Ageing in athletics tracks: a multi-technique experimental investigation

Stefano Tagliabue[1], Luca Andena[1,2,*], Andrea Pavan[1], Andrea Marenghi[3], Emanuele Testa[3] and Roberto Frassine[1]

[1] Politecnico di Milano, Dipartimento di Chimica, Materiali e Ingegneria Chimica “Giulio Natta”, Piazza L. da Vinci, 32, Milano (Italy)
[2] Politecnico di Milano, Engineering, Exercise, Environment, Equipment for Sport (E4Sport) Lab, Piazza L. da Vinci, 32, Milano (Italy)
[3] Mondo S.p.A., Piazzale Edmondo Stroppiana, 1, Alba (Italy)
[*] Corresponding author:
Luca Andena
Assistant Professor
Polymer Engineering Lab
Engineering, Exercise, Environment, Equipment for Sport Lab
Dipartimento di Chimica, Materiali e Ingegneria Chimica "G. Natta"
Politecnico di Milano
Piazza Leonardo da Vinci, 32 - 20133 Milano (Italy)
e-mail luca.andena@polimi.it
tel +39 02 2399 3289
fax +39 02 2399 3280
ORCID 0000-0001-8610-1782

Abstract: This is an extensive study of the ageing of athletics tracks, approached with a variety of experimental techniques. The effects of environmental variables, such as UV radiation, relative humidity, water immersion and temperature, were investigated using several artificial ageing protocols, applied to six prefabricated tracks of different color and chemical formulation. A few effective techniques capable of detecting and monitoring the changes occurring in track materials because of ageing were identified among a broad range of available experimental tests. In particular, semi-quantitative colorimetric analysis and dispersive electron spectroscopy were successfully employed to investigate surface degradation phenomena, while uniaxial compression and thermo-gravimetric analysis allowed characterization of the underlying bulk material. The combination of accelerated ageing protocols and monitoring techniques proved to be a powerful tool to study ageing in athletics tracks, with the aim of developing new products with improved durability for installations in critical areas.

Keywords: athletics tracks; durability; artificial ageing; mechanical properties; thermo-gravimetric analysis

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1. Introduction

The fundamental role played by modern synthetic surfaces in sport activities is widely assessed: they are extensively employed in several different sports, characterized by having different sets of desired properties. In the case of athletics tracks, the International Association of Athletics Federations (IAAF) provides a list of requirements for approval, involving both their performance and integrity [1-2]. Performance is strictly related to the mechanical behavior of the surface in connection with the athlete. The three most important properties are shock absorption [3], energy restitution and friction [4-5]. The elastic properties of polymers and their excellent capability of absorbing shocks greatly contribute to the enhancement of athletics track qualities, thus guaranteeing the athletes' safety and performance. Shock absorption prevents the propagation of vibrations throughout the musculoskeletal system, preserving it from quick deterioration and possible injuries [6-8]. Finally, the restitution of energy during the propulsion phase, in combination with friction between shoes and track surface, significantly influences the athletes' performance.

Modern athletics tracks can be divided into two main categories: *in-situ* systems and prefabricated tracks. The first one includes cast elastomers, resin-bound rubber crumbs and composite systems. As the *in-situ* term suggests, the track is produced directly on the field: it can easily adapt to the existing foundation, but it may present some issues of inhomogeneity, especially with respect to track thickness, which may negatively affect the overall behavior [9]. Prefabricated tracks are made by rubber mixtures containing mineral fillers and other additives, which are calendered and subsequently cured; being produced in a controlled environment, they possess more consistent properties in the whole volume. Prefabricated tracks are typically made of at least two different layers. The top finishing one is harder and colored as desired, with surface embossing to improve friction. The bottom layer is often designed with a geometrical structure aimed at adjusting the cushioning ability to the desired level and to respond with different stiffness along propulsion and cornering directions [10].

Tracks of both categories are complex systems in terms of constituent materials, additives and production process parameters. It is, therefore, not easy to predict the effect that material properties have on their final performance. To this aim several numerical models have been developed in the past [11-14].

Given the cost of sport facilities installation, it would be highly desirable that their properties were maintained at an acceptable level over the years. Environment exposure is likely to cause ageing and alter the material's microstructure and properties: as a result, the track behavior will probably change over time. Despite the availability of data regarding installed sport tracks all over the world, to the authors' knowledge only scanty research works have dealt with durability of tracks or sports equipment in general; they often concentrate on rather limited aspects, such as mechanical ageing [15] or leaching behavior [16]. The need for a more comprehensive scientific study of tracks durability, able to provide reliable tools for product development and weather resistance verification, motivated the present work. At first, relevant environmental variables were considered, such as UV radiation, relative humidity, presence of water and temperature. The different degradation phenomena produced by each of these ageing factors were then investigated and quantified using various characterization techniques, addressing chemical, physical and mechanical aspects.

2. Materials and experimental methods

The materials investigated in the present study were provided by Mondo S.p.A. (Italy). Six different prefabricated athletics tracks were considered, sharing an identical bottom layer with hexagonal honeycomb structure. The tracks differed in the top (exposed) layer belonging to two main families according to its color (blue and red). Thicknesses for top and bottom layers were about 6 and 7 mm, respectively, for all six materials.

Track labelling goes as follows:

Surface Color	Track Label	Force Reduction (FR)
Blue	B1	42 %
	B2	39 %
	B3	40 %
Red	R1	42 %
	R2	39 %
	R3	40 %

Tab. 1 Sample label, surface color and force reduction value (measured with a Berlin Artificial Athlete)

Force Reduction (FR) of the samples in their unaged status was measured using an Artificial Athlete (AA) apparatus, according to IAAF specifications [3]; as all of the samples investigated have nearly the same thickness and bottom layer (which is mainly responsible for shock absorption), they all lie in a narrow range of FR values (39-42%) [9].

They all share the same base chemical formulation, a blend of natural rubber (NR), styrene butadiene rubber (SBR) and ethylene propylene diene monomer rubber (EPDM). However, the actual composition and processing parameters differ significantly for the two families of tracks (blue and red), with differences within each family. The six materials were purposely prepared for this study, although there is a certain degree of similarity with existing Mondotrack™ commercial products. Complete tracks were considered, as well as top layers alone, after they were manually separated from the respective bottom layers.

A preliminary study was run on available aged track materials using a broad array of experimental techniques to probe and quantify occurring ageing phenomena, including:

- Image analysis
- Optical microscopy
- Scanning electron microscopy
- Energy dispersive spectrometry
- Infrared spectroscopy
- Thermogravimetric analysis
- Quasi-static mechanical testing (compression, tension, bending)
- Dynamic-mechanical testing (compression)
- Micro-scratching

Some of these turned out to be not effective for various reasons, including poor sensitivity, lack of capability to cover the spatial heterogeneity of track materials, or their inherent complexity. Following these results, only the techniques able to give significant results were used, with the aim of comparing different track behavior and monitor the effects of the considered ageing factors. In particular, image and thermo-gravimetric analysis were carried out on the top layers, while uniaxial compression tests were performed on both top layers and complete tracks. Tests were performed on the reference (i.e. unaged) materials and after each step of the ageing protocols described in section 3, at 250 h time intervals.

2.1 Image analysis

Starting from 2D images of the top surface of each sample, collected with a flatbed scanner (*Epson Perfection v33, acquisition at 240dpi@24bit*), a semi-quantitative colorimetric analysis was carried out. Images were analyzed using *ImageJ 1.48k* software, considering separately the red, the green and the blue (RGB) channels; for each one the range was set to between 0 (black) and 255 (white). Readings over the whole surface of each sample were averaged to get arithmetical mean and standard deviation. The channel of major interest was selected according to the top layer's color (blue and red channels for same-colored tracks). Its variation was then tracked during the progressive ageing tests carried out on the tracks.

2.2 Energy dispersive spectrometry (EDS)

In order to investigate the nature of surface ageing phenomena, a semi-quantitative elemental analysis of the surface of samples of a representative material of each family (B2 and R3) was carried out with energy dispersive spectrometry (*Zeiss Evo 50 EP*). EDS allows the measurement of the relative amount of a given element on the sample surface; in the present case, elements C, O, Al and Si were considered.

2.3 Uniaxial compression

Uniaxial compression tests were performed using a screw-driven *Instron 1185R5800* dynamometer, to obtain information on the mechanical behavior of both complete tracks and top layers. Tests were conducted at 23°C and 50% relative humidity (RH). The specimens were loaded at a constant strain rate of 0.006 s^{-1}, up to a compression ratio of 0.6 (the latter being the ratio between current and initial height of the sample), and then unloaded at the same strain rate. The maximum ratio of 0.6 was selected in accordance with the typical compression experienced by track samples during FR testing, as discussed in [12-14]. Following those works, specimens measuring 30x30 mm in-plane were cut from the full thickness of the complete tracks and from their corresponding top layers.

For each ageing step, two samples from the complete tracks and at least four from each top layer were tested to ensure sufficient repeatability of the mechanical response; in the case of top layers, a larger number was used to reduce potential issues caused by their manual separation.

2.4 Thermo-gravimetric analysis (TGA)

Thermogravimetric analysis was conducted on a *TA Instruments TGA Q500* to investigate the thermal degradation of the track constituent materials and the corresponding weight losses. A suitable program was defined by adapting that typically used for the determination of carbon black content in rubber blends [17]. The following stages were conducted in a nitrogen atmosphere:

a. Heating from 25 to 300 °C at 10 °C min-1
b. Holding at 300 °C for 10 min
c. Heating from 300 to 550 °C at 5 °C min-1
d. Holding at 550 °C for 15 min
e. Heating from 550 to 650 °C at 10 °C min-1

At the maximum temperature of 650 °C, the testing atmosphere was switched from nitrogen to standard air and this isothermal stage was continued for a further 30 min.

Because of the long testing times required by TGA, only unaged samples (taken as a reference) and samples subjected to the largest ageing time were analyzed (omitting some of the intermediate steps described in section 3), and only for the protocols which otherwise gave evidence of ongoing degradation. This was necessary in view of the high number of material/testing protocol combinations considered.

The presence of isothermal periods (stages b and d above) is very important to allow full completion of the thermal degradation phenomena involving individual rubber components before beginning the subsequent heating steps. Materials were sampled across the whole thickness of the top layer, with sample weight ranging between 100 and 150 mg. Both relative weight loss signal and its derivative with time were considered.

3. Artificial ageing protocols

Artificial ageing protocols were defined considering the environmental variables deemed to be responsible for polymer degradation phenomena, according to previous experiences [18]. The main ones identified in the case of athletics tracks were: UV radiation, relative humidity, water immersion and temperature. The choice of working parameters for each protocol was an attempt to reproduce the most critical conditions associated to real world situations while also separating the effects of the different variables. It is important to note that in the present study the possible contribution of mechanical actions (e.g. by running shoe spikes) was neglected.

Ten plaques measuring 180x100 mm² for each material were aged; test specimens were cut out at regular intervals of 250 h and tested – except for TGA which, as previously mentioned, was performed only on unaged samples and on those aged up to the largest testing time used.

3.1 Strong UV radiation

In this protocol, exerted by means of an *Erichsen Instruments SolarBox 3000e* environmental chamber, the main variable considered was UV radiation [19]. Environmental parameters aimed at reproducing hot/dry conditions were set as follows:

- Xenon arc lamp power: 900 W m^{-2}, corresponding to a solar irradiation of 75 W m^{-2} in the wavelength band between 300 and 400 nm
- RH: not controlled, but monitored as constant during ageing at about 20%
- Temperature: 40 °C
- High pass filter: with cut-off wavelength at 280 nm

Total ageing time was 1000 hours.

3.2 High relative humidity and UV radiation

This ageing protocol was also conducted in the above environmental chamber, with parameters set to mimic weathering in a more temperate climate (lamp power reduced and RH increased) as follows:

- Xenon arc lamp power: 550 W m^{-2}, corresponding to a solar irradiation of 50 W m^{-2} in the wavelength band between 300 and 400 nm
- RH: 90%
- Temperature: 40 °C
- High pass filter: with cut-off wavelength at 280 nm

Total ageing time was 1000 hours.

3.3 Water

For this protocol the samples were immersed in tap water, which was replaced once a week. Samples were then extracted at regular time intervals (up to 2000 hours) and dried for four weeks under controlled conditions (23 °C and 50% RH) before testing.

3.4 Temperature

The main environmental variable considered in this protocol was high temperature. Samples were kept in a forced convection oven at 75 °C, similar to the temperatures reached by the tracks on sunny days in a hot climate. Total ageing time was 2000 hours.

4. Results

4.1 Image Analysis / EDS

Figure 1 shows a qualitative comparison between unaged and the corresponding aged surfaces, for the specific case of applied strong UV radiation (which gave the most sensible variations).

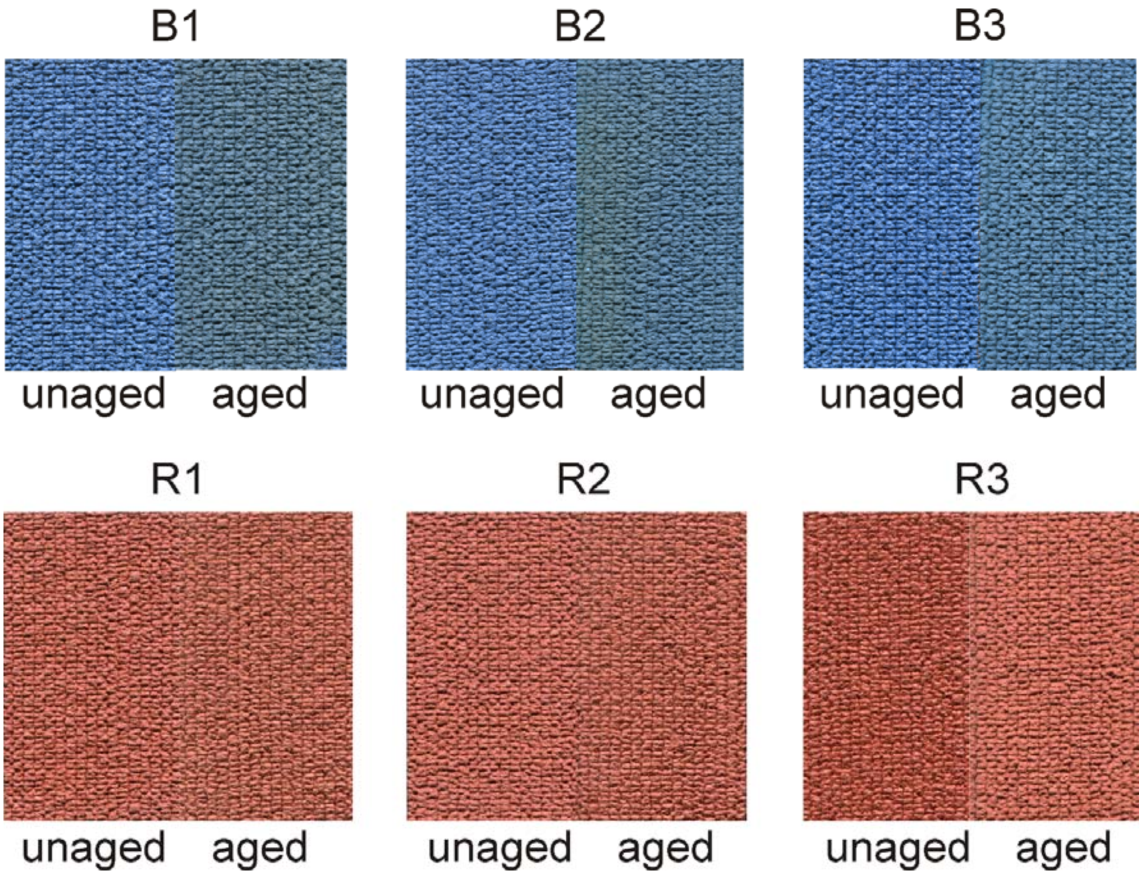

Fig. 1 Qualitative comparison between unaged track surfaces and corresponding ones artificially aged according to the strong UV protocol

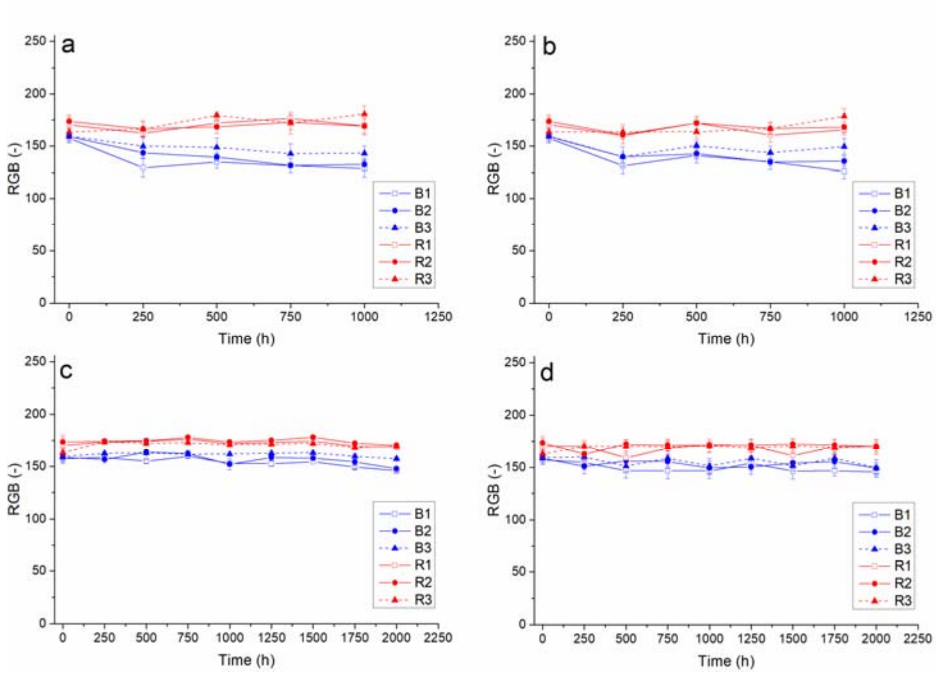

Fig. 2 Image analysis results for different ageing protocol: a – strong UV radiation, b – UV radiation and relative humidity, c – presence of water and d – temperature. Relevant color index (blue or red) and total ageing time are reported on x- and y-axis, respectively

Figures 2a-d show the main results of image analysis for the different ageing protocols: values of the main color channel (blue or red depending on the track color) are plotted as a function of ageing time. Mean values for all pixels are reported together with error bars representing the relevant standard deviation. Water and temperature do not seem to affect the top layer's color significantly even after 2000 hours of continuous ageing. Conversely, the presence of UV radiation induces some minor variations. In particular, the blue index decreases for blue tracks after the first 250 hours, indicating a slightly darker color.

In Table 2, the results of semi-quantitative elemental analysis of B2 and R3 track surfaces obtained by EDS are reported. The results are very similar for the two materials:

- Surface carbon dramatically decreases while oxygen increases with ageing
- Aluminum-Silicon complexes increase with ageing

These results are consistent with photo-degradative oxidation process (C reduction and O increase) which also causes mineral additives (indicated by Al-Si signal) to appear at the surface.

Track	Ageing	% C	% O	% Al	% Si
B2	**Unaged**	88.11	3.67	1.43	2.83
	1000 hours strong UV radiation	19.01	49.40	9.66	18.69
R3	**Unaged**	84.90	5.99	0.94	2.08
	1000 hours strong UV radiation	23.71	43.12	7.06	14.39

Tab. 2 Semi-quantitative elemental analysis results obtained by EDS on the surface of two unaged/aged tracks

4.2 Uniaxial compression

Figure 3 reports an example of two typical stress vs. stretch loading/unloading curves obtained for an unaged and a corresponding artificially aged sample. Negative values are used to indicate compressive stresses. As can be seen, the effect of ageing is to greatly increase stiffness during the loading phase.

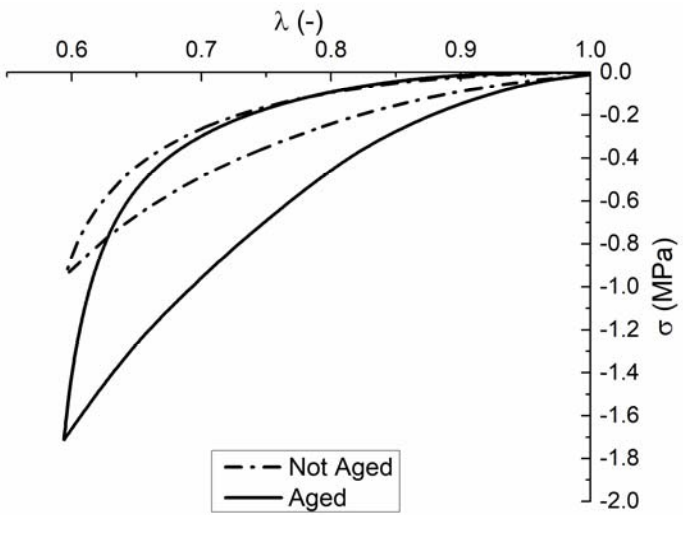

Fig. 1 Typical loading-unloading stress vs. stretch curves obtained from a mechanical uniaxial compression test for an unaged and aged (strong UV radiation) sample.

From each test the following quantities were computed:

- Total energy (E_{tot}), taken as the area under the loading curve
- Returned energy (E_{ret}), taken as the area under the unloading curve
- Dissipated energy (E_{dis}), taken as the difference (E_{tot}- E_{ret})

Two quantities were then taken to characterize the changes in mechanical behavior caused by the evolution of degradation phenomena:

- The maximum stress (σ_{max}) reached in the test at 60% compression
- The ratio (E_{dis} / E_{ret}) between dissipated and returned energy

Figure 4 and 5 show the results in terms of maximum stress as a function of ageing time for both complete tracks and top layers. Although data for a single testing protocol/time turned out to be quite repeatable, trends as a function of time are somewhat scattered, indicating a slight inhomogeneity of ageing for the different testing plaques. Somewhat larger data scatter is displayed by the top layers (Figure 5), probably due to some geometrical irregularities in the specimens caused by the operation of separating the two layers.

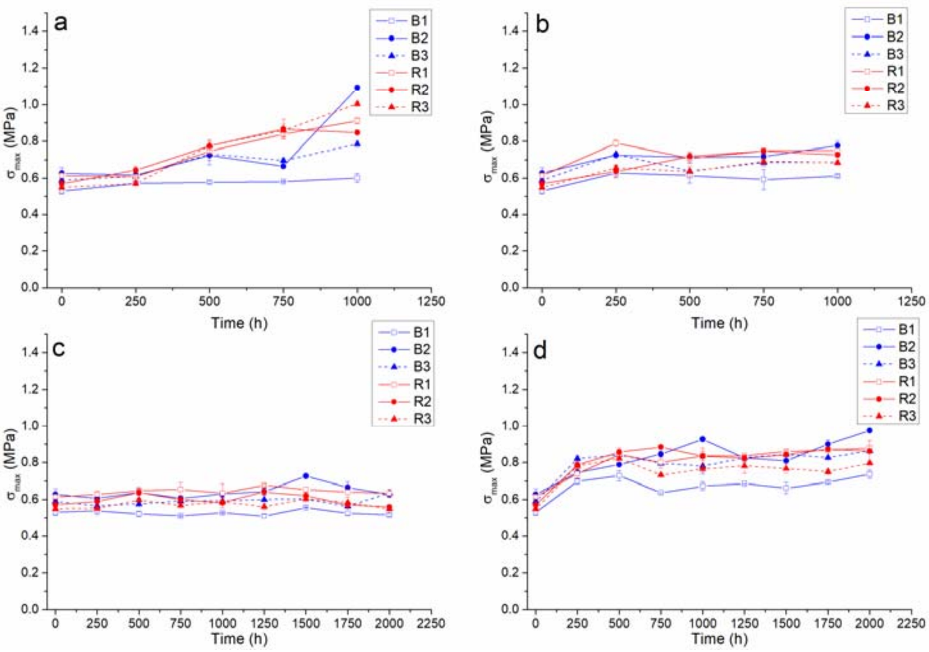

Fig. 2 Maximum stress at 60% of stretch obtained from compression tests performed on complete tracks as a function of total ageing time for the different testing protocols: a – strong UV radiation, b – UV radiation and relative humidity, c – presence of water and d – temperature

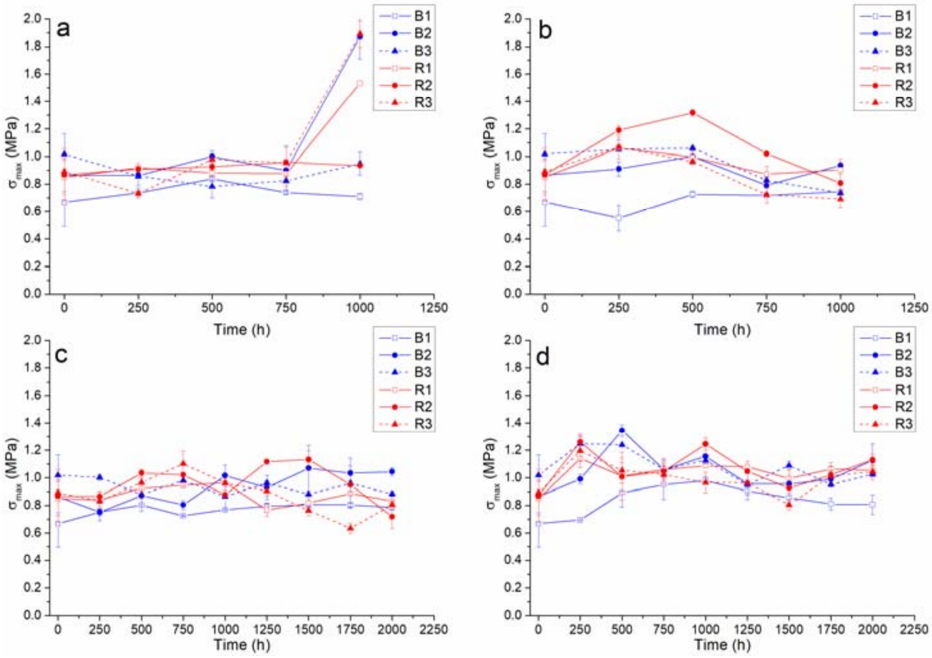

Fig. 5 Maximum stress at 60% of stretch obtained from compression tests performed on top layers as a function of total ageing time for the different testing protocols: a – strong UV radiation, b – UV radiation and relative humidity, c – presence of water and d – temperature

Significant variations occured, eventually, only with the application of the strong UV radiation ageing protocol for time longer than 750 hours (Figures 4a and 5a). This effect is much more pronounced in the separated top layers. Bottom layers are obviously less affected thanks to their shielding by the top ones; the mechanical behavior of the complete tracks is an average of the two.

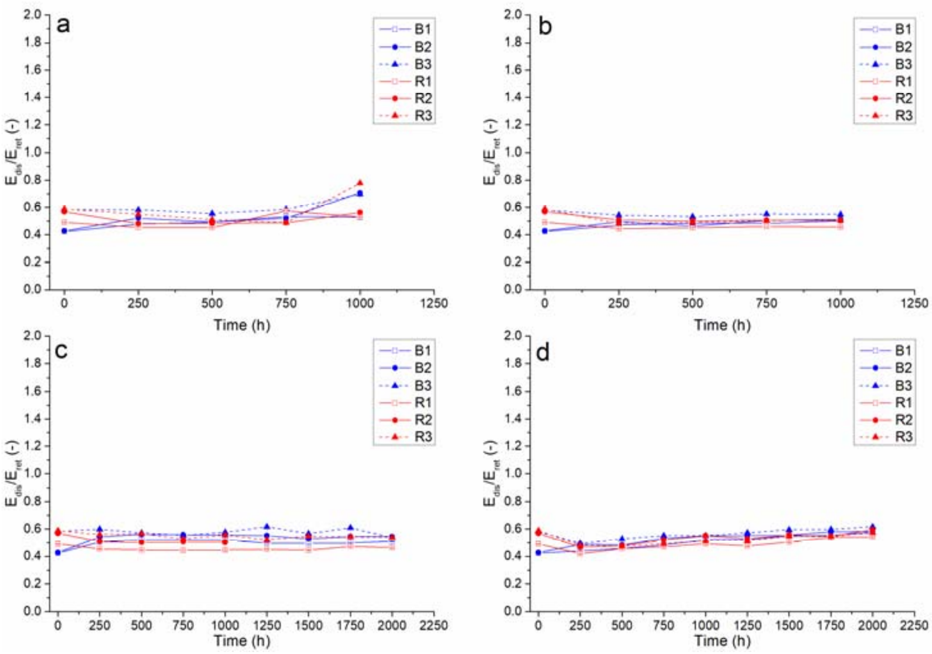

Fig. 6 Ratio between dissipated and returned energy from mechanical tests performed on complete tracks plotted as a function of total ageing time for the different testing protocols: a – strong UV radiation, b – UV radiation and relative humidity, c – presence of water and d – temperature

Looking at the energy dissipation ratios (Figures 6 and 7), the values are also quite constant with time for most protocols, lying around 0.5 for complete tracks and 0.7 for the top layers, with one exception. The ratio jumps well above unity in some of the top layers when they are exposed to strong UV radiation (Figure 7a) for more than 750 hours; a similar but much smaller increase can also be observed in some of the complete tracks (Figure 6a).

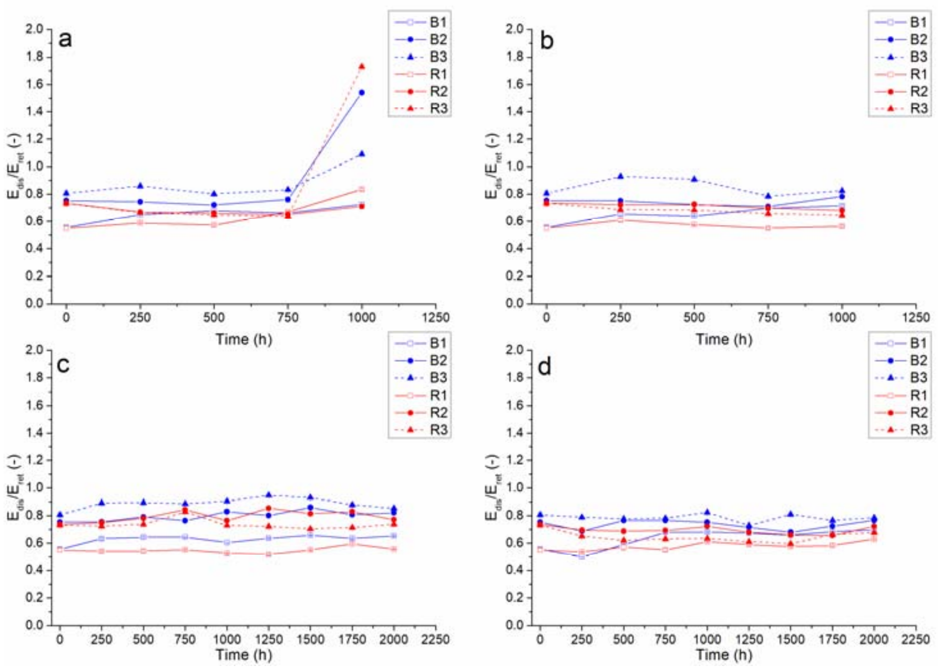

Fig. 7 Ratio between dissipated and returned energy from mechanical tests performed on top layers plotted as a function of total ageing time for the different testing protocols: a – strong UV radiation, b – UV radiation and relative humidity, c – presence of water and d – temperature

4.3 Thermo-gravimetric analysis

Figure 8a shows a typical signal obtained in a thermogravimetric analysis test of a top layer sample. The weight of the sample, normalized with respect to its initial value, is plotted as a function of time together with the applied thermal program. Three main steps can be identified:

1. a minor weight loss of about 10% occurring at temperatures below 300 °C, which can be attributed to loss of plasticizers and other organic additives;
2. a large weight loss of about 45% in the temperature ranges between 300 and 500 °C, which is related to the degradation of the main rubber mixture constituents;
3. another minor weight loss of about 10% at temperatures above 500°C, which can be associated to the degradation of the recycled rubber component of the mixture.

Looking at the derivative signal plot in Figure 8b, the individual degradation steps show themselves as peaks, which are easier to identify. Their attribution to individual constituents of the sample was made on the basis of existing thermal analysis literature [20-21] and of the results of some preliminary testing on simpler model compounds. This previous knowledge allowed recognizing the three peaks observed in the central region of the graph: they can be attributed to NR, SBR and EPDM. To be noted is the fact that the two peaks corresponding to SBR and EPDM frequently overlap. In the end, two parameters were considered to monitor ageing by TGA:

- the temperature of the NR peak (T_{deg} *NR*)
- the temperature of the EPDM peak (T_{deg} *EPDM*)

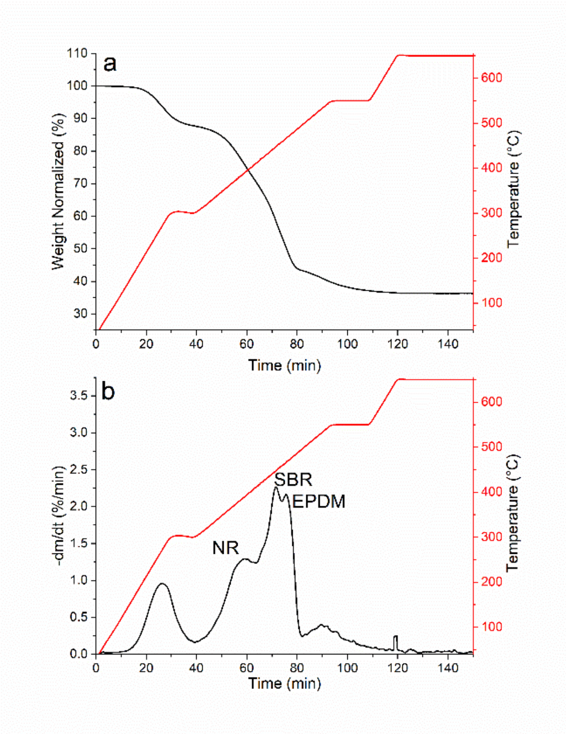

Fig. 8 Typical temperature program (in red) and weight signals (in black) obtained from TGA of samples studied in this work: a) absolute normalized weight; b) its derivative with time. Peaks corresponding to individual constituents of the rubber mixture are highlighted

In view of the results obtained from the mechanical tests, TGA was performed only on the top layers of samples subjected to strong UV radiation testing protocol, which had displayed a significant variation of the mechanical properties. Figure 9 reports relevant values of the two chosen parameters T_{deg} *NR* and T_{deg} *EPDM* as a function of ageing time.

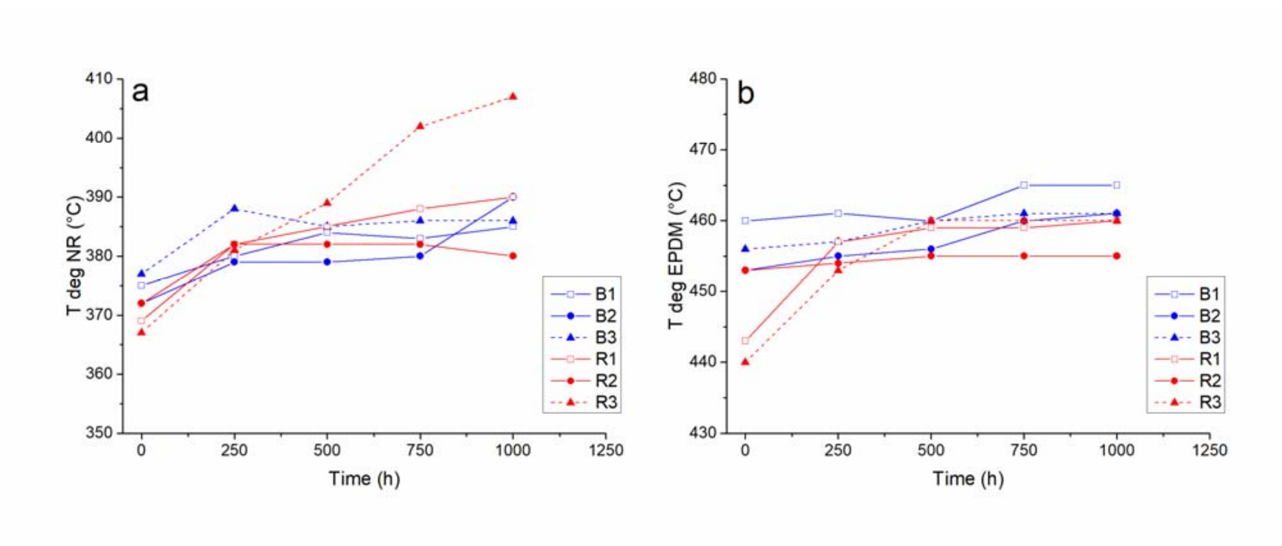

Fig. 9 Degradation temperatures of NR (a) and EPDM (b) for top layers as a function of total ageing time in the case of artificial ageing protocol with strong UV exposure

The temperature of the degradation peak of EPDM, T_{deg} *EPDM*, does not significantly change with ageing time for four out of the six samples. For the red tracks R1 and R3 EPDM starts degrading at a lower value but, after 250 h T_{deg}, EPDM levels off at about 455-465 °C as seen for the other tracks. The initial difference may be due to uncomplete curing of the two materials in their initial (as-received) condition, but this fact doesn't seem to affect their long-term behavior.

A similar initial increase of about 10 °C can also be observed for the degradation temperature of NR in all six materials, but some more important variations occur during the test on some of the samples' top layers with increasing exposure to the strong UV radiation protocol. T_{deg} *NR* progressively rises for R1 and R3: for the latter it increases up to 405 °C, i.e. 40 °C above its initial value. On the other hand, B2 is the only blue track showing a sudden increase of about 10 °C after 1000 hours.

5. Discussion

First of all, it is important to underline that the materials investigated were subjected to ageing protocols that do not include any kind of applied mechanical loading. This is a limitation of the present study, since the stresses experienced by normal track usage could trigger particular degradation phenomena or synergistically enhance the effects of the environmental factors accounted for so far. As an example, ongoing degradation could cause shoe spikes to more easily remove some material from the track surface, in turn accelerating the ageing process. Nevertheless, the methods examined in the present study can give a very useful insight into the intrinsic resistance of the different materials. While the action of mechanical stresses on the tracks cannot be limited, containing and/or delaying the effects of the ageing phenomena is an important strategy to improve their durability. What follow are the main outcomes of this research.

The ageing protocols used do not severely affect the general appearance of the tracks, perhaps because of their relatively short duration compared to the expected service life of tracks, which exceeds five years. However, even an exposure to UV radiation as short as 1000 hours was sufficient to highlight some minor color variations, with the change being different for red and blue tracks.

UV radiation was confirmed to be the main ageing factor also by the results of mechanical testing. Compression tests had been chosen because of their repeatability, because they introduce only minor uncertainties due to specimen cutting, and because they involve a material volume that is large enough to be representative of the overall track behavior. Moreover, the stress state applied is similar to actual in-service loading conditions. The sensitivity of the test to the variations induced by ageing turned out to be quite high. Indeed, compression results show a significant change in the mechanical response of UV-aged tracks, in particular when the top layers are tested separately. Several parameters can be used to adequately describe these variations; the maximum stress, σ_{max}, is easy to determine although it is the ratio (E_{dis} / E_{ret}) that should perhaps be preferably used for the early detection of incipient ageing, because of its even greater sensitivity.

As expected, the ageing processes do not affect the different constituents of the rubber mixture in the same way and to the same extent. While the thermal degradation rate of SBR and EPDM doesn't show significant changes after UV-exposure, the same does not hold for the NR component whose degradation peak temperature T_{deg} *NR* was shifted by a large amount.

The two parameters σ_{max} and T_{deg} *NR* were focused on to compare the behavior of the six different materials under study, considering in particular the isolated top layers (separated from their corresponding bottom layer) which were exposed to strong UV radiation and tested. For each material and ageing step, σ_{max} was normalized with respect to its value in the unaged condition. In a similar fashion, the shift in T_{deg} *NR* with respect to the corresponding unaged material was taken as a measure of the ageing progress, as monitored by TGA. The results are reported in Figure 10; the various data points shown for each material correspond to the different ageing steps, with all data for unaged samples obviously collapsing on (0;1) because of the normalization.

Ageing in red tracks R1 and R3 evolves progressively, as indicated by the variation of T_{deg} *NR*; the shift is larger for R3. However, σ_{max} is almost constant until the last ageing step (corresponding to 1000h of strong UV) when it suddenly jumps up. A similar effect can be observed for B2 while the other two blue tracks (B1 and B3) do not exhibit any significant variation during the entire experimental window of ageing time explored. Among red tracks, R2 was by far the most stable.

As details on the manufacturing process parameters used for the six materials were not available, it is quite difficult to correlate these findings with possible modifications of material structure and properties. One conclusion holds as valid: from a methodological point of view, the two proposed techniques (compression testing and TGA) can be valuable tools to detect and monitor ageing processes in existing track materials.

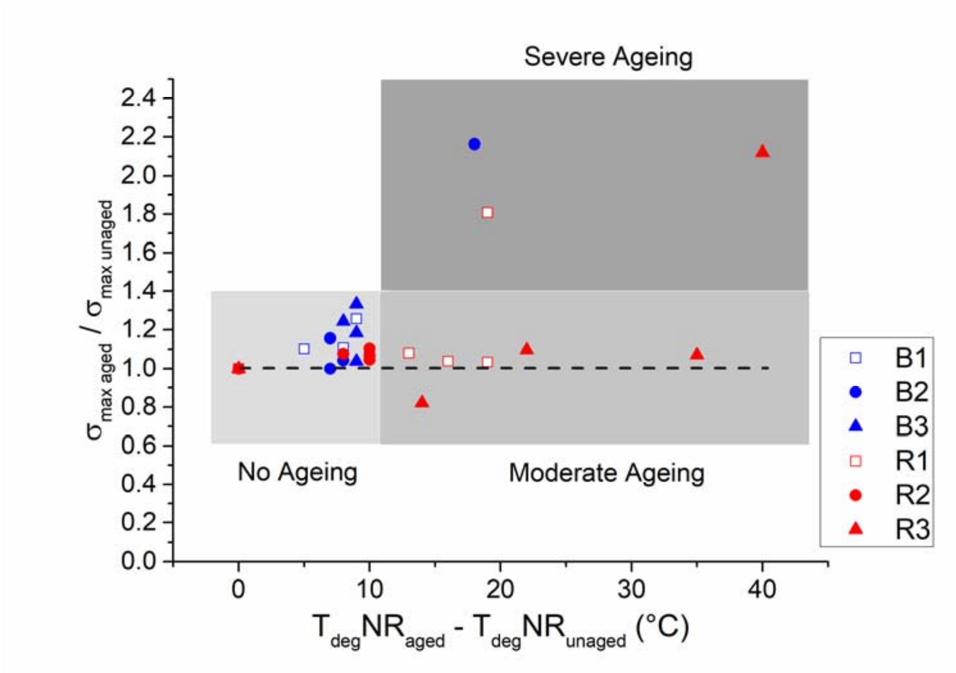

Fig. 10 Normalized maximum stress vs. NR degradation temperature shift (see text for more details) for all the materials and ageing steps. Data obtained from separated top layers and artificial ageing protocol with strong UV exposure.

6. Conclusions

Ageing of synthetic athletics tracks was investigated on six different track prototypes, differing in color (red and blue), chemical composition and processing parameters.

The materials' samples were subjected to controlled artificial ageing conditions for varying periods of time according to different protocols, involving several environmental variables: UV radiation, humidity, temperature, water immersion. It was found that, apart from some minor initial changes due to possible post-curing of the materials produced by the temperature applied during ageing treatment, the only variable which could actually induce degradation processes with a tangible effect on the track properties was UV radiation. This was confirmed by EDS, which highlighted the presence of oxidized material and the appearance of mineral charges at the surface of the samples after the ageing treatment.

Localization of degradation phenomena at the exposed surface (as expected) was also confirmed by the observed differences between the mechanical behavior of track top layers and complete tracks, the latter including a relatively well-preserved bottom layer. Duration of the artificial ageing treatment applied (according to the protocols used) was barely sufficient to show the first large changes in material properties at about 1000h exposure. The two main effects observed in two samples were a large increase in material stiffness (which is likely to bring about reduced shock absorption capabilities [12-14]) and an increased ratio between dissipated and returned energy (i.e. a loss of track elasticity, most likely affecting the track's performance in a negative way).

The evolution of degradation phenomena eventually leading to these important changes in tracks' response is a continuous process, which can be effectively probed and monitored using TGA. In particular, this technique allowed establishing a link between track ageing and the degradation temperature of the NR component of rubber mixtures.

It is believed that the combined application of an artificial ageing treatment according to strong UV testing protocol accompanied by this small set of experimental analyses (compression testing and TGA) can be of great help in studying the durability of athletics tracks and during the development of materials with better ageing behavior.

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