Viscoelastic behavior of athletics track surfaces in relation to their force reduction

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Abstract

The present paper is aimed at clarifying the dependence of the *force reduction* ability of sport surfaces used in athletic tracks on the material's viscoelastic properties and on the geometry of the sample. The study is based on laboratory tests carried out with an "artificial athlete" apparatus and dynamic-mechanical analysis. Seven different sport surfaces were tested; other polymeric materials were also examined, in order to widen the property ranges covered. The results show a prominent effect of sample thickness on the measured value of *force reduction*; a method to relate it to the intrinsic properties of the material is proposed.

Keywords

Force reduction; sport surfaces; thickness; viscoelastic behaviour; dynamic-mechanical analysis (DMA).

1. Introduction

Polymeric materials are extensively used in shoes and sport surfaces (in particular for athletics tracks) as shock absorbers to prevent joint and muscular injuries: in fact they are able to reduce the amplitude of incoming shock waves travelling through the human locomotion system while running or jumping [1-2]. There is a significant body of literature on the effect of shoes and surface materials in running impact, but these works primarily concern the athletes physiology or the study and prevention of sport injuries [3-7]. So far, the contribution of materials engineering to the design of products that can reduce the risk of such injuries has been relatively minor. Studies of system dynamics and energy aspects of impact have been performed with computer aided modelling [8-10]. These studies cannot neglect the characteristics of the surface material and its structure. In fact, on impact with the surface, different stress levels can be reached depending on, *inter alia,* its stiffness [6] or that of the shoe soles [11].

Nowadays, running track surfaces can be paved with an *in-situ system,* by machine mixing and laying of raw material ingredients directly on the substrate, or prefabricated and subsequently laid on the substrate of the track.

The *in situ-systems* may be sub-divided into three principal types: cast elastomers, resin-bound rubber crumb and composite systems. The cast elastomer type is laid as a free-flowing liquid polyurethane prepared by mixing two components (a liquid polyol and an isocyanate) with chopped rubber crumb. The second type comprises a principal layer of moisture-curing polyurethane resin mixed with rubber crumb and finished with a 0.5-2 mm thick coating made of resin and fine rubber granules, to confer the desired aesthetic and wear-resistance properties. The composite system is a hybrid of the two types: it is formed from a base mat of resin-bound rubber crumb with a cast elastomer layer applied as the top surface. The appearance of the finished facility is exactly as for a cast elastomer system but the surface is cheaper since less of the expensive cast polyurethane resin is used. These systems comprise the most widely installed group of synthetic surfaces for athletics.

The prefabricated type is made by calendering and curing synthetic rubbers with mineral fillers and additives. Prefabricated surfaces may have a particular pattern in order to adjust their cushioning ability to the desired level and to respond with different rigidity along different directions of imposed load. Producing the surfacing material in the controlled environment of a factory warrants uniform properties. Nonetheless, the installation of the surface requires a high degree of accuracy since the sheet is bonded to the substrate with weather-sensitive adhesives [12, 13].

Because of the wide differences in the characteristics of existing sports surfaces, the evaluation of the cushioning ability of a track is a complex task, which must take into account both the morphology and structure of the manufactured surface and the inherent mechanical properties of its constituent materials. The tests used to characterize such behaviour can be divided into two groups: those collecting quantities measured on the manufactured track, such as force, acceleration, or deformation resulting from a drop test, and others gathering the intrinsic mechanical characteristics of the constituent material. The International Association of Athletics Federations (IAAF) has preferred the first category and adopted two standardized tests for the homologation of track surfaces [12-15]. The test devised to evaluate the capability of the surface to reduce the impact force is referred to as the *force reduction* test (*FR*),which is performed with an *artificial athlete*, an instrument that attempts to reproduce the impact of the athlete’s heel on the surface. The apparatus, sketched in Figure 1, is composed of a 20 kg mass (1), which is dropped from the standard height of 55mm by releasing an electromagnetic brake (2). This also triggers the data acquisition system of the load cell (3) mounted on the base plate (4). The mass impacts onto another plate (5) placed on top of a spring (6) which transmits the force to the base plate and thence to the surface sample under test (7), and ultimately to the substrate (8). The load cell lying between the spring and the sample measures the force acting on the sample; the maximum force during impact, F_{max}, being identified from the force vs. time record.

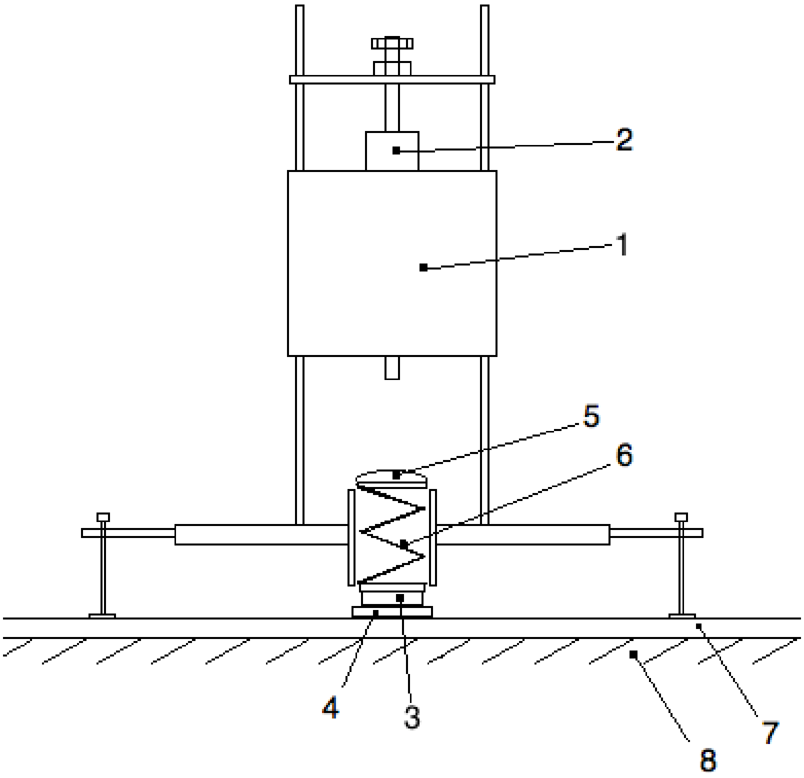


Figure 1. "*Artificial athlete*" apparatus. 1 falling mass; 2 electromagnetic brake; 3 load cell; 4 base plate; 5 upper plate; 6 spring; 7 track surface; 8 substrate.

The *base plate* is a steel disc, 70 mm in diameter, having the lower side slightly convex (with a 500 mm radius of curvature) and the lower circular edge rounded off (to a radius of 1 mm). Its geometry allows a gradual contact with the surface during impact and limits its penetration to a few millimetres.

The *force reduction* value is defined as the ratio between the peak force, F_{max}, measured on the track surface and a reference force, $F_{max,ref}$, which is the maximum value measured on a conventionally hard surface, such as concrete:

$$FR = \left(1 - \frac{F_{max}}{F_{max,ref}}\right) \tag{1}$$

In “on-field” tests the substrate is the actual base laid in place to accommodate the track surface and may vary from installation to installation. The characteristics of the substrate are not specified by the standard, despite the fact that they may affect the *FR* measurements. In laboratory testing the substrate is a concrete floor in accordance with the standard.

The standard prescribes at least three repeat tests on each sample; *FR* is taken as the average of the values obtained from the last two tests.

In the technical and scientific literature there is little agreement, not to say awareness, as to how the *force reduction* is affected by the material properties, the structure and the thickness of the surface and the nature of the substrate [9,16]. Focusing on the surface, it is interesting to seek a correlation between *force reduction* and the viscoelastic properties of the constituent materials, because it would help to select or develop optimal materials for such sport applications. Moreover, better knowledge of that correlation would allow prediction of how the material behaviour varies with external conditions such as temperature and humidity, two parameters that may vary considerably during use and substantially affect the viscoelastic characteristics of the constituent materials. A better understanding of the material's role in determining shock absorbing characteristics of a track would also help in improving correlation between material and subject tests, as discussed by Nigg and Yeadon [17] in their detailed review.

The work of Durà et al. [16] suggests that a relationship between *force reduction* and dynamic-mechanical properties of the materials should exist. In their work, dynamic-mechanical properties of three materials used as sport surfaces were measured and related to the corresponding *FR* values. The practical case described in their paper shows how, following IAAF and European standards [12-15], it is possible to obtain the same results of *FR* with materials having different loss tangent and dynamic rigidity values. The authors justified this fact by observing that an almost identical value of *FR* could be achieved by combining a high value of rigidity with a high value of loss factor, or a low value of both. The authors concluded that the two properties, rigidity and loss factor, directly influence *FR* values. On the basis of this observation, the present work set out a dynamic-mechanical analysis combined with *FR* measurements aimed at better understanding the materials' role.

Taking the work of Durà et al. [16] as a valid starting point, in the present study a wider range of materials was considered and the relationship between *FR* and viscoelastic properties of surfaces for athletics tracks was further investigated. Additionally, the effect of thickness was taken into account and its influence on *FR* was assessed.

2. Theoretical background on dynamic-mechanical properties

When a harmonic strain excitation of frequency f (expressed in Hz), or angular frequency $\omega = 2\pi f$ (expressed in radians per second), and amplitude ε_0,

$$\varepsilon(t) = \varepsilon_0 sin(\omega t) \tag{ 2}$$

is applied to an isotropic polymer, its steady state stress response is given by:

$$\sigma(t) = \sigma_0(\omega) sin[\omega t + \delta(\omega)] \tag{3}$$

with $\delta(\omega)$ being the phase shift angle between the stress and the applied strain. Resorting to a complex representation the stress can be also written as:

$$\sigma^*(t) = \sigma_0(\omega)\{cos[\delta(\omega)]sin(\omega t) + isin[\delta(\omega)]cos(\omega t)\} \tag{4}$$

In uniaxial tension/compression, a complex modulus can be defined as the ratio between complex stress and strain:

$$E^*(\omega) = \frac{\sigma^*(t)}{\varepsilon(t)} = \frac{\sigma_0(\omega)}{\varepsilon_0}\{cos[\delta(\omega)] + isin[\delta(\omega)]\} = E'(\omega) + iE''(\omega) \tag{5}$$

where the real part, *E*', represents the ratio of the in-phase component of the stress to the strain and is related to the energy exchanged elastically between the viscoelastic body and the external force generator and is thus called storage modulus. The imaginary part, *E*", represents the ratio of the $\pi/2$ out-of-phase component of the stress to the strain and is related to the energy dissipated by the viscoelastic material in each cycle and is thus called the loss modulus. The ratio of the imaginary part to the real part, usually called loss tangent and indicated as tan δ,

$$tan[\delta(\omega)] = \frac{E''(\omega)}{E'(\omega)} \tag{6}$$

represents the relative energy dissipation characteristic of a given material at a given frequency.

The absolute value of the complex modulus:

$$\left|E^*(\omega)\right| = \sqrt{E'^2 + E''^2} \tag{7}$$

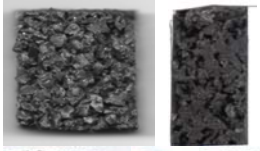
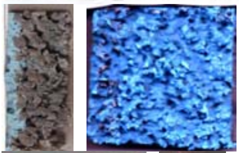
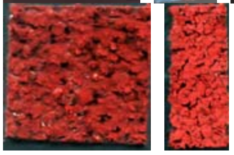
is referred to as the dynamic rigidity of the material, a property that will also be considered later in this study.

3. Materials and methods

The investigated materials are listed in Table 1. Seven of them (identified as A to G) are actually used for running tracks, while the next four (identified as PE, PB, NR and PU) are plain polymeric materials not commonly employed as sport surfaces: they were included in this study for comparison. In order to investigate the influence of the sample thickness on *FR*, slabs of different thicknesses were prepared. For those materials available in only one thickness, thicker samples were obtained by stacking several layers on top of each other. On-field measured data of *FR* and thickness were also collected from tracks of four different Italian fields. As these data are confidential they will be treated anonymously and generically referred to as “on-field measurements”.

All *FR* tests were carried out with the *artificial athlete* following the procedure described in section 1 [12].

Table 1 - Materials tested.

ID	**Description**	**Single layer thickness (mm) (*)**	**Number of layers in FR tests**	**Assembly**	**Single layer structure**
A	In-situ system *resin-bound rubber*	16.0	from 1 to 8	free	
			from 1 to 8	glued	
B	Prefabricated *rectangular cells*	13.5	from 1 to 6	free	
			from 1 to 6	glued	
C	In-situ system *material A with coating*	16.5	1	---	
D	Prefabricated *rectangular cells*	13.0	1	---	
E	Prefabricated *rectangular cells*	13.3	1	---	
F	Prefabricated *diamond cells*	13.2	1	---	
G	In-situ system *cast elastomer*	13.4	1	---	
PE	---	5-10-20-40	1	---	---
PB	---	3-5-10-20	1	---	---
NR	---	8	from 1 to 5	free	---
PU	*foam*	6.5-12.5-18-25-44-56	1	---	---
Fields	FR and thickness measurements at different positions of tracks from 4 Italian athletics fields				

Legend: A to G: sport surface products from different manufacturers; PE: polyethylene; PB: isotactic polybutene-1; NR: natural rubber; PU: foamed polyurethane.
(*) The thickness used in DMA testing is listed underlined.

The instrument used was a model KS20 manufactured by IST, Switzerland, using a Keithley analyser to process the data acquired by the load cell, which was subsequently conditioned using a filter having a 2nd order Butterworth characteristic with a -3 dB frequency of 120 Hz, as specified in the standard [12,18]. All samples tested with the artificial athlete were at least 400x400 mm in size, with various thicknesses according to Table 1. The tests were performed by laying the samples on a hard floor as required by the standard; the specimens were not glued onto the floor.

The dynamic-mechanical analyses (DMA) were performed in compression mode with a *TA Instruments Rheometrics Series RSA III*. The samples were put between 25 mm diameter parallel plates . All specimens for the dynamic-mechanical analysis were cut by means of a band saw; their thickness was equal to that of a single layer, as listed in Table 1. Different in-plane specimen sizes were tested in order to assess possible confinement effects. Indeed, for specimen sizes smaller than 30x30 mm some differences were observed. For larger sizes the differences were negligible, and thus a 30x30 mm size was finally selected as optimal since it gave accurate results while keeping sample dimensions limited. Moreover, in the case of prefabricated materials, the selected size allowed inclusion of a sufficient number of characteristic features (‘cells’, see Table 1) so as to average out a possible effect of the pattern on the sample’s mechanical response.

The specimens were pre-loaded with a compressive nominal stress of 30 kPa, which was maintained during the whole test; measurements were then performed in strain control mode, with the sinusoidal alternating strain of amplitude 10^{-3} superposed to the strain produced by the pre-load. Frequencies from 1 to 50 Hz were covered. The testing configuration (compression) and parameters (pre-load, strain amplitude and frequency) were selected so as to reproduce the actual conditions experienced by sports surfaces during *FR* testing. At least three samples were tested for each material.

All laboratory tests, i.e. both *force reduction* laboratory tests and DMA tests, were performed at 21±2°C. Field tests were performed under various environmental conditions.

4. Results and discussion

The aim of DMA testing was to characterize the inherent viscoelastic behaviour of the materials in terms of dynamic rigidity, $|E^*|$, and loss factor, tan δ. In doing so, all tested materials were assumed as being homogenous with isotropic behaviour (at the *meso-scale*) for the purposes of this characterization.

Actually, some of the samples considered in the present study are neither homogenous nor probably isotropic, as is the case for structured or patterned track surfaces. Under such circumstances, the measured quantities are not strictly intrinsic material properties. Nevertheless, for the purposes of this work, these “apparent” material properties were considered representative of the overall material behaviour, in a way that is consistent with the *FR* characterization, with which correlation is sought.

The repeatability of the dynamic-mechanical measurements was first checked by a series of tests performed on all the materials: three replicates were conducted on identical specimens and under the same test conditions adopted during all analyses. The results are shown in Figure 2 for material A: the average standard deviation is of the order of 1%. Similar standard deviations were obtained for replicated measurements on the other materials.

The results of the dynamic-mechanical analysis of all materials tested are shown in Figure 3 and Figure 4, where the dependence of the storage modulus, E', and the loss factor, tan δ, on the imposed frequency is shown.

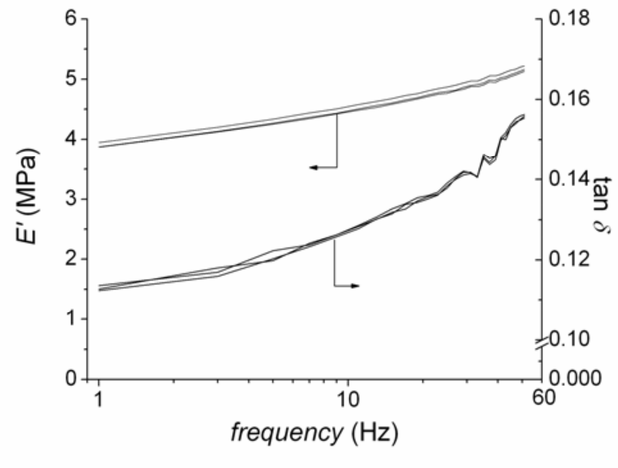


Figure 2. Example of repeatability of the dynamic-mechanical measurements performed on three specimens of material A. The corresponding lines are almost undistinguishable for all three properties considered.

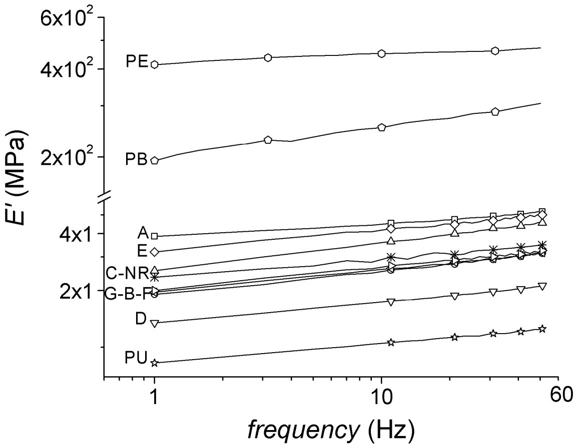


Figure 3. Storage modulus *E'* vs. frequency. The symbols are only meant to tag the curves and do not represent all the actual experimental data points. (Labels identify materials as in Table 1).

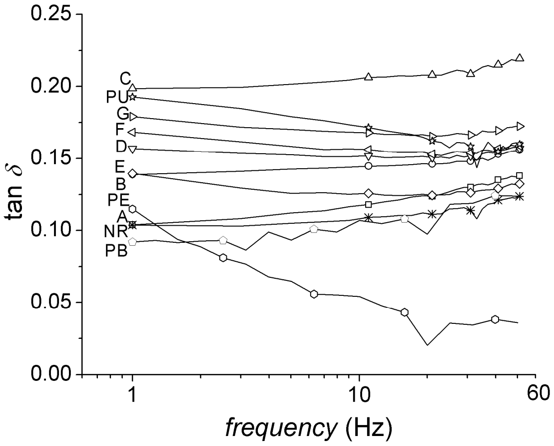


Figure 4. Loss factor tan δ vs. frequency. The symbols are only meant to tag the curves and do not represent all the actual experimental data points. (Labels identify materials as in Table 1).

These data show that the loss factor does not vary considerably between the tested materials and remains almost constant over the investigated range of frequencies, with the expected exception of PE [19], which shows a decreasing trend (Figure 4). More significant differences (orders of magnitudes) can be observed in the storage modulus (Figure 3). Values of *tan* δ are small enough to make dynamic rigidity $|E^*|$ and E' almost identical for all tested materials.

In Figure 5, an example of force vs. time record is shown for each material. It is clear that track surfaces and PU show similar behaviour, rather different from that of the other three materials (PB, PE and NR), which in turn behave almost identically.

To assess the existence of a correlation between *FR* and the dynamic-mechanical properties of the track materials, *FR* was plotted vs. dynamic rigidity in Figure 6(a) and vs. loss factor in Figure 6(b), as suggested by Durà et al. [16]. Given the limited sensitivity of both properties to the frequency (as shown in Figure 3 and Figure 4), only a single representative value - the one measured at 10 Hz - was considered for each material. The data show no apparent correlation between *FR* and dynamic-mechanical properties.

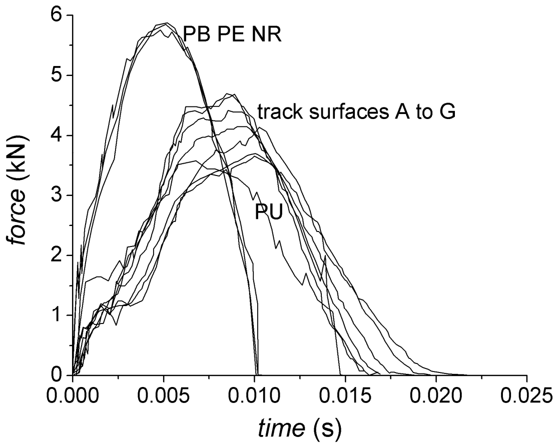


Figure 5. Raw (unfiltered) records of the signal acquired by the load cell of the artificial athlete. Results refer to tests performed on single layer samples with thicknesses as reported underlined in Table 1. (Labels identify materials as in Table 1).

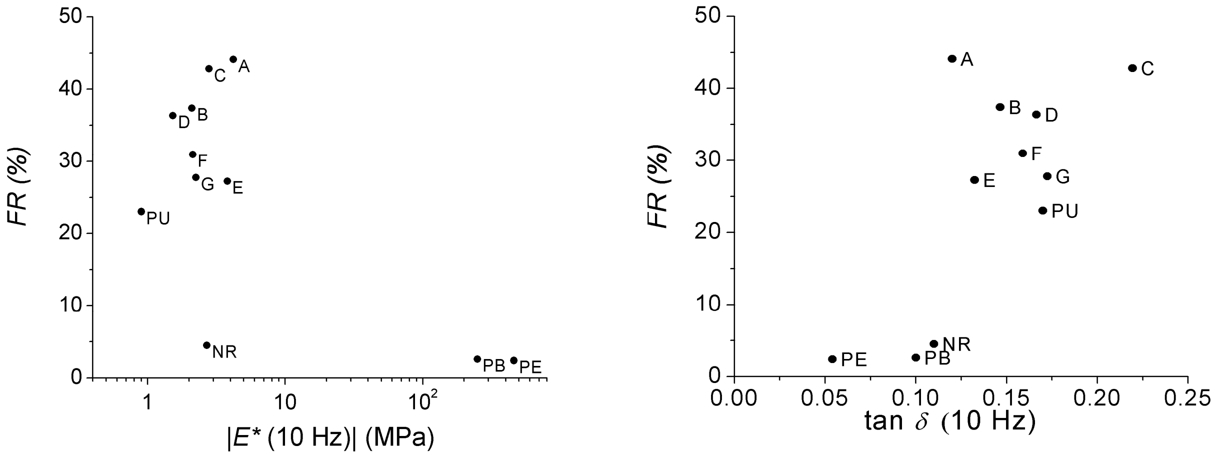


Figure 6. *Force reduction* vs. *(left)* dynamic rigidity $|E^*|$ and *(right)* loss factor (tan δ) measured on sport surfaces and other polymeric materials. Results refer to tests performed on single layer samples with thicknesses as reported underlined in Table 1. (Labels identify materials as in Table 1).

It is worth observing, in particular, the cases of natural rubber (NR) on one side and of polyethylene (PE) and polybutene (PB) on the other. NR has dynamic-mechanical properties, both in terms of dynamic rigidity and loss factor, similar to those of the tracks; yet it displays a considerably lower *FR* value, similar to that of PE and PB which, in turn, show dynamic-mechanical properties, especially dynamic rigidity, substantially different from those of the tracks. This result clearly points out that the measured *FR* response is driven by factors other than just the dynamic-mechanical properties of the constituent material.

It is worth noting, in particular, that the above comparison ignores the possible influence of the thickness of the sample, whereas it is sensible to presume that this variable affects the response to impact. It can be expected that in thinner samples there will be an interaction with the substrate, which would produce a lower *FR* than in thicker samples. It can be further supposed that samples of similar thickness may differently interact with the rigid substrate depending on their mechanical properties. Moreover, IAAF specifications set out the requirement of an optimal thickness to be defined during the laboratory homologation tests, and the further requirement that this thickness is to be maintained during the entire service life of the running track, thereby implicitly acknowledging the existence of a thickness effect in the track performance [13]. Ignoring this effect when looking for correlations between *FR* and dynamic-mechanical properties of sport surfaces can be misleading. This topic has not been seriously investigated and reported in the open scientific literature to the best of the authors' knowledge. It was thus investigated in the present work by carrying out a series of *FR* tests on track surfaces and some plain polymeric materials of different thicknesses.

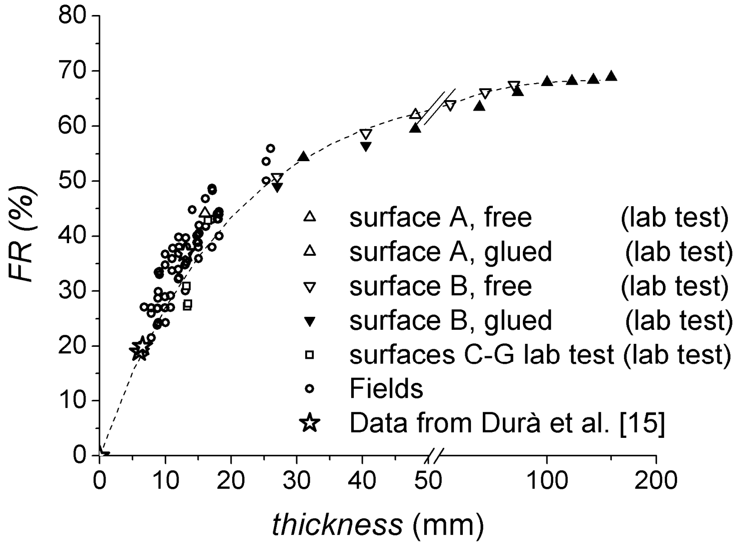


Figure 7. *Force reduction* data plotted vs. sample or track thickness in laboratory tests and on-field measurements. The line through the experimental points is just a guideline and not an actual fit of the experimental data.

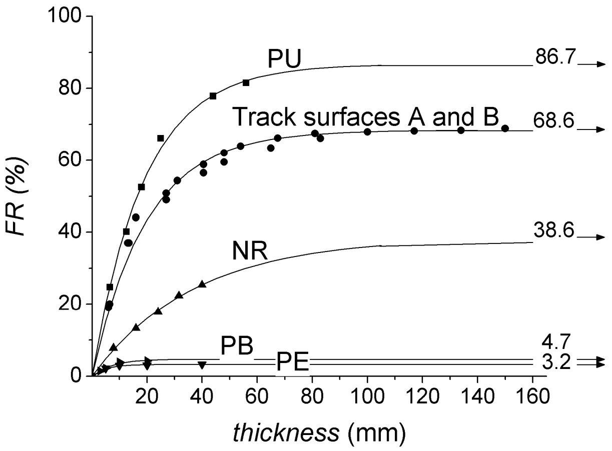


Figure 8. Experimental data (dots) and fitting (continuous lines) of *force reduction* FR vs. thickness for some of the tracks (A and B) and the plain polymeric materials tested. The asymptotic values of FR are displayed. (Labels identify materials as in Table 1).

The results obtained on track surfaces are reported in Figure 7. On track surfaces A and B the effect of thickness was studied by stacking a number of layers one upon the other. The possible effect of the sliding of the superimposed layers during impact was assessed by comparing the results obtained on simply superimposed layers to the values obtained by gluing the layers together. No appreciable difference between the two could be detected. The data gathered and reported in Figure 7, which include some results from the work of Durà et al. [16], clearly show that *FR* changes dramatically with the sample thickness; the overall behaviour is similar for laboratory and field tests. It is interesting to note that the highest sensitivity to thickness occurs in the range below 25 mm, which is the range of thicknesses commonly used in practice. The observed thickness-dependence reveals, of course, the presence of an interaction with the substrate. As the substrate manufacture is not standardized, the differences observed among the tracks of different athletics fields may be imputed not only to track material and thickness but also to the presence of a different substrate, as well as different environmental conditions.

The collective results obtained in laboratory tests on some track samples and on plain polymeric materials are reported in Figure 8, in which A and B are considered as representative of the behaviour of all track surfaces. Altogether, the data show an increase in *FR* with thickness, up to a limiting, asymptotic value, which depends on the material. These values are displayed to the right of each corresponding curve.

This behaviour justifies the lack of a direct correlation between the material's dynamic-mechanical properties and *FR* when thickness, and hence the presence of an interaction with the substrate, is not taken in due account. A correlation can, in turn, be sought by considering the asymptotic value of *FR,* upon which the substrate has no relevance.

To do that, the asymptotic value of FR for each sample was determined by best fitting the experimental data set of Figure 8 with the following empirical equation:

$$FR(s) = FR_{\infty}\left(1 - e^{-s/s_0}\right) \quad (8)$$

in which, the asymptotic value of *FR*, corresponds to thicknesses, *s*, adequately larger than a characteristic value, s_0. Both parameters are obviously material dependent.

In Figure 9 the values of FR_{∞} and s_0 resulting from data fitting for each material are plotted vs. the relevant dynamic properties (at 10 Hz).

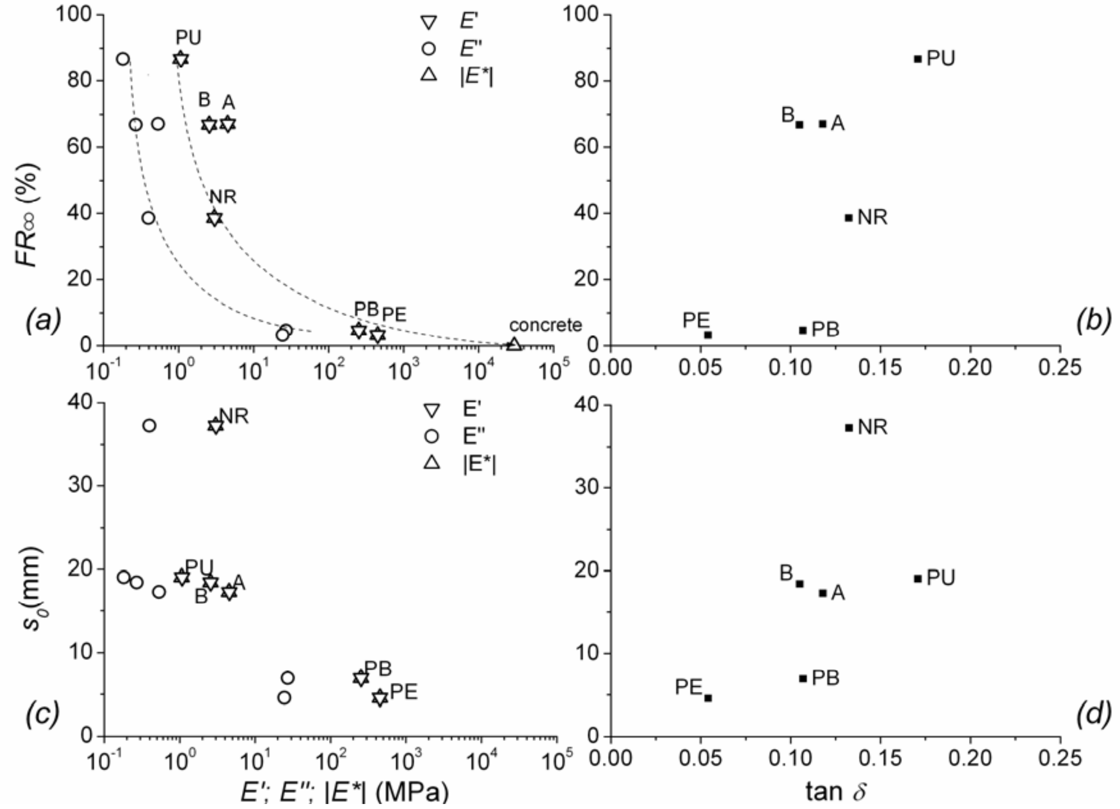


Figure 9. Correlations of the two fitting parameters FR_{∞} and s_0 with: *(a)-(c)* the moduli (*E', E'',* |*E**|) and *(b)-(d)* the loss factor of the materials. The lines drawn in *(a)* are just guide-lines and not actual fits of the data. (Labels identify materials as in Table 1).

Figure 9(a) shows FR_∞ plotted vs. $|E^*|$, E' and E''. As already mentioned, the values of $|E^*|$ almost coincide with the values of E',since the latter is significantly larger than E''. The three data sets show a similar trend: an inverse correlation seems to exist between FR_∞ and the moduli, which is sensible since it is common experience that stiffer materials respond to impacts with a higher peak force.

In Figure 9(a), the datum point representing the modulus E' of the concrete is also shown, which is the conventionally "rigid" material used to calculate the FR according to (1). For this case, $FR=0$ irrespective of thickness and the FR_∞-E' correlation rightly comprises that point too.

Figure 9(b) shows FR_∞ plotted vs. $\tan\delta$. Over the limited range of $\tan\delta$ variability covered by the materials investigated, no clear correlation appears to exist but a generic increasing trend of FR_∞ with increasing $\tan\delta$ can be observed. Hence, no significant conclusion on the effect of the viscoelastic damping characteristics of the materials on the (asymptotic) FR can be drawn.

In Figure 9(c) and 9(d) the values of the second parameter appearing in eq. 8, s_0, are plotted vs. dynamic moduli and loss factor, respectively, for the same set of materials. According to eq. 8, s_0 represents a sort of "sensitivity" of the material under test to the thickness.

The scatter in the data points here does not allow drawing any sensible indication of correlation of this parameter with either material dynamic-mechanical properties – dynamic moduli or loss factor.

5. Conclusions

A correlation of the shock absorbing ability of materials for track surfaces with their inherent mechanical properties was sought. *FR* was chosen as representative of this ability, in agreement with international standards.

A first set of tests, performed on samples of different materials with similar thicknesses – each one taken “as it is” from the producer – showed no apparent correlation of *FR* with dynamic rigidity or loss factor.

The influence of the sample thickness was investigated next: a strong effect on *FR* was found, especially in the thickness range that is of practical interest in sport surfaces applications. It was observed that, with increasing thickness, the value of *FR* increases and tends to a limiting value, which is indeed related to the dynamic rigidity of the material. The behaviour of all materials tested, sport surfaces and plain polymeric materials, allows identification of a simple inverse relationship between the limiting value of *FR* and the dynamic rigidity or its most significant component E'. The (limiting value of) *FR* appears less clearly correlated with the dissipative properties of the materials, as characterized by the loss factor, over the range of property variability covered in this work. Dissipative properties are expected to have an influence on the cushioning characteristics of sport surfaces, with important dampening effects on the high frequency peaks generated in the very first moments of the impact, thus increasing the comfort and the safety of the athlete; however it seems that *FR* is not sensitive to these aspects. This topic is to be investigated further.

Other aspects need to be considered in order to completely characterize the material’s behaviour and thus gain the knowledge required for a design which may successfully combine safety and performance. Moreover, it should be pointed out that the correlation between *FR* and properties determined by DMA was carried out in a phenomenological fashion, performing DMA tests in conditions similar to those of the *FR* test. Of course, further investigation is required to gain a deeper insight into the phenomena occurring during *FR* tests and more in general during an impact on a track surface. For example, our tests showed clear evidence that the substrate interacts in the shock absorption behaviour of the tracks for the thicknesses used in the common practice. Since the thicknesses required to reach the *FR* asymptote with ordinary track materials is impractical, the effect of the substrate must be taken into consideration. This topic, and in general the strain state produced in the track during the impact, is also worthy of further investigation . Numerical analyses are currently being carried out in the authors’ laboratory to quantify the thickness influence under various conditions and to determine how material properties control the sensitivity of FR with respect to the thickness.

The effect of the physical structure of the tracks is also worthy of investigation, in order to achieve a complete picture of the “structure-material properties-performance” relationship system.

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