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ARTIFICIAL AGING EXAMINATION OF PVC FIBERS AS VIBRATING STRINGS

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Abstract

Changes in material properties are examined in this work by vibration diagnostic techniques. In the article examinations of soft poly(vinyl chloride) (PVC) fibers, which were tested as vibrating strings are presented after different UV light induced aging times. The developed experimental system is presented in this manuscript and the main goal is to determine material changes as the results of artificial aging by special vibration diagnostic methods. The damped oscillations, where PVC fibers are stretched and twanged as strings are analyzed in this work. Parameters are also determined and their values are given after different aging time and relevant property changes are identified. The general equation of damped oscillation is written in a modified form, and the change of the traditional damping coefficient proves to be significant and the angular acceleration introduced by us also well characterizes the property changes induced by artificial aging.

Keywords: aging, degradation, material properties, poly(vinyl chloride), vibration

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1. Introduction

Today poly(vinyl chloride) (PVC) is still one of the most important world-wide produced plastics. It has the advantage of low cost, long-term stability and controllable mechanical properties (Ito and Nagai, 2007). One of the major problems associated with PVC is its sensitivity to weathering, especially to UV irradiation (El Raghi et al., 2000), which gives the main sense of examining its behavior and property changes during aging.

From the various and numerous aging processes we want to focus on photochemical aging effects in this work. Numerous experiments were carried out before both under laboratory and natural conditions, where property changes due to UV radiation were studied (Arvidsson and White, 2001; Attwood et al., 2006; Carrasco et al., 2001; Dintcheva et al., 2010; Huang et al., 2017; Ito and Nagai, 2007; Matuana et al., 2001; Nowicki et al., 2003; Real et al., 2003; Shyichuk et al., 2004; Sombatsompop and Sungsanit, 2004; White, 2006). The level of degradation is generally characterized by mechanical parameters, such as elongation at break, tensile strength etc. (Attwood et al., 2006; Carrasco et al., 2001; Djidjelli et al., 2001; Ito and Nagai, 2007; Jachowicz et al., 2017; Léveque et al., 2005; Mousa et al., 2003; Sombatsompop and Sungsanit, 2004; Visser et al., 2010; Yarahmdi et al., 2003). These parameters are useful for determining the examined plastic's status, but the measurements of these parameters can be done often only by the destruction of the sample. Our goal was to approach the determination of the mechanical properties of the PVC samples from a non-destructive way, from which we expect fine tracking of the aging process. The applicability of our idea can

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be seen in this publication. Based on its most important advantage, as it gives characterization in a non-destructive way, we think that similar vibration tests can be done in the future on more complex structures (for example pipes), where also their vibration response should be analyzed.

In our work semi-finished plastic products were artificially aged by UV lights and the possible property changes were investigated in a self-developed experimental system. In order to accelerate the aging process lower-wavelength UV light sources were used than generally for modeling the effects of weather. In publications the opinions about using these types of UV lights are divided, but in our case more intensive aging process was preferable than accurate simulating the exact weather conditions, therefore Sylvania G30W Ultraviolet lights were chosen. The specimens irradiated for different time periods by these lights were examined by the experimental system introduced in the following.

In general, a sequence of oxidative reactions occurs as the effect of UV aging, both chain scission and crosslinking may appear, and as a result the embrittlement of the material occurs. Oxygen diffused in from the surface is required for these processes. The oxygen is rapidly consumed by reactions, so the depth of the oxygen diffusion is not considerable. The major part of the degradation is forming quite a thin layer near the surface (White, 2006). Several studies examined the depth profile in different materials before, for this reason fibers with relatively small diameters were chosen for our tests.

The fibers were stretched out on a table, and after twanging as strings the property changes were examined after different aging times. Simple mathematical model can describe a string vibrating in a plane, and many previous works can be found focusing on its vibration. String vibration can be examined using point or distributed forces, and other methods are based on tension variation or boundary control. Belotserkovskii (2011) investigated the transient transverse vibration of a string, bearing a concentrated mass. Alsahlani and Mukherjee (2010) examined the problem of a string vibrating against a smooth obstacle. In their work the obstacle was located at one of the boundaries and the string was assumed to wrap and unwrap around the obstacle during vibration. The analysis of string vibration is often in connection with musical instruments: Malashin (2011) investigated waves and vibrations taking into account their interactions in musical strings with windings; Stulov and Kartofelev (2014) simulated and analyzed the vibration of a grand piano’s string terminated at a capo bar, which is situated above the strings. Zhu and Zheng (2008) determined the exact response of a translating string with constant tension and varying length. Another work introduced a method for the control of string vibration (Alsahlani et al., 2012) with the application and removal of a constraint at one point on the string. Less publication focused on the effect of aging on vibration properties like Noguchi et al. (2012) where successivelyvibration properties of aged wood were compared with recently cut wood. A similar experimental system was used before in previous works, such as Fouda et al. (1991), where density measurements with stretched fibers were executed. In this paper a modification is performed in the classical equation of damped oscillation in order to characterize the high-speed influences (collision, twanging, etc.) more accurately. Changes in material properties due to artificial aging are described by vibration parameters in the case of the examined PVC material.

2. Experimental

2.1. Test material

In the measurements soft poly(vinyl chloride) fibers extruded from LE 411 type granulate (BorsodChem Kazincbarcika, Hungary) were tested. The diameter value of the specimens was approximately 2 mm.

2.2. Instruments

The aging process was executed in a self-made aging chamber with Sylvania Ultraviolet G30W fluorescent lamps. The PVC fibers were radiated from four directions in the self-made aging chamber. The Fig. 1 shows the positions of the UV sources (4 pieces) in the chamber.

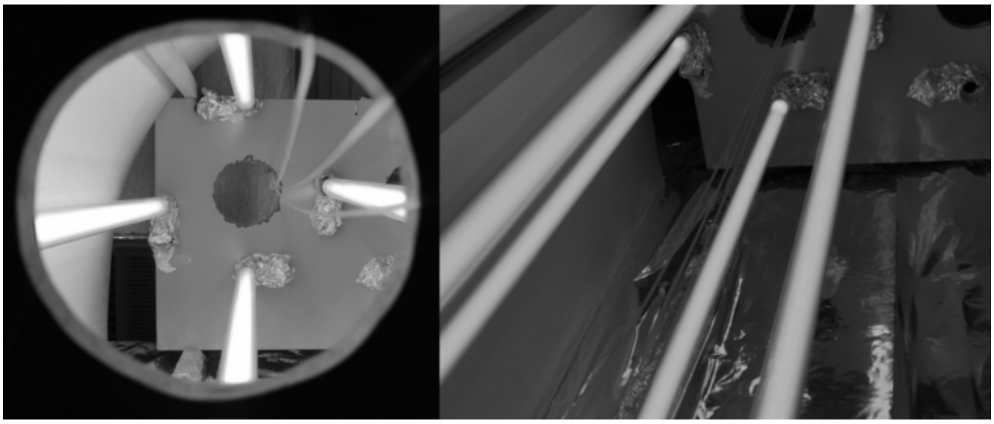

Fig. 1. Aging chamber with one series (3 pieces) of PVC fibers

The tests were implemented on a self-made vibrating table, where vibration measurements were done by a PCB 356A24/NC type triaxial accelerometer and noise measurements by a G.T.A.S. 46AF type microphone, both of them were connected to a Sinus Soundbook MK2_8LE 8-chanel measuring system. We used the Samurai (SINUS Messetechnik GmbH) universal software package to evaluate the noise and vibration results. The experiments were recorded by a Casio Exilim EX-FH 25 photographic apparatus, and the videos were processed using Photron FASTCAM Viewer software. During the tests a Rinstrum N320 load cell was operating.

2.3. Technical execution of tests

A self-constructed vibrating table was built for the measurements. During the tests the fibers were stretched as strings by a tensional force and the specimens were tested successively. The same length strings were fixed at one end (A) at the load cell (B) and ran over two prisms (C) then passed over a pulley (D) and loaded with an 821.16 g mass (E). The distance between the prisms was 800 mm, from the midpoint of this distance the fibers were diverted always to the same direction by 100 mm (F). A millimeter scale (G) was placed on the table surface for the later optical analysis, and the video was recorded by the photographic apparatus (H) viewing from above. We also stuck a triaxial (I) vibration accelerometer on the table surface and a microphone (J) was also working during the measurements. The motion of the specimens following the twanging was recorded with 240 fps. Meanwhile the sound and vibration parameters were also gathered. Schematic drawing of the experiment system can be seen in Fig. 2.

During the tests 3-3 fibers of each aging categories were examined. We analyzed unaged fibers and UV aged fibers, therefore four categories were determined by different aging time: 0 hour; 200 hours; 1000 hours and 2200 hours.

From the measurement results the first ten deflections after twanging of each fiber were determined by using the video records. Moving frame by frame the maximum deflections were specified by the help of the scale under the string. One swinging out of the string was considered to be a deflection (amplitude) so one period is consisted two deflections.

3. Results and discussions

The results were obtained for both the unaged and the aged fibers. The Table 1 includes the first ten deflection averages by the different aging categories and their standard deviation.

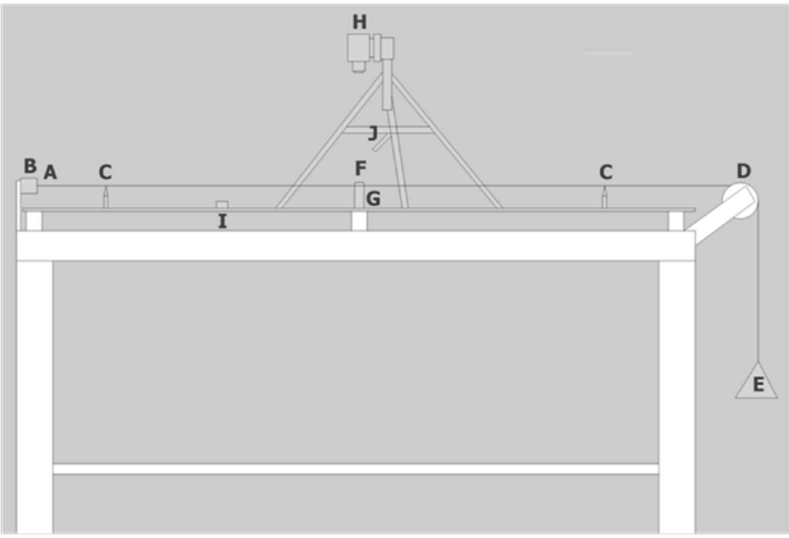

Fig. 2. The experimental system (side view) constructed for the vibration measurements

Table 1. Average of deflection values and their standard deviation after different aging time

	Deflection [mm] (Standard deviation of deflections [mm])									
Aging time	***1.***	***2.***	***3.***	***4.***	***5.***	***6.***	***7.***	***8.***	***9.***	***10.***
0 hour	**86.61** (0.38)	**73.41** (3.18)	**65.80** (5.02)	**55.51** (3.02)	**51.92** (3.35)	**44.23** (3.35)	**43.60** (3.33)	**37.44** (2.79)	**39.16** (3.01)	**33.46** (2.91)
200 hours	**84.21** (2.29)	**73.15** (1.15)	**64.63** (3.35)	**56.48** (1.40)	**52.04** (1.95)	**44.78** (2.56)	**43.36** (1.56)	**38.15** (0.85)	**38.15** (0.85)	**34.63** (0.64)
1000 hours	**83.84** (1.19)	**68.33** (2.00)	**57.89** (1.06)	**48.71** (1.95)	**44.63** (1.40)	**37.78** (1.11)	**36.85** (1.15)	**32.78** (1.11)	**33.52** (1.16)	**30.19** (1.16)
2200 hours	**74.61** (1.02)	**53.54** (2.21)	**45.17** (2.12)	**34.45** (1.52)	**34.50** (1.59)	**28.61** (1.27)	**30.35** (1.44)	**25.74** (0.85)	**28.24** (1.05)	**23.63** (0.71)

Logarithmic decrement as a typical index to characterize damped oscillation is the natural logarithm of the ratio of two successive amplitudes of the same meaning. The values of logarithmic decrements for the first 10 deflections can be seen in Table 2.

From Table 1 and Table 2 important property-changes can be identified. It can be seen, that the deflection of the same meaning values is decreasing with aging time, and the logarithmic decrement also represents differences between fibers aged for different time. Representing these changes, the Fig. 3 shows the deflection changes focusing on the first 3 deflections after different aging time.

Fig. 3 illustrates well how the deflection values decrease after increasing aging time, highlighting the first 3 deflections. After 2200 hours of aging with UV lights a significant change can be identified in the amplitude values. Not only the deflection values change by increasing aging time but the frequency also. Fig. 4 represents the first ten maximum deflection averages after twanging versus time.

Table 2. Logarithmic decrement values after different aging time

Aging time	*Logarithmic decrement*							
	1-3	**2-4**	**3-5**	**4-6**	**5-7**	**6-8**	**7-9**	**8-10**
0 hour	0.27	0.28	0.24	0.23	0.17	0.17	0.11	0.11
200 hours	0.26	0.26	0.22	0.23	0.18	0.16	0.13	0.10
1000 hours	0.37	0.34	0.26	0.25	0.19	0.14	0.09	0.08
2200 hours	0.50	0.44	0.27	0.19	0.13	0.11	0.07	0.09

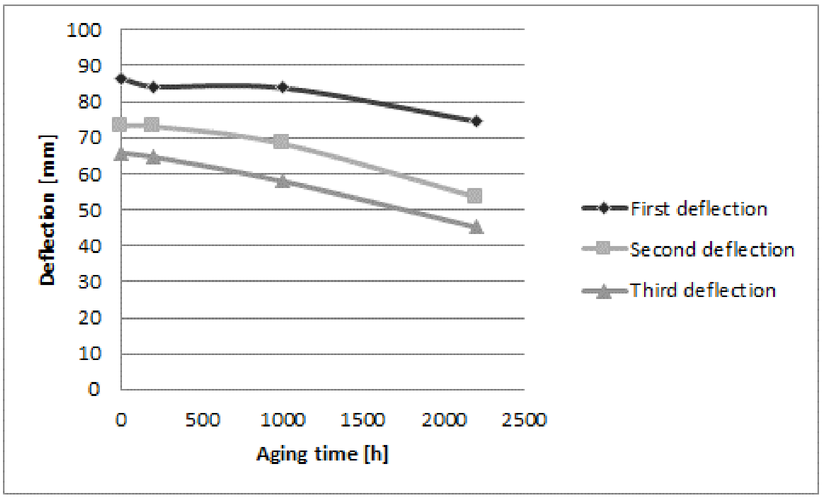

Fig. 3. Changes of the deflection values after different aging time

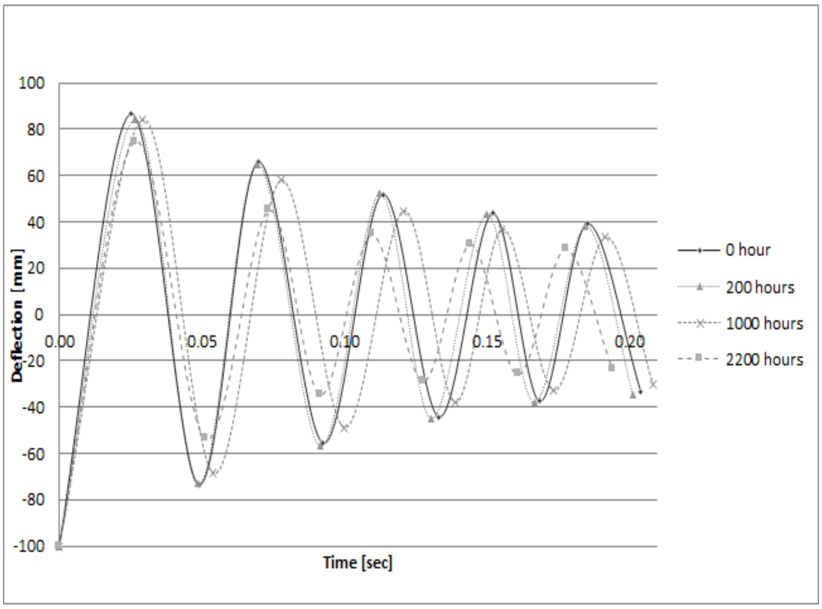

Fig. 4. The averages of first ten deflection of fibers after twanging versus time

From Fig. 4 not only the lower deflection values can be identified with increasing aging time, but the changing of the oscillation frequency values also. It can be seen, that the frequency is lower (the period of oscillation is higher) in the case of 1000 hours aging time, then in the case of unaged fibers. The frequency after 2200 hours aging time is increased, and shows a slightly higher value then the unaged fibers' frequency.

From these results deeper examination of the oscillation becomes interesting and necessary. We have seen so far, that the deflection values change significantly and there is also a detectable change in the frequency of the different tests. It becomes expedient to investigate not only the amplitudes of the oscillation but also the string's position in every available frame. Therefore, the string's position versus time was also defined for the same time interval as before (first 10 deflections) in every video. From this we gain a more accurate view on the oscillations and their damping processes. The mathematical model of the string with damping (Eq. 1) (Alsahlani et al., 2012):

$$T\frac{\partial^2 y}{\partial x^2} = \rho\frac{\partial^2 y}{\partial t^2} + C\frac{\partial y}{\partial t} \qquad (1)$$

where T is the tension, ρ is the mass per unit length, and *C* is the string's damping coefficient. Applying the $y(x,t) = X(x)\phi(t)$ separation of variables the general solution is given by Eq. (2):

$$y(x,t) = e^{-\xi\omega t}\{\alpha\cos\lambda x + \beta\sin\lambda x\}\left\{A\cos\left(\omega\sqrt{1-\xi^2}\right)t + B\sin\left(\omega\sqrt{1-\xi^2}\right)t\right\} \qquad (2)$$

where:

$$\omega \triangleq c\lambda\,,\ \xi \triangleq \frac{K}{2c\lambda}\,,\ K \triangleq \frac{C}{\rho}\,,\ c \triangleq \sqrt{\frac{T}{\rho}}$$

With simplifications in our case ($x = \frac{l}{2}$) we get the following generally used equation for the string's damping oscillation:

$$y(t) = \mathrm{A}_0 * e^{-\beta t} * \cos(2\pi f_0 t + \varphi) \qquad (3)$$

where A_0 is the amplitude, β is the damping coefficient, f_0 is the oscillation frequency and φ is the phase. The experimental data is more precisely described by the Eq. (4) (the average of the adjusted R^2 values with Eq. (3): 0.79; with Eq. (4): 0.93) thus for the analysis of the first period of the damped oscillation, we fitted the following equation on the damped curves:

$$y(t) = \mathrm{A}_0 * e^{-\beta t} * cos(2\pi(f_0 + f_t t)t) \qquad (4)$$

where f_t is the angular acceleration. The Fig. 5 represents the difference between the two fitting functions' results. The average results for β, f_0 and f_t can be seen in Table 3.

Based on these results it can be seen that the β well characterizes the damped oscillation after different aging time in our case. For further examination we found necessary to focus on the relationship between β, f_0, f_t and other parameters. Therefore, material tests were performed, where each fibers' tensile strength (σ), elongation at break (A) and Young modulus (E) were measured. These parameters are generally measured in aging experiments, when relevant information of the degradation's level is aimed.

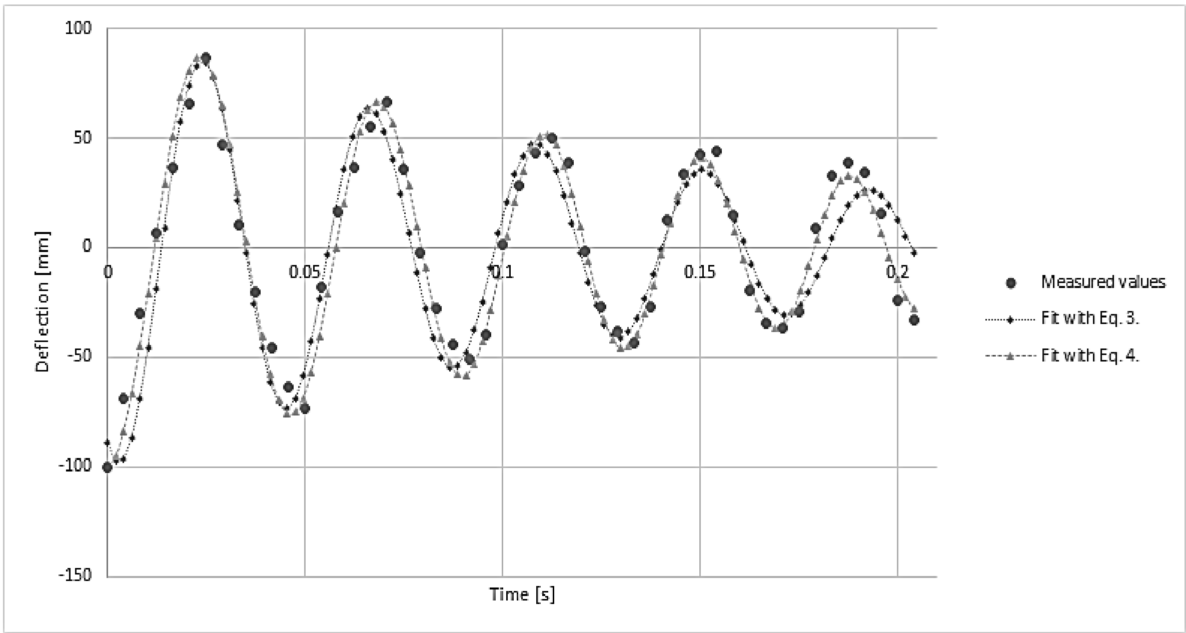

Fig. 5. A sample's results for the two different fitting functions

Table 3. The average values of the examined parameters after fitting processes

Aging time	***Parameters***					
	β		***f_0 [Hz]***		***f_t [1/s²]***	
	value	***standard deviation***	**value**	***standard deviation***	**value**	***standard deviation***
0 hour	5.94	0.51	20.92	1.27	19.73	4.83
200 hours	5.97	0.17	20.45	0.83	23.88	1.35
1000 hours	6.81	0.39	17.95	0.05	31.78	3.20
2200 hours	9.52	0.09	20.54	1.46	30.91	4.07

In previous study, where the tensile strength of PVC was measured after different weathering time (El Raghi et al., 2000), an increase was identified in tensile strength compared to the unaged samples. Our results are similar to that one, because we also measured higher tensile strength values than in unaged case. As it was expected the elongation at break values were decreasing as the aging time increased like in previous weathering experiments (El Raghi et al., 2000; Ito and Nagai, 2007; Real et al., 2003). The Young modulus also significantly increased versus time.

For finding connection between these commonly measured parameters (σ; A; E) and the three parameters introduced in Eq. (1) (β; f_0; f_t) correlation coefficients were calculated. We found that in our measurements β showed a significant negative linear relationship (correlation coefficient (r) = -0.86) with elongation at break. The value of β shows an increase versus aging time, while the elongation at break decreases. With their linear relationship both of these parameters well characterize the degradation of the specimens. But we think that the main advantage of our examination is the fact, that it is a non-destructive method. Major linear correlation was not identified between f_0 and the other parameters, but f_t was strongly correlated to the σ (r=0.96). A (r=-0.93) and E (r=0.96) values. As this examination based on a dynamic test f_t well characterizes the material's properties and shows a strong relationship with the mechanical parameters.

Examining and gathering information about the material's mechanical properties and degradation level in a non-destructive way can be the main advantage of using this kind of vibration-based technique. From determining the introduced parameters, a reasonably accurate status of the degradation in the PVC fibers becomes achievable. With the introduced vibration diagnostic method used for fibers the determination of the degradation changes by vibration parameters in the case of semi-finished materials (e.g. fibers, rods, plates and pipes) may be possible.

4. Conclusions

PVC fibers become more rigid as the UV aging time increases. This rigidness can be detected by stretching the fibers as strings and twanging them. Examination of the damped oscillation shows lower deflection values with higher aging time. In this work characteristics and parameters were identified and calculated for the damping process and these parameters' relationships were examined to other commonly measured indexes. The identified parameters enable to evaluate the degradation level of the test material in a non-destructive way. This new approach of determination of property changes in PVC fibers exposed to photochemical aging can be an applicable method.

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