar Thermal Applications, Wiley-VCH, Weinheim, pp. 301–317.

Streicher, W., Dittmann, A., Höller, P., 2004. Solaranlagensimulation in Vaillant WinSoft basierend auf SHW. In: 14. Symposium Thermische Solarenergie, 371-376.

Wallner, G.M., Lang, R.W., 2005. Guest editorial, Solar Energy 79 (2005) 571–572.

Wallner, G.M., Povacz, M., Hausner, R., Lang, R.W., 2016. Lifetime modeling of polypropylene absorber materials for overheating protected hot water collectors, Solar Energy, 125, 324-331.