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INFLUENCE OF ARTIFICIAL AGEING ON PROPERTIES OF ARCHITECTURAL MEMBRANE AND MEMBRANE CONNECTIONS

LORETA ŠVEIKAUSKAITĖ*, VAIDA DOBILAITĖ† AND MILDA JUCIENĖ†

* Kaunas University of Technology, Institute of Architecture and Construction, Tunelio str. 60, 44405
Kaunas, Lithuania
E-mail: loreta.sveikauskaite@ktu.edu

† Kaunas University of Technology, Institute of Architecture and Construction, Tunelio str. 60, 44405
Kaunas, Lithuania
E-mail: vaida.dobilaite@ktu.lt; milda.juciene@ktu.lt

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Summary. This study presents the investigation of the changes in mechanical properties of PES/PVC architectural membrane and three types of itsconnections, including overlap seam, pocket connection and laced connection (with grommets) exposed to different accelerated aging conditions. Before the aging, all specimens were rubbed with fine coated abrasive sheet (P180), that to simulate the effects of dust and other airborne impurities. The test objects were heated at a temperature of 70 °C (thermal aging) as well as immersed in water, exposed to cold and exposed to dry heat (cyclic aging). Trapezoidal tear and uniaxial tensile tests were caried out and the failure performance were discussed. A strength reduction factor were determined revealing the effect of aging factor on membrane/bonding strength. The results of the research showed that in most cases the mechanical properties of the membrane and connections change after exposure to the aging factors under investigation.

1 INTRODUCTION

Structures made of architectural membranes are quite popular due to their light weight, excellent performance and construction properties. Such popularity is related to the ability to implement impressive architectural ideas, as well as with low construction costs, fast structure installation and sustainable use of resources[1, 2]. As regards the design of structures made of architectural membranes, it is necessary to take into account changes in mechanical properties of these materials due to long-term environmental impact and constant loads during use.

Architectural coated membranes are usually directly exposed to a natural environment, i.e. sunlight, tempetature changes, rain, atmospheric pollution, wind, friction between sand and material, etc., resulting in deterioration of functional properties of these materials over time[3, 4, 5]. High temperature and significant temperature fluctuations can accelerate harmful chemical reactions and soften some polymers[6]. Heat and moisture induce degradation of polymer coating surface, change mechanical properties of architectural coated fabrics[7]. Highly wind-blown sand or gravel can damage the surface layer of the architectural membrane[8].

Various loads and harmful environmental factors have an impact on changes in physical and mechanical properties, gradually changing their strength, elasticity, tear strength, which has a significant impact on structure safety and reliability and shortens the life cycle of the structure[2,9]. The expected durability of these structures depends on durability of materials used in the buildings and their connections. For large-scale constructions, architectural coated materials are connected (usually by welding) and fastened under tension. The service life of a whole structure depends on durability of the material and connections, constant stresses, different loads applied when stressing the structure. Studies by many researchers, along with changes in other physical properties after aging, are based on the assessment of changes in the tensile strength of architectural membranes[3, 10, 11, 12]. Basic mechanical parameters of these materials were found to decrease with increasing aging duration, including tensile strength, modulus of elasticity and tear strength[5, 9, 13, 14]. The tensile strength and tear strength characteristics are relevant to safety and serviceability requirements of the structure[9]. Membrane tear strength and tear propagation resistance is critical to structural integrity of a building. Tear strength is one of the key characteristics associated with the building's lifetime. Even micro cracks can affect, propagation of which under extreme conditions can cause serious damage[15]. Knowing the nature and strength of tear of membrane and connections and trying to avoid breakings during manufacturing or installation of structures made of architectural membranes can effectively increase the service life of the structure[9].

As due to different layers during welding, fittings, etc., architectural membrane connections have a different strength and stiffness than a membrane without a connection; this can be a decisive factor in determining the service life of the entire construction made of the architectural membrane. It has been found that the welded seam and the flexible edge connection can reach about 90 % of the membrane strength, the glued seam reaches about 80 % of the membrane strength and the rigid edge connections have a lower strength up to 75 %[16]. Mechanical strength of connections is a very important factor ensuring durability of the entire membrane structure. In order to ensure high level of performance of architectural membrane structures, the environmental resistance of connections must be investigated and assessed during the design of such structures, but there is a lack of research on architectural membrane connections, although connections are very important for general safety and reliability of the entire structure.

The aim of this thesis is to investigate changes in mechanical properties of architectural membranes and its connections under different conditions of artificial aging. Research results could be useful for improvement of technological solutions for coated materials and their connections and in expanding research in this area.

2 MATERIALS AND METHODS

The investigations were carried out with PVC-coated polyester membrane suitable to use in tensioned membrane structure. The fabric taken for the research (fabric code M) had the following structural parameters, areal density was 848 ± 2.2 g/m^2, thickness was 0.65 ± 0.01 mm, number of yarns was 5.5 per cm in longitudinal and transverse directions. Weave of basic material was plain, the top of the material was lacquered with acrylic lacquer.

Three types of membrane connections, an overlap seam (OS), a pocket connection (PC) and a laced connection (with grommets) (LC) were selected for investigation (Fig. 1). An overlap seam is a mean of permanent joint the most commonly used in tensile structures to connect adjoining panels of membrane. A pocket connection is one of the flexible curve edges configurations made in such a way, membrane edge is folded and welded along leaving the space to run a cable into inside. The last connection was made as before, but grommet with an overall diameter of 25 mm and 12 diameter of cable hole was inserted into the material to form a laced joint. Such a tape of connection is engineered actual because such temporary or reusable joints allow easy to connect parts of membranes and demountable them if require. A hot air welding method with a Leister Uniplan-500 was used to produce connections. The welding was carried out following these conditions: temperature of hot air was 570 °C, the speed of welding was 5 m/min., the pressure of welding was 2.45 bar.

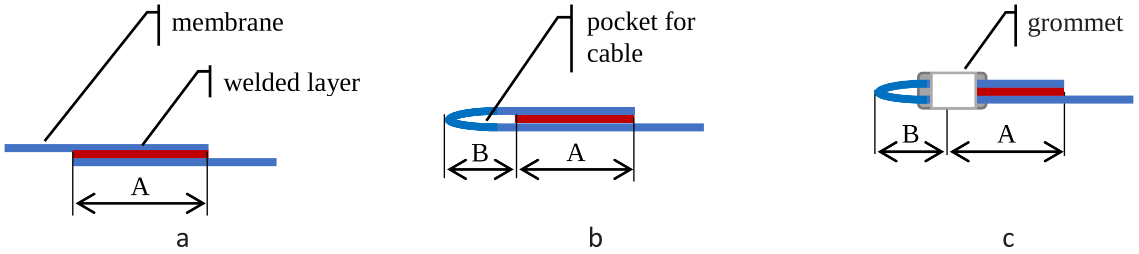

Figure 1: Membrane connections: a - overlap seam, b - pocket connection, c - laced connection, where A is 30 mm, B is 20 mm

For accelerated artificial aging test the specimens without and with three connection types were prepared in longitudinal and transverse directions. Before aging the specimens were pre-treated with fine coated abrasive sheet (P 180) to damage the protective coating layer in order to simulate an impact of dust and other airborne impurities. All test specimens were divided into two parts (Fig. 2).

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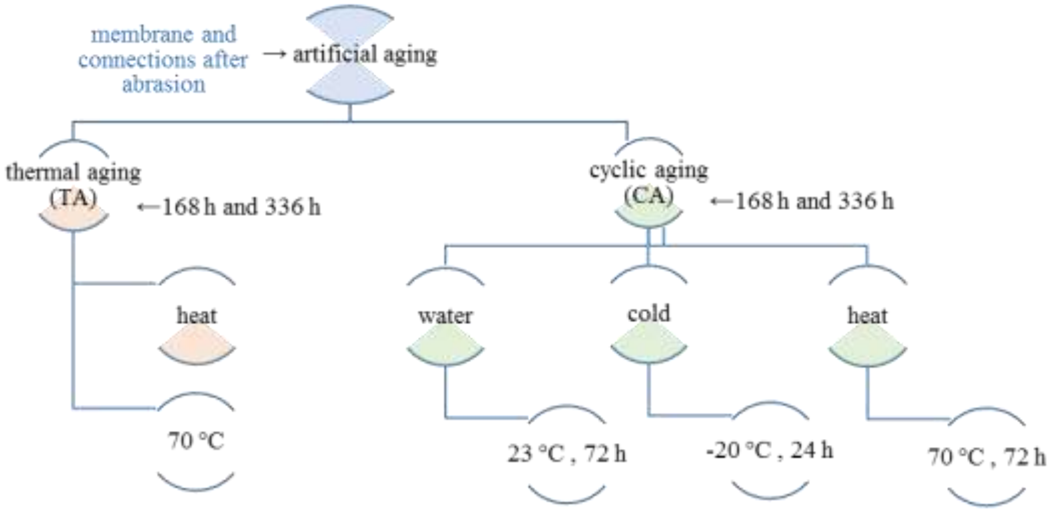


Figure 2: Artificial aging steps after abrasive pre-treatment

The specimens of the first part were subjected to hot air aging at a temperature of 70 °C and at atmospheric pressure (thermal aging) according ISO 1419 standard. The specimens from second part were used to perform cyclic aging according ISO 9142. The specimens were immersed in water at temperature 23 °C for 72 h and later exposed to cold (-20 °C) for 24 h and dry heat (23 °C) for 72 h. The evaluation of membrane and it's connections properties was carried out after 168 h (1 cycle) and 336 h (2 cycles) of accelerated aging and 24 h conditioning in temperature (23 ± 2) °C and relative humidity (50 ± 5) %.

The uniaxial tensile and trapezoidal-tear tests were carried out according ISO 1421 and EN 1875-3 standards respectively. A universal test machine BTI FB-050 TN (Zwick) was used for the test, when the constant speed of the clamps was 100 mm / min. The connections were tested according the above mentioned standard positioning the joint in the middle of working length

Tear strength (N), maximum force (N) and elongation at break (%) of the aged PES/PVC membrane and connections from this material with those of the unaged were compared. All obtained data were statistically processed using statistical analysis methods of quantitative research. The residual tensile strength after thermal and cyclic aging, which is the percentage change in tensile force of aged and initial speciments, was estimated. Strength reduction factor considering aging impact was calculated as ratio between the initial and aged specimen tensile properties. It is calculated by the equation (1)[17]:

$$A=\frac{n23}{nw23} \tag{1}$$

where n_{23} is the tensile force of the initial samples at room temperature of 23 °C, n_{w23} is the tensile force of the aged samples at room temperature 23 °C.

The failure modes of membrane and connections were also studied to observe the influence of aging factors on change in properties.

3 EXPERIMENTAL RESULTS AND DISCUSSION

The PES/PVC coated material M and the three types of connections OS, PC and LC were treated with abrasive P180 grain material prior to aging to simulate the friction caused by dust and other airborne impurities. The effect of abrasion was evaluated by the change in mass of the sample. The results showed that weight loss of the rubbed specimens was negligible (up to 0.05 % of initial weight), hence, it can be stated that the specimens were not significantly damaged. It should be noted that the aim of the abrasion was to carry out micro cracks in the protective layer of acrylic lacquer. This layer which protects the coated material from harmful environmental factors such as UV radiation, moisture, industrial pollutants and reduces the migration rate of plasticizers to the surface[4]. Within the scope of the study, it is believed that damage of the protective layer of laquer can accelerate the influence of aging factors.

Due to sensitivity of architectural membranes to environmental factors, it is important to evaluate characteristic of the tear strength after aging in order to avoid damage to structures. The tear failure test measures the tear strength when individual threads of a fabric break due to deformation caused by tensile.

The coating is known to reduce the tear strength of fabrics by reducing the mobility of yarns in the fabric structure. The bond between the basis and coat is important for tear strength. Fabric yarn elasticity and weaving density are the main factors affecting the tear strength of coated fabrics[18, 19]. The integrity of architectural membranes depends on the aging of PVC coating, as it loses its protective properties during aging changing in the mechanical strength of the material as a result.

Analysis of tear failure modes showed that tapes of yarn pulled out and even fracture are typical for membrane M and joints from this material. It was revealed that the tear failure of the membrane M and the OS seam is similar, in this case even fracture appears (Fig. 3 a, b). The PC connection tear analysis demonstrated that the warp threads of the specimens in longitudinal direction remained unbroken after they are pulled out (Fig. 3 c). Meanwhile, a even tear fracture is observed for specimens cut in transverse direction (Fig. 3 d). When analyzing the tear failure of the LC connection with grommet (Fig. 3 e), the tear to the grommet is most often observed. In individual cases, complete tear of the specimen is detcted (Fig. 3 f).

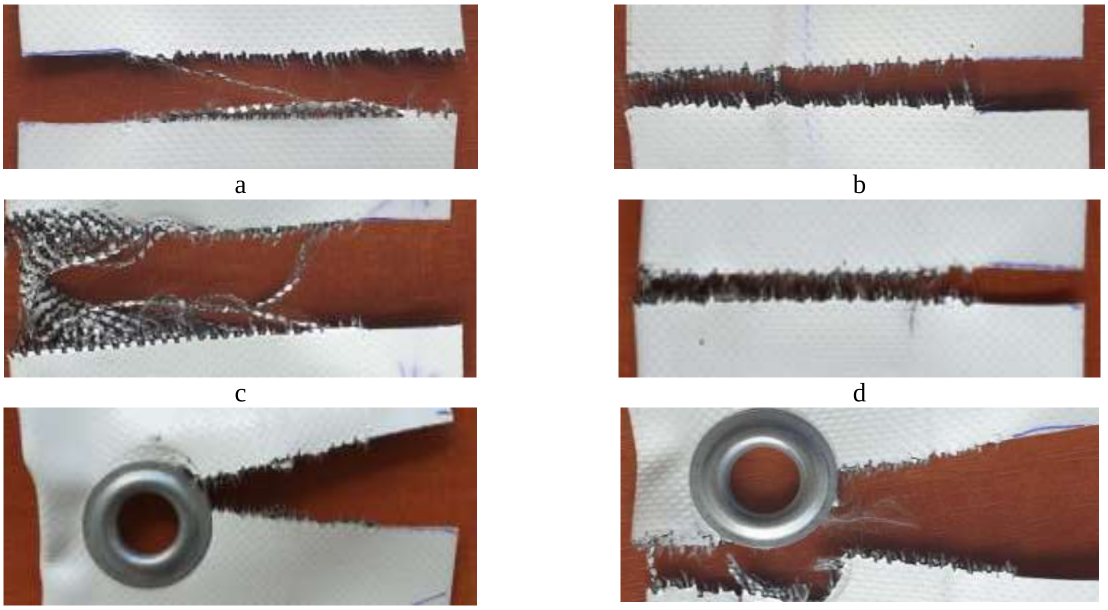

a b c d e f

Figure 3: Failure modes of specimens in tear test: a –M, b – OS, c, d – PC, e, f – LC

The results of the tear strength are shown in Fig. 4. Tear strength of the membrane M was about 198 N in longitudinal and about 197 N in transverse direction, for the OS seam it was about 244 N and about 236 N in the appropriate directions. The tear strength of OS is about 20 % higher compared to the membrane M. Pocket connection PC tear strength is significantly higher that the OS seam. The tear strength for the PC connection is about 413 N in longitudinal and 365 N in transverse direction. The tear strength of the PC connection is even twice as high, compared to the membrane. Higher tear strength is obtained due to two layers formed at the point of hot welded connections. It is obvious that after insertion of LC fittings into the analogous PC connection the tear strength of the connection decreases again due to the broken membrane threads after insertion of a grommet (about 38% compared to PC connection). LC connection showed the greater differnce of the tear strength in longitudinal and transverse directions, about 313 N and 246 N. LC connection tear strength is up to 25 % higher compared to the membrane M. The results of the study show that the nature of the tear and the change of the tear strength are significantly affected by the fittings. Compared to a PC connection without grommet, the tear strength in both longitudinal and transverse directions is lower for an LC connection, therefore lower tear strength is sufficient to damage this connection, but in most cases specimens do not break completely as the grommet help to stop further tear propagation.

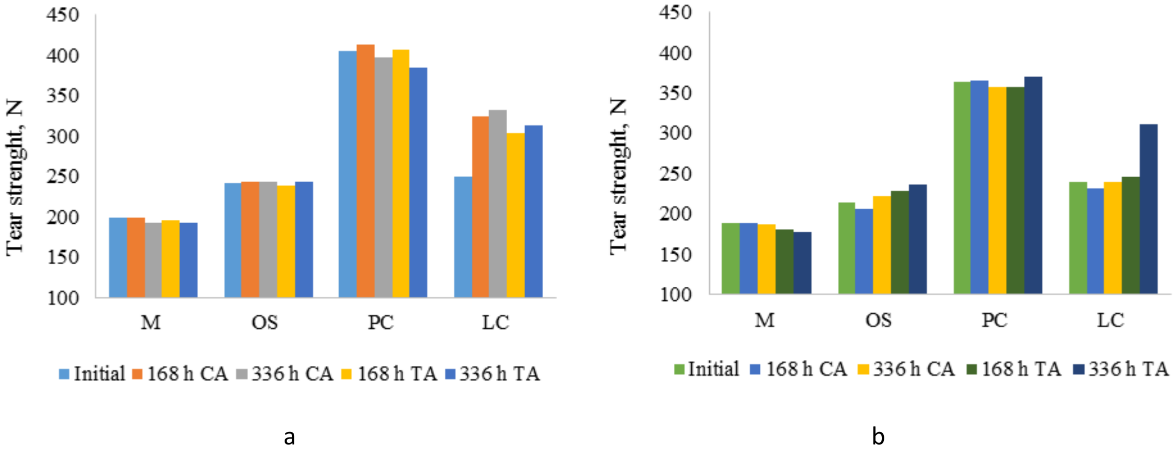


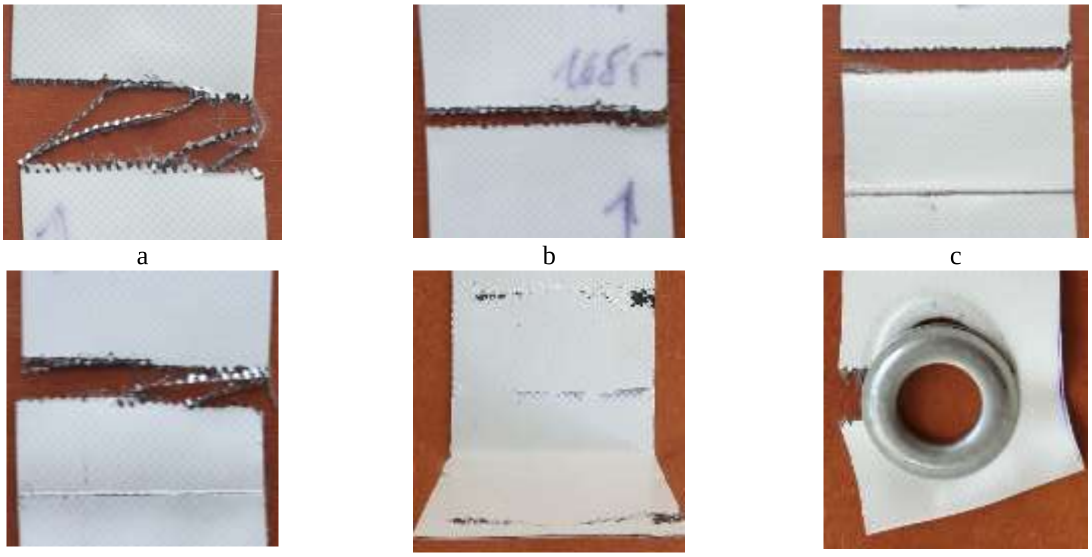
Figure 4: Results of tear strenght in: a - longitudinal direction, b - transverse direction, aging is marked CA, thermal aging is marked TA

The results of the investigation of the influence of aging on tear strenght showed that the tear strength of the membrane M did not change after 168 h of cyclic aging. The change was not significant and after 336 h of cyclic aging, for both membrane M and connections OS and PC change in tear strength varied about 4 % (in longitudinal and transverse directions). Meanwhile, the tear strength of the LC connection with a grommet for the specimens in longitudinal direction increased by more than 30% both after 168 h and after 336 h of cyclic aging. The analysis of 168 h and 336 h thermal aging showed that the change in tear strength of specimens of membrane M and connections OS and PC in both directions was also insignificant (up to 6 %). After 336 h of thermal aging, the tear strength of the OS specimens in transverse direction changed by 10 %. Significant changes were again observed at the connection LC with a grommet. After 168h of thermal aging of the LC connection specimens in longitudinal direction the tear strength changed by 22 %, and after 336 h by 26 %, while in longitudinal direction after 168 h of thermal aging the tear strength changed by only 3 %, and after 336 h of aging it increased by 30 %. This change may have been due to a grommet inserted in the connection, which could have affected the high dissemination of the tear strength results. The tear strength can also be influenced by other factors such as the length of the notch[20].

The obtained results showed that both thermal and cyclic aging did not have any significant effect on the tear strength of the membrane M, overlap seam OS and pocket connection PC. After aging, these joints do not change their tearing properties and change only to the extent that the properties of the membrane itself change. The tear strength after aging varied within the error limits, which means that the membrane M and its connections remain sufficiently resistant to tearing after aging and meets the requirements for tear resistance specified in EN 15619. Besides, the tear failure studies with other PES/PVC coated materials that have been exposed to abrasives, humidity and high temperatures have shown similar results[14]. High temperatures have been found to have a greater effect on changes in tear strength compared to other factors. High temperatures change the structure of the polymeric material, causing the material to lose its plasticity[6, 10].

During analysis of the type of tensile failure of the membrane M speciments, a case of yarn pulled out was observed (Fig. 5 a), as in the case of tear failure. Stress concentration increases load on some of the yarns, causing the weaker yarns to break and tear to spread throughout the specimen. The nature of the fracture depends on the strength of the bond between the coating and the fabric. In some cases the failure is a yarn pulled out, in others an even fracture (Fig. 5 b).

Coating increases strength of material and prevents spread of failure[15, 20]. The nature of failure is also influenced by the direction of tension [21]. The seam OS has a even failure, which usually occurs right next to a welded seam, and a break when yarn pulled out (Fig. 5 c, d). Analyzing welded butt seams, the researchers found that failure can occur when the seam or adjacent membrane failure, fibers pulled-out out, welded layer slippage and mixed failure[16]. The failure of PC connection was generally even, in some cases the pocket connection broke from the base when the specimen was exposed to 168 h of thermal aging and after to 336 h of cyclic aging (Fig.5 e). This indicates that aging weakens welding seam connection. In all cases the connection LC broke near to the grommet (Fig. 5 f).

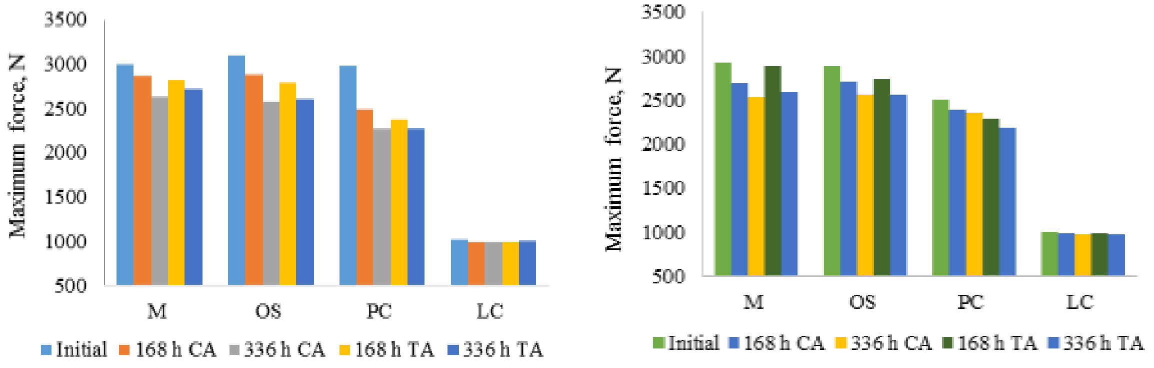


a b c

d e f

Figure 5: Failure modes of specimens in uniaxial tension: a, b – M, c, d – OS, e– PC, f - LC

The results of maximum tensile force are shown in Figure 6. Comparing the maximum force of membrane M , of the seam OS and PC connetction is found to be similar. The membrane maximum force was about 3000 N in longitudinal and 2930 N in transverse direction, for the seam OS - about 3090 N in longitudinal and about 2880 N in transverse direction. Pocket connection PC in transverse direction is about 14 % weaker that the membrane. PC maximum force was about 2980 N in longitudinal and 2510 N in transverse direction. The connection LC with a grommet was the weakest of the ones tested - more than 66 % weaker than the membrane. The maximum force for LC connection was about 1020 N in longitudinal and 1000 N in transverse direction. This shows that the connection is significantly weakened due to insertion of a grommet into a flexible edge of the connection.



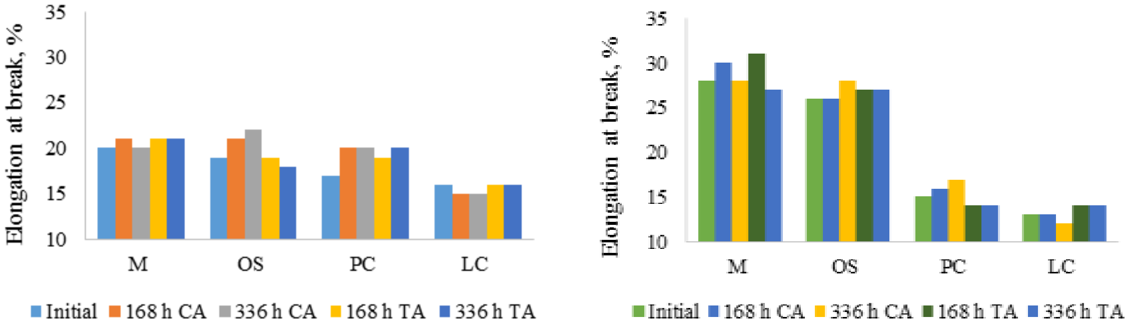
a b

Figure 6: Results of maximum tensile force: a - longitudinal direction, b - transverse direction, where cyclic aging is marked CA, thermal aging is marked TA

The analysis of the change in tensile force for specimens after friction and 168 h and 336 h cyclic aging revealed a decrease of maximum force, except for LC connetion. Of LC connection with a grommet changed insignificantly after aging was about 4 %. For M membrane, the maximum force did not change significantly after 168 h of cyclic aging - about 4 % in the longitudinal direction and 8 % in the transverse direction. After 336 h of aging the change was from 12% in longitudinal to 14 % in transverse direction. A similar trend is observed for the seam OS - the maximum force changed up to 7 % in longitudinal direction and up to 6% in transverse direction after 168 h of aging, and after 336 h of cyclic aging decreased by about 16 % in longitudinal and by 11 % in transverse direction. The maximum force of connection PC in longitudinal direction decreased from 16 % after 168 h to 24 % after 336 h of cyclic aging, in transverse direction the change was only about 6 %.

The analysis of thermal aging showed a decrease in maximum force both for membrane M and connections OS, PC and LC specimens. Membrane maximimum force changed from 6 % after 168 h of aging (in longitudinal direction) to 11 % after 336 h of aging (in transverse direction). Compared to the first cycle, the membrane strength decreased approximately by 1.8 times after cycle 2. This happens due to the loss of plasticizers after thermal aging, which reduces the strength and stiffness of membrane and seams [11, 22]. The maximum force of the OS seam in longitudinal direction changed from 9 % after 168 h to 16 % after 336 h aging. Meanwhile, the maximum force of the PC connection decreased to 21 % already after 168 h aging, and to 24 % after 336 h aging. Changes in the maximum force of the LC connection with the grommet were not significant (about 3 %). Other researchers studied the effects of temperature on seam strength and was found that seam strength increases with increasing width of the seam connection[16]. In the study of hot air welded joints for the repair of waterproofing membranes, it was found that thermal aging increases stiffness of membranes, resulting in changes in their mechanical strength[22].

The results show that elongation at break for membrane M increases up to 11 % after 168 h thermal aging and up to 7 % after cyclic aging (Fig.7). For the seam OS elongation increases up to 16 % after 336 h cyclic aging, and for the connection PC the change in elongation reaches 18 % after 336 h thermal and cyclic aging (in longitudinal direction). For connection LC with a grommet elongation at break after 336 h of thermal aging was about 8 %, a similar change was observed after cyclic aging. As can be seen from Figure 7, both thermal and cyclic aging had a similar effect on elongation at break. This is affected by the exposure time and the type of membrane connections. After inserting additional fittings into the connections, their tensile force is reduced.



a b

Figure 7: Results of elongation at break a: - longitudinal direction, b - transverse direction, where cyclic aging is marked CA, thermal aging is marked TA

The variation coefficient of tensile and tear tests results sought up to 12 %, however the variation of the tear strength results of the laced connection was higher.

After performing uniaxial tensile tests, the residual tensile strength after thermal and cyclic aging was evaluated. The results of residual strength are presented in Table 1. For membrane M the residual strength ranged from 90.6 % to 87.6 % in longitudinal direction, and from 88.7 % to 86.3 % in transverse direction. With increasing aging duration, the residual tensile strength decreases marginally. No clear trend was observed between thermal and cyclic aging.

Table 1: Residual tensile strength after aging, %

Aging time	Membrane M LD/TD	OS seam LD/TD	PC connection LD/TD	LC connection LD/TD
Thermal aging				
168 h	94.0/98.6	90.6/95.1	79.5/91.2	96.9/99.0
336 h	90.6/88.7	84.1/89.2	76.5/86.8	98.0/97.2

Cyclic aging				
168 h	95.6/92.2	93.2/94.1	83.5/95.2	96.5/98.7
336 h	87.6/86.3	83.5/88.8	76.5/94.0	96.9/98.0

The results showed that the residual strength of both OS and PC connections is slightly lower than of the membrane. This means that connections exposed to both thermal and cyclic aging remain sufficiently durable. Similar conclusions are presented by other researchers[5].

The architectural membranes adversely affected by moisture, high temperatures, cold and other factors; therefore it is necessary to take into account the destructive effects of these factors on architectural materials and to assess the strength reduction factor. This factor is needed to specify the safety range of the structure. The highest value among all tested specimens was found to be 1.30 (in longitudinal direction) for the connection PC specimen after 336 h of thermal aging at 70 °C. This corresponds to a 23 % reduction in tensile strength (Table 2).

Table 2: Strength reduction factors

Aging parameters	Thermal		Cyclic	
	168 h LD/TD	336 h LD/TD	168 h LD/TD	336 h LD/TD
Membrane M	1.06/1.01	1.10/1.13	1.04/1.09	1.14/1.26
OS seam	1.10/1.05	1.19/1.12	1.08/1.06	1.20/1.13
PC connection	1.26/1.10	1.30/1.16	1.19/1.05	1.30/1.06
LC connection	1.03/1.03	1.02/1.01	1.04/1.04	1.03/1.05

The analysis of the results both the membrane and the connections remain sufficiently durable after cyclic and thermal aging. By estimating the strength reduction coefficient, it is possible to predict the influence of one or another aging factor on the reduction of resistance and to apply the values when designing structures from architectural membranes. In order to obtain more detailed results on the changes of architectural membrane and their connections after aging, it would be appropriate to include more aging factors and prolong the duration of the effects of aging.

4 CONCLUSIONS

The results of the study showed that both thermal and cyclic aging did not significantly affect the tear strength of the membrane and its overlap seam and pocket connection (change up to 10 %). After artificial aging, the membrane and its connections remain sufficiently resistant to tearing and meet the requirements for tear resistance. Studies have shown that the grommet inserted into the edge connetction changes the tear strength and gives a greater variation in the results, so it is proposed to increase the number of specimens and perform further studies. The results revealed that tear strength of the connections is higher than the membrane. The tear strength of the overlap seam and the laced connection with grommets increase up to 20-25 % compared to the membrane, while the pocket conection even doubles.

The maximum force of the overlap seam and pocket connetion was found to be similar to that of the membrane. Maximum force of the pocket connetion was being 14 % lower than that of the membrane in transverse direction. The weakest of the connetions was the laced connetion with the grommet. It reached approximately 34 % of the maximum force of the membrane.

Membrane and connections were found to change tensile strength after thermal and cyclic aging. Membranes maximum force decreased by about 11 % after thermal aging and up to 14 % after cyclic aging, overlap seam about 17 %, pocket connection up to 24 %, laced connection with grommet maximum force changed slightly about 4 %.

After thermal aging, the residual tensile strength of the membrane is from 91% in the longitudinal to 88% in the transverse direction, after cyclic aging from 88% in the longitudinal to 86% in the transverse direction. The results showed that the residual strength of the membrane connections is slightly lower than that of the membrane. This indicates that after artificial aging, connentions remains sufficiently resilient and still meets design requirements.

Assessing the strength reduction factor, it was found that thermal aging reduced the tensile strength of the pocket connection. The value determined was 1.30 in the longitudinal direction of the sample. When designing structures from membranes, it is recommended to take into account the reduction of membrane and connections strength due to various environmental factors.

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