Characterization of aged textile for archeological shelters through thermal, optical and mechanical tests

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The paper deals with the measurements of thermal, optical and mechanical properties for aged textiles. The use of textiles for building temporary shelters is a widespread common practice for the protection of archaeological sites. Temporary shelters often become long-term structures, because of the necessity of prolonged excavation and the need to gather sufficient resources to design and build a permanent shelter. Materials and structures of temporary shelters are often less expensive (and, unfortunately, less durable) than permanent ones: their major advantages consist in their flexibility, modularity, easy and fast assembly and dismounting, reversibility, low impact on the soil and ruins and impermeability. Therefore, the authors studied the effects of ageing on a very common and low cost textile for temporary shelters in a polluted environment through the heating test, reflectance spectrometry, colorimetry and uniaxial mechanical tests, with the aim of exploring the potential applications of fabrics that usually do not fit with high mechanical stress but have a widespread use for small structures. The authors used an integration of non-destructive tests in three ageing conditions and, due to their destructivity, they applied the mechanical tests only in the initial and final ageing condition.

Keywords: Technical textile, Textile durability, Infrared thermography, Fiber optic reflectance spectrometry, Uniaxial mechanical behaviour, Archaeological sites

1. Introduction

This paper shows the role of non-destructive testing (NDT) in the characterization of innovative materials for the protection of archaeological sites. Over recent years, several papers have shown the change in the trend of designing shelters in archaeological areas: mainly for aesthetic issues for effective protection involving an as low as possible impact on the micromanagment of the site. The protection of archaeological sites requires a multidisciplinary approach that safeguards the remains of the ruins on the site, with a delicate balance of sustainable use and mitigation of the negative interaction on the exposed surfaces with the environment. In addition to this, there is the question of site management, continuous maintenance and the optimization of the available resources. At present, the perspective is to mitigate the causes of field damage as much as possible; the relocation of the finds in a museum is preferable only in the case of the impossible conservation on site, even where the museum is situated on the same archaeological area or nearby it. The development of innovative shelters to protect the ruins remains pivotal in all the steps of finding-excavation-restoration-display of the architecture [1].

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To build a shelter from the excavation phase (therefore before the restoration) of the finds and maintain it during visitor display means satisfying many requirements of different types, and that belong to many different scientific disciplines. Only a close collaboration of archaeologists, scientists, restorers, landscapes designers, etc. can meet such requirements.

At present, the compelling concern of conservators, scholars, designers, and the authorities for the protection of archaeological areas requires the testing and adoption of new solutions that better meet the requirements of conservation. The protection of ruins in archaeological areas represents one of the controversial perspectives for the preservation and promotion of local historical resources. In previous publications, the authors have analyzed many aspects [2–5] of the present debate, among them the evidence that traditional shelters can contribute to damage instead of protecting ruins. On the contrary, the design of new shelters needs to combine the requirements for preservation: compatibility and reversibility of new materials, to be waterproof and breathable for moisture, reflecting the solar rays while allowing the display of the findings, not releasing any dangerous substances under critical conditions like fire etc. New issues concerning their use including

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flexibility, feasibility, low maintenance costs and easy dismantling to allow the reuse of the shelter in different locations and/or seasons, are now under debate too. In fact, the use of temporary or seasonal shelters increases as they better respond to a more flexible management of archaeological areas.

While a covering is not a mandatory requirement for the protection of most archaeological finds, the design of even a small canopy constitutes a challenge for the safeguarding of particularly fragile sites. Causes of damage include: rain (that causes loss of mortar binders and facilitates the growth of biological patina); wind (mechanical stress and abrasion of surfaces); solar rays (thermal stress, different and opposite dilatation of materials); ultraviolet (UV) rays (damage to colors and pigments); fast evaporation/condensation cycles (causing salt crystallization and its spread both on surfaces and within materials); and their combinations [6]. The most common pathologies connected with the presence of water are the chemical dissolution of binders, the presence of salt efflorescence and subflorescences, and biological attack, which can lead to spalling, flaking, cracking and exfoliation. Moreover, the landscape of the archaeological site, including changing weather conditions throughout the year and day, imposes an accurate assessment of the environmental impact coming from the new shelters.

An increasing number of tensile structures composed of a thin pre-tensioned membrane as a covering element and supported by light structural elements have been built as protective shelters for archaeological or heritage areas. They potentially offer several advantages such as high flexibility, low visual impact, natural shapes, modularity, suitability for any geometry, reusability, lightness of supporting structure, easy transportation, low maintenance requirements and fast installation or dismantling. Nevertheless, the performance of the technical textile materials needs further investigation, because their behavior is not yet perfectly known under severe climatic conditions and pollution [7–9].

Recent research [10–12] on high performances textiles and ultra-light structures is very promising, and brings an important innovation concerning the realization of shelters, together with meeting most of the listed requirements. Nevertheless, scientific literature does not report enough information regarding the durability and drop of performance of textiles, especially if exposed to pollution or aggressive environments [14].

This paper describes the tests of a PVC-coated polyester textile, mostly commonly used for multi-purpose shelters and the comparison of its characteristics and performance throughout 65 months of natural ageing in a polluted environment. The choice of the PVC-coated fabric among many tested textile materials was led by its cost-effectiveness that allows a widespread use and application on the field and the suitability for a provisional shelter application. Nevertheless, a wider range of types belonging to the same PVC-polyester family, different weights, kind of coatings and finishing layers, allow the designer to make the most effective choice of the technical textile in relation to the expected service life of the shelter [15–17].

The aim of this work was to apply a multidisciplinary approach to study the effects of natural ageing on textiles, and proposing a preliminary procedure to evaluate “health conditions” of aged shelter textiles in terms of durability, decrease in specific performance and thermal protection. This would also allow the authors to measure the condition of the textile both in the laboratory and in situ where even more knowledge of the condition and the efficacy of the protection is needed.

Finally, the purpose of the work is not to test the absolute durability of the textile, which depends on its characteristics and, in some cases, could be guaranteed up to 30 years. The authors addressed their findings in testing the decrease in performance specific for an archaeological area. Moreover, these tests can be useful especially where temporary shelters are initially built and then used as permanent protection.

2. Materials and methods

2.1. The sample material and the ageing

The textile material under test is a PVC-coated polyester fabric, which is 0.41 mm thick and weighs 450 g/m^2. It belongs to the technical textiles family, where the polyester fabric provides the strength and the PVC coating layer provides a durable protection to external agents. This material was selected for its widespread use in the building construction of tensile structures, for its cost-effectiveness, high suitability in the temporary and provisional sheltering of archaeological areas in terms of water, wind and sun protection.

The researchers applied the main checks on the brand new material, and on samples taken after 15 and 65 months of ageing in a polluted environment. Four metre square of a whole piece of brand new textile was mounted, simulating a sheltering structure, on the roof of the ABC department of the Polytechnic, located in the city center of Milan. Ten pieces of the textile were cut at different times and analyzed in the laboratory, according to the procedures described in the following paragraphs.

2.2. Thermographic tests

The authors measured both thermal and optical characteristics in reflection and absorption set-up [13].

In scientific literature, only few papers describe the thermal property of fabrics or textiles. The main literature deals with general fabrics [14–17] with a lack of specificity for temporary sheltering purposes. The authors realized an experimental set-up to test the material in two heating conditions, reproducing the heating of natural radiation. The first experiment was made in reflection mode (Fig. 1-left), with two halogen lamps as the heating source (500 W each) placed at 1 meter distance and with the axis of lighting at 45° from the surface of the sample. The lamps directly shone on the external part of the textile and the 45° degree of inclination allowed the avoidance of any specular reflection on the sample. Due to this inclination, two lamps were necessary to maintain a uniform heating.

In the second test, the geometry of shooting was made in transmission mode (Fig. 1-right) with a single heating source (650 W) placed at the back of the sample at 80 cm distance. This set-up was necessary to avoid any direct heating from the lamp to the thermal camera, as would take place if the heating sources were shifted to the side of the sample. Different power, position and distance were designed also to maintain the same irradiance on the sample surface: average irradiance at the center of the samples was of 128 W/m^2 in reflection mode and 120 W/m^2 in transmission mode. In both configurations, the samples were mounted on a cardboard frame and the heating up time was of 270 s until the sample surface achieved a maximum temperature of equilibrium. Thermal images were shot every 10 s for 5 minutes, placing the thermal camera (AVIO TVS700, 320 × 240 uncooled microbolometer array, 0.07 K thermal resolution) in front of the sample surface at 75 cm distance.

2.3. Reflectance/transmittance measurements

Optical property was measured using fiber optic reflectance spectroscopy (FORS) equipped with a UV-visible-near infrared fiber optic probe [18]. The spectrometer was a Ocean Optics HR4000, spectral range: 200–1050 nm. A BaSO4 99% was used as reflectance standard while for the transmittance measurements a diffusing neutral density glass ($T = 10\%$) was used as calibration reference to

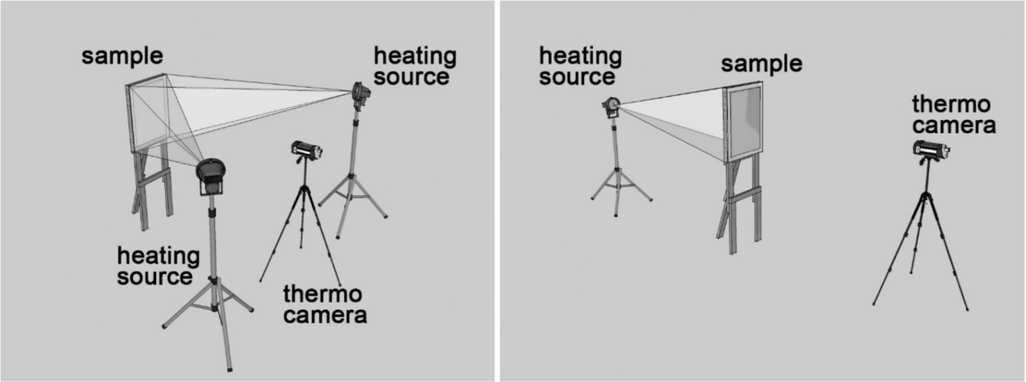

Fig. 1. Scheme of the measurement experimental set-up. In the reflection mode, samples were placed in front of both the camera and the heating at 45° to the normal of the sample surface (left). In transmission mode, samples were placed with a single back-heating source (right).

have comparable optical properties of the examined textiles which have an intrinsically high diffusivity. A xenon lamp was the source light.

The authors measured the reflectance and the relative transmittance on ten areas (4 mm^2) and they calculated the average over the whole test area.

2.4. *Colorimetric measurements*

The colorimetric measurements allowed the authors to evaluate the colour changes of the samples during ageing. The colorimeter used was a Minolta CR-400 Chroma Meter, with a measurement area of 10 mm of diameter. Also in this case, the authors averaged the results for 10 areas of the considered textile. Data was represented using the CIELAB colour space [19] using the CIEDE2000 formula for colour differences [20]. In the CIELAB color system L^* represents the lightness while the red/green opponent colors are represented along the a^* axis, with green at negative a^* values and red at positive a^* values. The yellow/blue opponent colors are represented along the b^* axis, with blue at negative b^* values and yellow at positive b^* values.

2.5. *Microscope observations*

In order to measure and compare the effect of decaying in the aged textile, authors made measurements using optical microscopy. A Microviper Everest, 500 × microscope was used with a direct image digitalization of 768 × 576 pixels, saved in tiff format.

2.6. *Mechanical measurements*

The tensile uniaxial mechanical behaviour of PVC-coated polyester fabric Type I was investigated. Differently than the other measurements, the uniaxial mechanical tests have been performed on the brand new material and the one exposed after 65 months of ageing in a polluted environment, aiming to measure the extremes of situations.

2.6.1. *Samples features*

The test campaign was performed on twenty textile specimens, ten in the warp direction and ten in the fill. In each direction, five of them were cut from the brand new material and the other five from the 65 months aged textile. The specimens were cut from the rolls, following precisely the way of the weaving stitches of the warp and fill: this is an important test procedure step to obtain correctly standardized measurements [21].

The typical specimens for uniaxial testing have a length of 40 cm and a width of 5 cm; as Fig. 2 shows, the two lines that delimit the area where the specimen is fixed to the grips which are placed at a 10 cm distance from the edges, so that the free area between the grips has a 20 cm length.

2.6.2. *Experimental set-up*

The biaxial tensile tests were performed using a TextilesHUB Polimi home-design device [27] equipped with twelve independent jacks along two orthogonal axes. The jacks are place in between two stiff square steel frames and can slide on two rails, one on each side, to permit the transversal displacements in the direction being orthogonal to the load. The connection system of the jacks has a hinge allowing the correct alignment to the load direction. Each jack has a brushless motor equipped with an absolute encoder and coupled with a planetary gearbox to transform rotational into linear motion through a ball screw mounted on the axis. The maximum speed is 240 mm/min and the maximum stroke is 512 mm with a displacement accuracy of ± 0.05 mm. Two load cells are available for each jack with maximum nominal load of 15 and 50 kN. The clamping system adopted for the specimens considered in this work is represented in Fig. 3. It consists of a pin and two shaped metallic plates. The arm of the specimen is wrapped on the pin and both are fixed between the two plates by two screws. The clamp system and the jack are connected with a hinge to have a correct alignment of the load and the arm.

2.6.3. *Experimental procedures*

The requirements were a sample of uniaxial tests to rupture point in a normal environment ($T = 23\,^{\circ}C$, RH = 43%), in order to determine the mechanical tensile strength and the elongation until the rupture of the aged textile. These measurements have been compared with those of the brand new textile.

The specimens were tested according to the method I of the test strip described in the EN ISO 1421 [21]. In detail, the samples were clamped in grips maintaining a 20 cm distance between them. (Fig. 3). Subsequently, the specimens were subjected to tensile stress, imposing the total speed equal to 100 ± 10 mm/min until failure of the specimen. The movements of the grips, as well as the forces detected by the load cells on the actuators, have been recorded with a frequency of 8 Hz.

3. Results

3.1. *Thermography*

Data reported in Fig. 4 and the images in Fig. 5 showed the effect of aging on the heating of the textile by front and back-heating. Thermal images of the samples during the heating showed that in the front heating tests (Fig. 5-left), a trend is evident in increasing

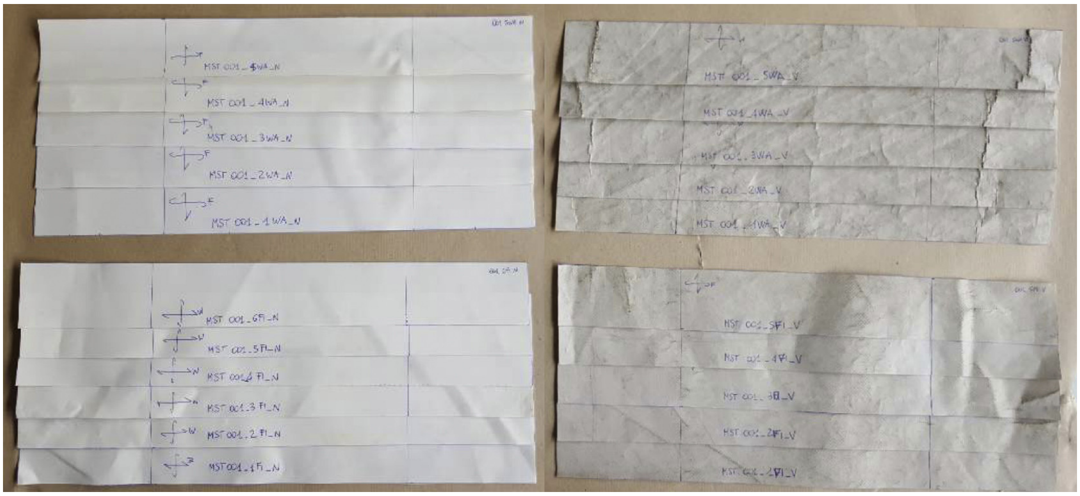

Fig. 2. Part of the specimens ready to be tested.

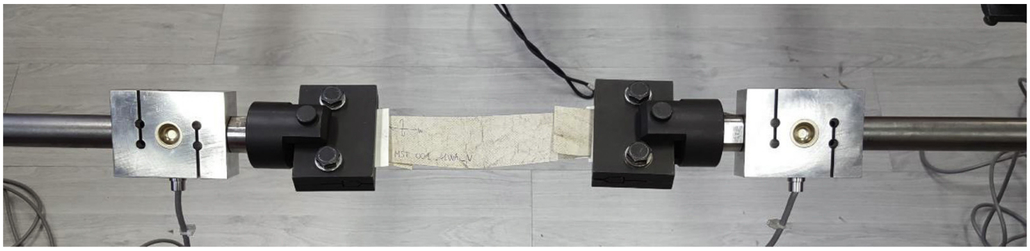

Fig. 3. Uniaxial tensile test machine.

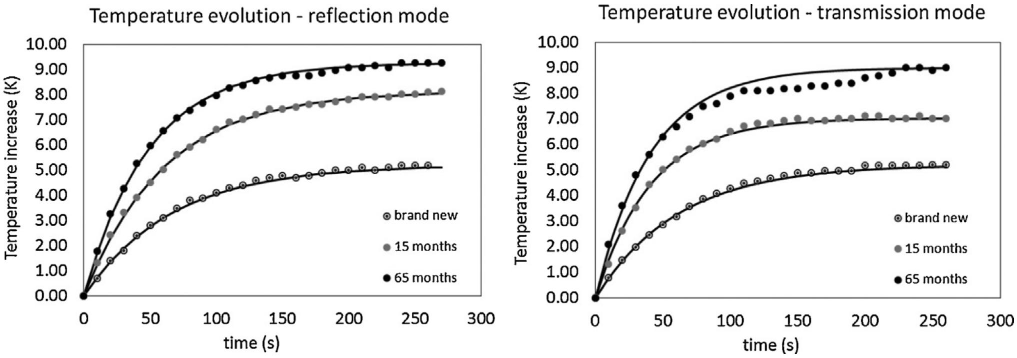

Fig. 4. Thermal trends of the surfaces of the textile samples at different conditions of ageing in reflection mode (left) and transmission mode (right). The dots represent the increase of temperature with respect to the non-heated sample during the heating up time (270 s) for the three ageing conditions. The solid lines describe the exponential fits whose asymptotic values are the equilibrium temperature.

the maximum equilibrium value with months of ageing. The brand new sample showed the minimum heating according to its lower absorption coefficient (Figs. 6 and 7). The difference reaches 4 K comparing brand new and 65 months sample. Similar behaviour is seen in the back-heating test (Fig. 5-right), with a slight difference in the maximum increment between brand new and aged samples.Temperature increase with respect to the non-heated sample were plotted vs. time (Fig. 4). Data showed that for all the samples, the temperature goes up to a maximum value, T_{max}, corresponding to asymptotic behaviour where the sample surface reaches the radiative equilibrium with the environment. Considering this T_{max} value, data is well represented in an exponential fit given by:

$$T_t = T_{\max}\left(1 - e^{-\frac{t}{\tau}}\right) \tag{1}$$

Where τ represents a characteristic time constant which describes the sample response to the heating. It can be related to the speed at which the sample reaches the maximum temperature of equilibrium, under fixed conditions of heating and environmental heat exchange. This value has been found as the best fit of the experimental data. The brand new material, due to its lower absorption coefficient, is characterized by the lowest T_{max} and the maximum τ both in reflection and transmission mode (Table 1). Accordingly, the 65 month aged sample shows the maximum T_{max} and the lowest τ values (Table 1).

Table 1
Time constant values for the samples in reflection and transmission mode.

Sample	τ (s) Reflection	Transmission
Brand new	66.5	63.0
15 months	61.5	41.0
65 months	49.5	41.0

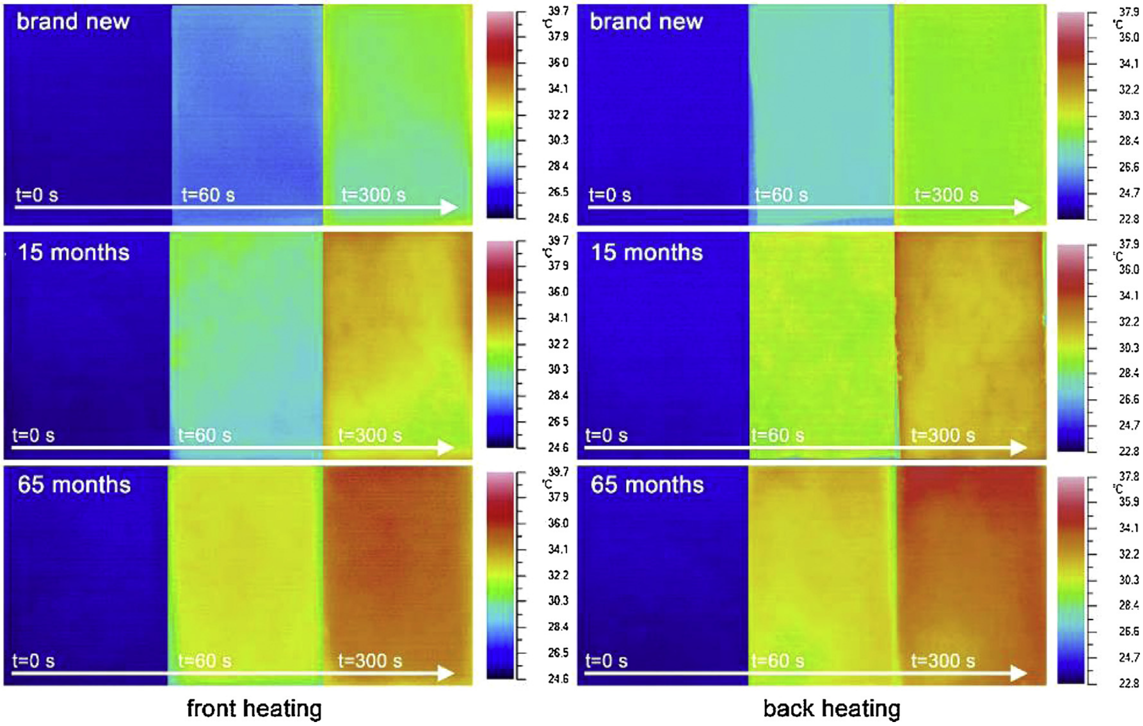

Fig. 5. Thermal images of textile samples at environmental temperature ($t = 0$) and after 60 and 300 s of front heating (left) and back-heating (right).

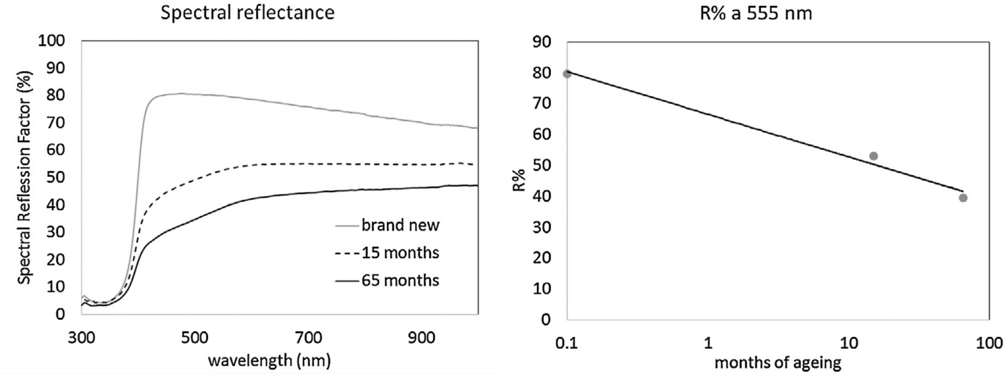

Fig. 6. Spectral reflectance factor of the textile samples (left). Fit of the spectral reflection factor measured at 555 nm wavelength. Data shows a logarithmic time trend (right).

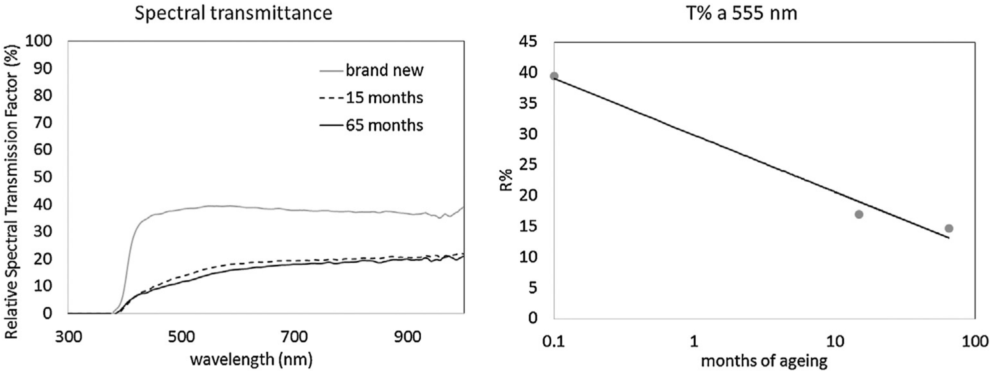

Fig. 7. Relative spectral transmission of the textile samples, obtained by using 1% transmittance that diffuses the reference standard (left). Fit of the spectral reflection factor measured at 555 nm wavelength. Data shows a logarithmic trend (right).

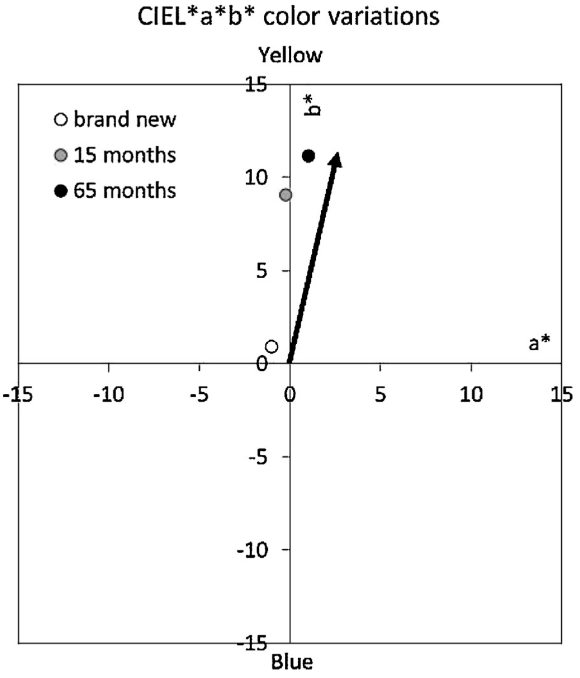

Fig. 8. Plot of the a*–b* data of the samples with the shift along the b axis caused by the ageing indicated with the arrow.

Table 2
Colorimetric data of the textile samples with the colorimetric differences between the brand new material and the aged one.

Sample	L*	a*	b*	ΔE_{00}
Brand new	88.52	−1.03	0.93	–
15 months	72.7	−0.26	9.09	12.85
65 months	63.19	1.02	11.17	20.24

3.2. *Reflectance/transmittance measurement*

After having measured the thermal properties, the authors measured the optical characteristics of the textile samples. The test measured the spectral reflectance factor (Fig. 6), and the relative spectral transmission factor (Fig. 7) of the material. To evaluate the optical darkening of the material, reflectance at 555 nm was considered, because of the maximum photopic sensitivity of human vision at this wavelength.

3.3. *Colorimetric measurements*

Beside the thermal and spectral variations, also colorimetric measurements were performed to evaluate the colour change in the textile samples. Fig. 8 and Table 2 show the colour data in CIELAB colour system [19] using the CIEDE2000 formula for colour difference [20], it is apparent that the colour variations principally take place along the b* axis (which represents the blue-yellow variations). Therefore, the main effect of ageing on the examined samples is the yellowing of the surface, although the variations take place also on the lightness coordinate. The evaluation of colour difference gives a ΔE_{00} of 12.85 between brand-new and 15 month aged samples while a ΔE_{00} of 20.24 occurs between brand new and 65 months aged sample.

3.4. *Optical microscope images*

The microscopic images (Fig. 9) represent the 500 × magnified details of the three textiles. Fig. 9a shows the brand new samples, Fig. 9b the 15 months aged textile and Fig. 9c the 65 months aged textile. A first observation deals with the average gray level of the images, which varies from 162 to 138 and finally 106. Images indicate that irregularities and cracks increase with age, then pollution and dirt fill the damaged parts, globally darkening the surface. Gray level values were calculated using as reference a white 99% reflectance standard (Fig. 9).

3.5. *Mechanical measurements*

The rupture of the specimens was within the limits allowed by normatives, in most of the cases, rupture was in the middle of the 200 mm, as expected in method I of the test strip described in the EN ISO 1421 [28]. Table 3 shows the results of the tests represented by the mean values of five specimens.

The brand new material belongs to the strength class C according to EN 1619 [22], because it reaches the minimum requirements of that strength class, which provides tear strength of the test specimen of at least 2 kN/50 cm. The ultimate strength in uniaxial warp direction is 2 kN/50 cm, the one in the fill direction is 2.35 kN/50 mm (Fig. 10). The average nominal elongation at break amounts to 20.81% in the warp direction and 19.62% in the fill.

The ultimate strength of the aged textile in uniaxial warp direction is of 1.75 kN/50 cm, and 1.41 in the fill direction, below the minimum requirements of the strength class C (Fig. 10). The average nominal elongation at break amounts to 16.71% in the warp direction and 18.29% in the fill one.

4. Discussion

Although a small number of samples were considered in this preliminary study, thermal data obtained during the tests reported in Fig. 4 can be considered as a useful parameter for comparing textiles both in laboratory and on field conditions. The use of an exponential fit to find out a characteristic time parameter which represents the thermal properties of the material can then be associated with the ageing condition of the material. For the reflection mode, this parameter decreases with age, showing a lower ability to reflect the heat of degraded textiles while in the transmission mode, the time constant decreases immediately passing from the brand new to the 15 months ageing and remains unchanged for the 65 months ageing. The first possible explanation is the complexity of the multilayered material that during the transmission of heat can behave very differently due to the thermal properties of different layers. Another reason is connected with the heating source; in

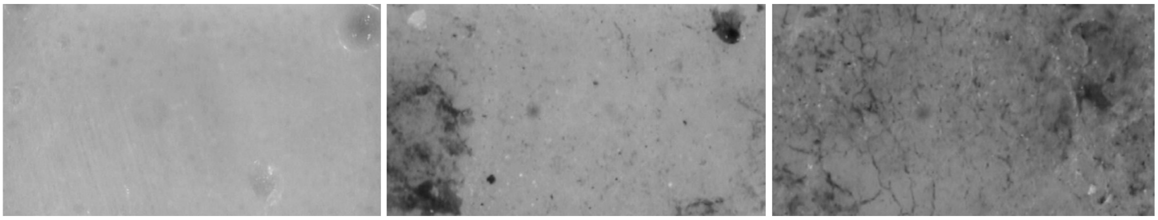

Fig. 9. Microscopic images of selected areas of the aged textiles.

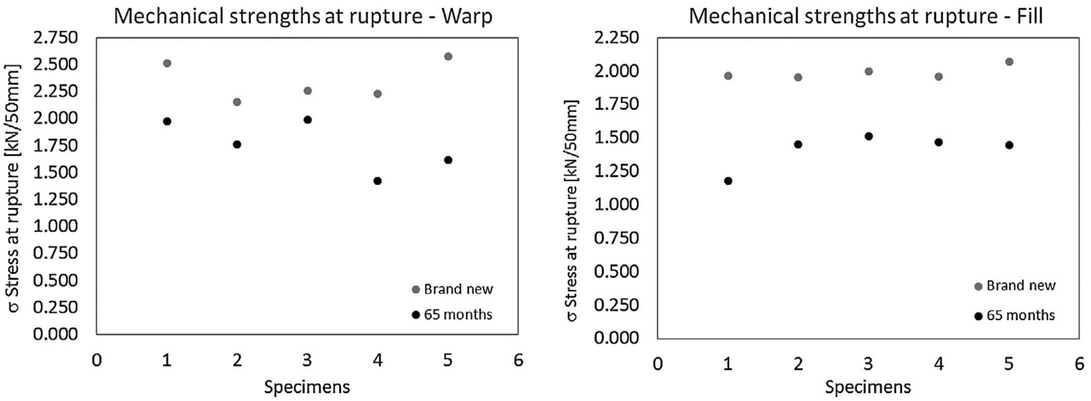

Fig. 10. Comparison of the mechanical measurements between the five brand new specimens and the five aged specimens, in warp (left) and fill directions (right).

Table 3
Mechanical strengths at rupture after uniaxial tests of the brand new and aged textiles.

Ageing	Orientation	σ Stress at rupture (kN/50 mm)	ε Strain (%)
Brand new	Warp direction	2.348 ± 0.187	19.618 ± 1.230
	Fill direction	1.991 ± 0.049	20.815 ± 0.401
65 months	Warp direction	1.754 ± 0.243	16.716 ± 2.520
	Fill direction	1.413 ± 0.132	18.289 ± 1.446

Table 4
Summary table of all the results of the test made on the textile.

Ageing (months)	τ Refl. (s)	τ Trans. (s)	R% @555 nm	T% @555 nm	τ E_{00}	Gray level	σ Stress at rupture (kN/m)	
							Warp	Fill
0	66.50	63.00	79.80	39.50	0.00	162.00	47.0	39.8
15	61.50	41.00	53.00	17.00	12.85	138.00	–	–
65	49.50	41.00	39.60	14.70	20.24	106.00	35.0	28.2

fact, in transmission mode, the lamp was placed behind the sample, in front of the camera, and part of the long wave radiation emitted by the lamp could reach the detector without having contributed to the heating of the sample's surface. The optical reflection and transmission tests show the strong decrease of the reflectance in the green-blue regions of the spectrum (Fig. 6-left), as well as transmittance (Fig. 7-left). Well aware of the small quantity of data, a logarithmic fit can be found for both the spectra, taking as reference the value of reflectance at 555 nm (Fig. 6-right and 7-right) which can suggest a non-linear change in the optical properties of the textile. In addition, the microscope images show that ageing modifies the superficial integrity of the material in particular several black areas and dots arise with ageing, crack size increases especially in the oldest sample.

Table 4 presents a summary in representing all the results of the analyses performed on the textile. Although the analyses concerned only three ageing conditions, this preliminary study emphasizes the association between all the results of the tests. This association can suggest the hypothesis that irregularities and cracks increase with age, then pollution and dirt can better reach those areas producing a global darkening of the surface. This darkening causes a higher optical absorbance of the material.

No conclusion is achievable, using this technique, concerning the chloride coating that protects the textile from UV radiation; nevertheless, the results of the colorimetric measurements indicate that the yellowing could be due to the damage or alteration. Mechanical uniaxial tests, owing to their destructivity, could be performed only twice: on the new material and after the complete ageing. After the 65 months aging, the results show how the material loses mechanical strength in both directions, around 25% in warp and 29% in fill, considering the average σ Stress at rupture. This decreasing in resistance is due to the hardening and micro cracking of the PVC coating, as shown by the previously mentioned microscope images, which leaves the polyester fabric exposed in some areas; consequently, the non-protected fabric could influence the decrease of performance. Finally, as shown in Fig. 9, after the exposure to a polluted external environment, the PVC-coated polyester fabric visually shows a variation of the almost orthogonal intersection of the warp/fill in the weaving, especially in the fill direction, probably due to natural thermal cycles during aging too. The type of tested technical textile is ultra-lightweight, cheap and typically used for covering few-meter-span structural solutions, which require low loads and stresses, and/or for temporary lifespans (9–12 months). The uniaxial mechanical measurements of both new and aged samples clearly show that this kind of ultra-lightweight coated-textile is not suitable for a long-lasting application neither for permanent shelters. The decreasing of the mechanical performances, after few months, does not respect the minimum requirements of the strength, according to standards. Furthermore, the authors report that the supplementary information of on field colorimetry is essential as a smart indication when a yellowing or blackening of textile surface is taking place. Often, a colorimeter can be easily used, better than the expensive instruments used by the authors.

The association between colorimetric data with thermal, reflectance/transmittance and mechanical data is utilizable on site during the monitoring campaign. Future developments could, in fact, improve the present study with the application of the proposed method also on site.

5. Conclusion

The use of textiles for sheltering archeological areas has recently achieved a great deal of approval from conservationist scientists and professionals, both for its suitability and effectiveness. Nevertheless, its application can cause some damage to the fragile materials under the shelter, as well as happening to glass, steel, and even traditional materials like straw and timber. With this multidisciplinary approach, the authors propose an efficient methodology to evaluate the condition of textiles on site too. Although having a small number of samples, these preliminary results showed an association between each type of test, which highlights the concurrence of results among thermal, optical and mechanical tests. Nevertheless, a single test is neither valid nor exhaustive in the representation of the actual performance of the material.

The main result of the research is that the variation measured by one test is able to predict variations also in the others. The results of the present study indicate that the coated textiles do not show a linear decay, as many technical specifications from the producers seems to suggest, and the tests are mandatory to determine a more appropriate lifespan for these materials when installed in polluted or aggressive environments.

Finally, the proposed method was designed for a preliminary study, where all the experimental conditions can be kept under control in laboratory. At these conditions, we can hypothesize that the ageing is responsible for any variation in the textile properties. The next step of the research will need the extension of the study at the real conditions of an archeological site, using a sample of new textile as reference.

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