ORIGINAL PAPER

The Third Generation of Artificial Football Turf: Effect of the Structural Components on Shock Absorption

Reza Ghasemi, Abdolhossein Sadeghi*, and Ali Asghar Asgharian Jeddi

Abstract- **This study aims to investigate the effect of different components of artificial football turf (infill height and free pile height) and wear on the shock absorption of artificial turf. Eight samples of turf from two different manufacturers with different rubber infill heights were tested. The experimental results showed that the rubber height (three heights of 10, 20, and 30 mm) has a significant effect on shock absorption. Wear affects shock absorption so, but the effect of wear on shock absorption (namely the number of cycles required to reduce shock absorption), varies for different samples. Although free pile height (two heights of 10 and 20 mm) does not affect shock absorption, it has an important role to keep rubber inside the artificial turf, thus reduces the wear effect. These results demonstrate the importance of properly designing artificial turf components to obtain proper shock absorption.**

Keywords: **artificial football turf, shock absorption, infill height, free pile height, wear**

I. INTRODUCTION

In recent years, the usage of artificial turf has grown significantly due to its many benefits, and FIFA (fédération internationale de football association) support. Much progress has been made in artificial turf, especially in efficiency and safety, from the first generation to the third one [1,2].

The first generation of artificial turf was developed in the 1960s. It was made from nylon fibers and had a 10-12 mm pile height without any infill. The second generation was introduced in the 1970s, made from

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polyethylene and 20–25 mm pile height and filled with sand. The third-generation (3G) was developed in the 1990s, and was aimed to simulate natural turf, has a long pile height, of 40–65 mm, and was filled with sand and rubber [3].

The recent research areas on artificial turf is vast, due to its rapid growth. The first research area is artificial turf temperature, temperature simulation, toxicity and heavy metals in artificial turf, and its environmental friendliness [3-8]. The second one is investigations on the extent of injury of the player during use [4-12]. The third one is investigations on the parameters affect the physical and mechanical properties that determine the quality of play [5].

Alcantara *et al.* studied the effect of wear of artificial turf on some of its properties, including shock absorption and vertical ball rebound. They conclued that wear reduces shock absorption and increases the vertical ball rebound, and less than 200 cycles wear has no effect on the mentioned parameters [6]. Charalambous *et al.* have studied the effect of surface temperature on some characteristics of grass and soccer game. They subjected two types of grass to cold (1.8-2.4 ºC) and hot (14.5-15.5 ºC) temperatures and concluded that temperature has an effect on shock absorption and some other properties, and the increase in temperature increases shock absorption. While the research of Sánchez *et al.* rejects this result. Sánchez and his colleagues performed the impact absorption test in very cold (-5 ºC) and very hot (40 ºC) temperatures [7].

The hardness of artificial football turf pitches varies as a function of the state and characteristics of the rubber filler and shock-pad layer [8]. Kerdok *et al.* have studied the biomechanical technique of running, which the safety of players is relevant to it. They concluded that higher or lower shock absorption of the surface affects the biomechanical

technique of running [9].

Alcantara *et al.* have concluded that the use and repeated loading lead to increase compaction of the rubber infill, which increases the hardness and decreases the shock absorption ability of the surface [10]. Studies by Sanchez *et al.* showed that pile length, bulk density, tuft/m², and sub-base material all influence the mechanical properties of the surface such as shock absorption, vertical deformation, rotational resistance, and ball roll [11]. Previous studies by Sanchez *et al.* also has shown the influence of structural components on the mechanical behavior of the third generation artificial football turf systems [12].

Besides, these components also influenced the player–surface interaction variables, such as shock absorption, vertical deformation, and energy restitution [3,13].

Previous studies of Sanchez *et al.* showed that:
1) Wear on the artificial football turf causes an increase in rotational resistance, and decrease of shock absorption and vertical deformation,
2) Temperature does not significantly alter the mechanical behavior of the surface, and
3) Humidity decreases the shock absorption of the artificial football turf [8].
They investigated the effect of shock pad layer on the rate of shock absorption reduction, which was lower in the samples with the shock pad layer [8]. Meuleman sutdied 50 fields, over 7 years (2001-2008). These sutdies showed that wear reduces shock absorption and the effect of maintenance processes on reducing shock absorption is significant [14].

Harper in his thesis showed that the tuft pile height without incorporated infill correlated directly with shock absorption values. Thus higher tuft pile height improves shock absorption. But, the contribution of infill on the overall shock absorption values achieved was more significant than the pile height [15].

The effect of free height of fibers on wear and impact absorption and the effect of wear on other parameters have not been reported in previous studies.

This study aims to analyze the influence of infill factors, including infill height and free pile height, on the shock absorption of artificial football turf of football pitches and evaluate the effect of induced wear on the mechanical properties of the surface through laboratory testing.

II. EXPERIMENTAL

A. Materials and Methods

For construction of the artificial football turf in the present research, the tufted carpet was prepared from two different manufacturers, which their specifications are shown in Table I.

Eight football artificial turf specimens were constructed

TABLE I
CARPET SPECIFICATIONS OF SAMPLES

Fiber	PE (LLDPE)
Type	Monofilament
Thickness (μm)	130
Width (mm)	1
Number of piles per meter (width)	63
Pile weight (g/m²)	1100
Tuft density (tuft/m²)	10240
Carpet mass (g/m²)	2400

TABLE II
CHARACTERISTICS OF INFILL HEIGHT

Free pile height (mm)	Rubber infill height (mm)	Sand infill height (mm)	Pile height (mm)
10	20	20	50
20	20	10	50
10	30	10	50
20	15	15	50

from these two type tufted carpet, by different strutures and then evaluated. The selected systems of artificial turf are third-generation, and the surface certificate is based on the laboratory regulation requirements established in the FIFA Test Method. The structural variables used were: infill height, free pile height, and other characteristics of artificial carpets are listed in Table II. Fig. 1. shows the profile of two types of pile fibers.

As Fig. 2 shows, based on the DSC diagram, two fibers are of the same type, but with different crystallinity, because each component of the blend has its melting peak. These individual melting peaks are on other existing melting peaks and where the melting peaks are close together, they appear as a more diffuse and broader melting peak. If the melting peaks of a blend of polymers are more spaced then the peak will be broadened further or the peaks will either appear separately or a "shoulder" will appear on the overall melting peak [16].

Thus, according to the DSC diagram and the calculation of the percentage of crystallinity, the fibers of the two companies are of the same type but with different
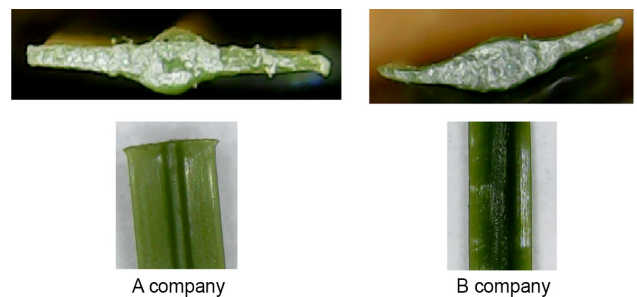

A company   B company
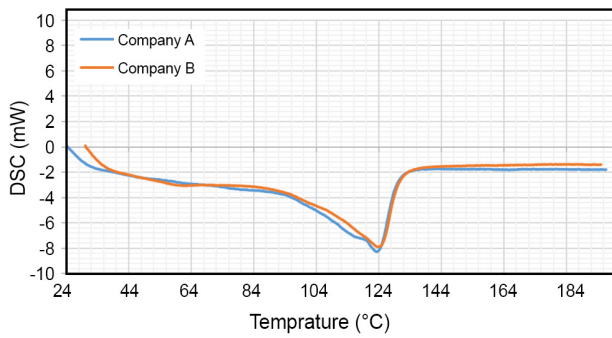
Fig. 1. Profile of pile fibers.

Fig. 2. DSC diagram of fibers.

crystallinity. The crystallinity percentage of the fibers of company A is 16.6% and company B is 14.8%.

The amount of infill per unit of the surface was weighted separately and then applied progressively. During this process, the fibers of the turfs were put in a vertical position out of the infill layers. The thickness of layers and overall infill were controlled by using a standardized test method. Thus, once the infill was applied, sand and rubber amount were tested separately using the floor test device, as shown in European Standards, EN 1969.

B. Test Methods
The tests on shock absorption and wear were performed as described in the following subsections.

B.1. Shock Absorption or Force Reduction
A mass (20 kg) with a spring (2000±100 N/mm) attached to it is allowed to fall onto the surface. The acceleration of the mass is recorded, from the moment of its release until its impact on the surface. Shock absorption was calculated by comparing the maximum force on the surface with the reference force of impact on concrete. Shock absorption was calculated as a reduction of the impact force on the sample compared to a reference force. Reference force (F_{ref}) was fixed to 6760 N (theoretical value calculated for a concrete floor).

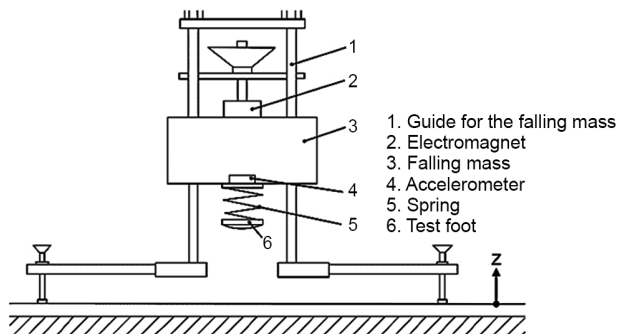The apparatus used to measure shock absorption is

called the advanced artificial athlete (AAA). The schematic design of the AAA apparatus is depicted in Fig. 3.

The peak force (F_{max}) at the impact can be calculated with the following formula [16]:

$$F_{max} = m.g.G_{max} + m.g \tag{1}$$

where, F_{max} is the peak force, expressed in Newton (N). G_{max} is the peak acceleration during the impact, expressed in g (1 g=9.81 m/s²), m is the falling mass including spring, test foot, and accelerometer, expressed in kg and g is the acceleration by gravity (9.81 m/s²). The shock absorption, SA, is calculated by using the following formula [16]:

$$SA = \left[1 - F_{max} / F_{ref}\right] \times 100 \tag{2}$$

where, SA is the shock absorption in %, F_{max} is the maximum force measured on the sport surface in N and F_{ref} is the reference force fixed to 6760 N (theoretical value calculated for a concrete floor).

The test was performed at three points in each sample. At each test point, it was repeated three times. The average of the second and third test results was the amount of the shock absorption test at that point. The mean of 6 tests was reported as the result of the sample shock absorption test (FIFA standard test method) [16].

B.2. Wearing Machine
Lisport machine was used for the wear of artificial football turf. The machine has two cylinders, each cylinder weight 28.5±2 kg, 118±5 mm in diameter, and has plastic studs. The number of studs per cylinder is 145-150. The studs are made of hard plastic with a hardness of 96±2 Shore A. The Shore durometer is a device for measuring the hardness of a material, typically polymers, elastomers, and rubbers. The A scale is for softer ones, while the D scale is for harder ones. The linear velocity of the cylinders is 0.25±0.05 m/s and the traverse speed of the sample tray is 0.015±0.005 m/s [16]. Fig. 4 shows a view of the wearing machine.

1. Guide for the falling mass
2. Electromagnet
3. Falling mass
4. Accelerometer
5. Spring
6. Test foot

Fig. 3. Shock absorption (AAA) test apparatus [16].
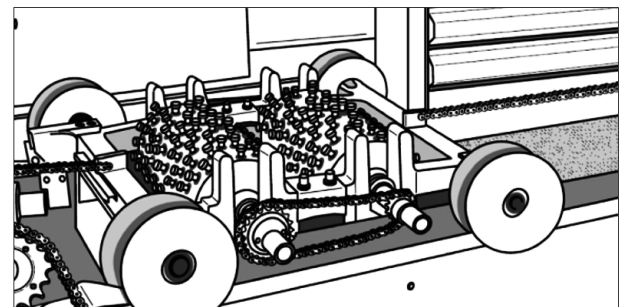

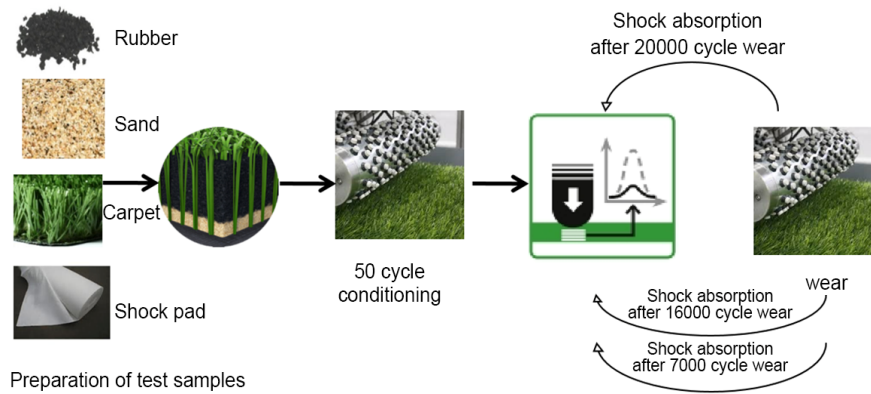Fig. 4. Wearing machine (Lisport) [16].

Fig. 5. Procedure of shock absorption measurement.

B.3. Procedure

All of the tests were performed under stable and dry conditions with a minimum temperature of 21 °C and a maximum temperature of 25 °C. These conditions are within the ranges and protocol as defined in the FIFA Quality Program for Football Turf. Test methods for mechanical properties are explained here.

Test samples were prepared with 40×80 cm² dimensions. The parameters related to shock absorption on the surface were all tested in the laboratory. All test specimens were conditioned before testing by passing a Lisport machine over them for 50 cycles at the laboratory conditions. The amount of shock absorption was measured at three points of each sample.

To analyze the effect of wear on the shock absorption property, the mechanical tests were carried out in four levels of the mechanical wear, namely no wear and 7000, 16000,

and 20000 cycles. After wear, the samples were removed from the Lisport for testing. The test specimen was refilled with material that had been previously dislodged. Fig. 5 shows a brief procedure of shock absorption measurement.

III. RESULTS AND DISCUSSION

To analyze the results of the shock absorption tests, six data from nine were selected. Thereafter an analysis of variance (ANOVA) was done using the general linear invariant model to analyze the influence of wear, rubber height, and free pile height on shock absorption. Then Duncan test was performed to categorize the results. To identify significant changes, a confidence level of 95% was selected. Table III presents the mean value and standard deviation of shock absorption due to artificial football turf parameters (i.e., rubber height and free pile height), before and after of 7000, 12000, and 20000 wear processing cycles.

TABLE III
SHOCK ABSORPTION (%) OF ARTIFICIAL TURF IN DIFFERENT STAGES

| Height of artificial turf component (mm) | | | Shock absorption (%) | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Before wear | | | | | 7000 cycle wear | | | | | |
| Rubber infill | Sand | Free pile | Company A | | | Company B | | | Company A | | | Company B | | |
| | | | Ave | Std | | Ave | Std | | Ave | Std | Reduction | Ave | Std | Reduction |
| 15 | 15 | 20 | 55.1 | 1.3 | | 54.5 | 1.64 | | 54.5 | 1.87 | 1.1 | 53 | 1.17 | 2.8 |
| 20 | 10 | 20 | 57.2 | 1.36 | | 56.3 | 1.17 | | 55.2 | 1.94 | 3.5 | 55.7 | 1.21 | 1.1 |
| 20 | 20 | 10 | 57.9 | 1.41 | | 58.2 | 1.52 | | 55.3 | 1.63 | 4.5 | 56.7 | 2.07 | 2.6 |
| 30 | 10 | 20 | 62.9 | 1.28 | | 63.7 | 0.84 | | 56.2 | 1.47 | 10.7 | 54.7 | 1.26 | 14.1 |
| | | | 16000 cycle wear | | | | | 20000 cycle wear | | | | | |
| | | | Company A | | | Company B | | | Company A | | | Company B | | |
| | | | Ave | Std | Reduction | Ave | Std | Reduction | Ave | Std | Reduction | Ave | Std | Reduction |
| 15 | 15 | 20 | 52.2 | 2.14 | 5.3 | 52.8 | 2.19 | 3.1 | 52 | 1.55 | 5.6 | 52.2 | 1.64 | 4.2 |
| 20 | 10 | 20 | 55.3 | 2.14 | 3.3 | 56.8 | 1.21 | -0.9 | 56 | 2.28 | 2.1 | 55.7 | 1.75 | 1.1 |
| 20 | 20 | 10 | 54.5 | 1.52 | 5.9 | 53.8 | 2.32 | 7.6 | 54.2 | 0.98 | 6.4 | 51.2 | 1.17 | 12.0 |
| 30 | 10 | 20 | 56.8 | 1.21 | 9.7 | 57 | 1.75 | 10.5 | 55.5 | 2.26 | 11.8 | 54.5 | 1.25 | 14.4 |
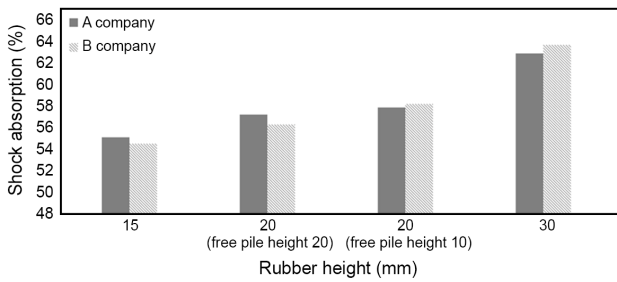
Fig. 6. Effect of rubber height and free pile height on shock absorption.

A. Effect of Rubber Height

Shock absorption results showed a direct relation between rubber height and S.A. (Fig. 6). As the height of the rubber increases, the shock absorption increases. These results are consistent with previous research [9,13].

B. Effect of the Free Pile Height

Statistical analysis of all samples showed that the free pile height did not affect the shock absorption. Fig. 5 shows that there is not any significant difference in the amount of S.A. for the first time (without wear), between turfs with 20 and 10 mm free pile height.

But, the behavior of these two types of turf (20 and 10 mm free pile height) against the wear is different. The artificial turf with longer free pile height is less affected by wear (Fig. 7).

C. Effect of Fiber Type

The artificial football turfs manufactured by the two companies, although are identical in their carpet construction characteristics, but differ in their fiber type. However, by analyzing all the data obtained from the shock absorption test of these two products, we were able to conclude that these two types of shock absorption fibers are not different. As it was expected, this result, like the
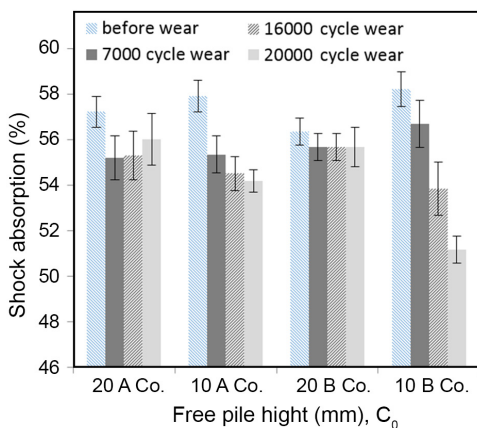

Fig. 7. Effect of free pile height on the variation of shock absorption of artificial football turf under the wear (20 mm rubber height).

free pile height, will not affect the wear. But, as it is evident from the case study of samples with rubber height of 20 mm and free pile height of 10 and 20 mm, the effect of wear on shock absorption for these two types of fibers is not the same.

D. Effect of Wear

In Fig. 8, the evaluation of the shock absorption can be observed as a function of the applied wear cycles and rubber height. The results revealed a significant decrease in the shock absorption between the previous analysis at the start of the wear process (0 cycles) and after 7000 cycles for 15 mm rubber height and 16000 cycles for 20 and 30 mm rubber height. As mentioned, the increase in rubber height has a significant effect on increasing the shock absorption of samples.

Wear in different samples affects shock absorption and reduces it. The onset of the decrease in shock absorption and the amount of this decrease depend on the structural characteristics of the turf, occurred in different cycles.

Fig. 8 shows that the effect of wear on the samples with 20 mm rubber height and 20 mm free pile height is not significant. The effect of wear on shock absorption of samples with 20 mm rubber height and 10 mm free pile height is not the same. Wear affected the shock absorption after 7000 cycles on A samples, whereas in sample B the wear was affected after 16000 cycles. Based on these results, it can be concluded that free pile height shows its effect on shock absorption, wear, and post-play on artificial football turf.

Table IV shows the details of ANOVA (and Duncan's test) for samples with 20 mm rubber height and 20 and 10 mm
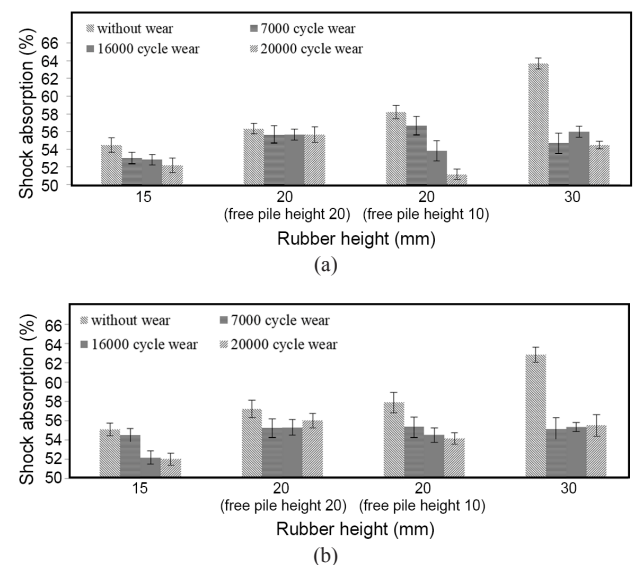

(a)

(b)

Fig. 8. Evolution of the shock absorption (%) during wear processing: (a) A company and (b) B company.

TABLE IV
ANOVA OF SAMPLES WITH A RUBBER HEIGHT OF 20 MM

Free pile height 20 mm					
A company			B company		
Duncan[a]			Duncan[a]		
	N	Subset for alpha = 0.05		N	Subset for alpha = 0.05
		1			1
20000 cycle wear	6	54.3333	7000 cycle wear	6	55.6667
Without wear	6	55.5500	20000 cycle wear	6	55.6667
7000 cycle wear	6	56.1667	Without wear	6	56.3267
16000 cycle wear	6	56.8333	16000 cycle wear	6	56.8333
Sig.		0.345	Sig.		0.269

Free pile height 10 mm								
Duncan[a]				Duncan[a]				
	N	Subset for alpha = 0.05			N	Subset for alpha = 0.05		
		1	2			1	2	3
20000 cycle wear	6	54.17		20000 cycle wear	6	51.17		
16000 cycle wear	6	54.50		16000 cycle wear	6		53.83	
7000 cycle wear	6	55.33		7000 cycle wear	6			56.67
Without wear	6		57.9	Without wear	6			58.22
Sig.		0.19	1.0	Sig.		1.000	1.000	0.16

Means for groups in homogeneous subsets are displayed. Used harmonic mean sample Size =6.000.

free pile heights (this analysis had been done for all the above-presented conclusions).

Wear affects shock absorption, and the fibers, also. Wear causes the fibers to break and flatten. Fig. 9 illustrate the effect of wear on fibers that have been broken and torn.

In a case study, we examined the breakage rate of fibers in the sample of two companies (A, B) with a 20 mm rubber height. In these four samples, the breakage rate of fibers was counted in the sample area 50×40 cm². Table V shows the number and percentage of broken fibers. As can be seen, the fracture rate of fibers in specimens with a 20 mm free pile height is greater than 10 mm free pile height after 20000 cycles. The fiber breakage rates also differ between the two companies, indicating that the type of fiber can influence the rate of fiber breakage.

The longer the free length of the pile, the less force is required to bend it and the more it is exposed to force. As a result, more broken piles are seen.

Wear produces a significant increase in the hardness of the surface and therefore a reduction of shock absorption. This reduction implies a deterioration of the mechanical property. These results are similar to those obtained by others [12,15,17]. Wear of artificial football turf reduces shock absorption.

Although the results showed that the type of fibers before the wear did not affect the shock absorption, the results of the shock absorption after the wear showed that the wear affected the broken rate of the fibers. As shown in Table III, the rate of shock absorption reduction after 20,000 cycles, for samples with 20 mm free pile height, in sample A is 3% and in sample, B is 7%. Therefore, it can be concluded that the type of fibers has an effect on the preservation of artificial football turf quality (shock absorption) over a long-term period.

Statistical analysis of all samples for two artificial football turf revealed that fiber type had no significant effect on shock absorption. Also by analyzing the data, the free pile height of the fibers did not affect shock absorption.
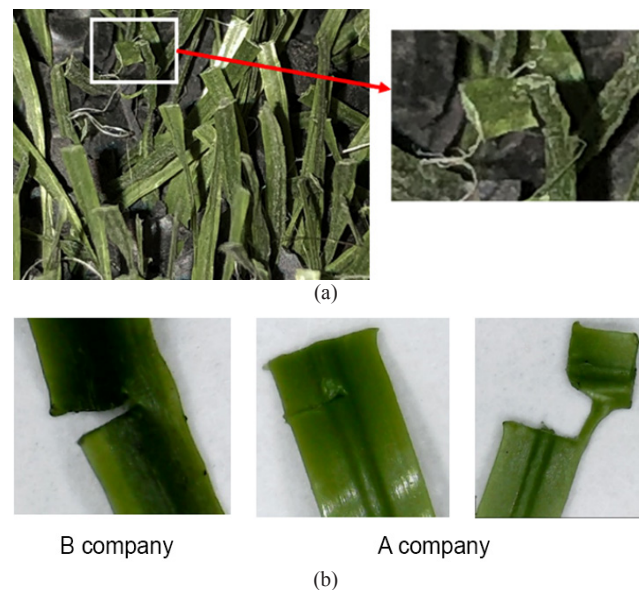

(a)

B company   A company

(b)

Fig. 9. Fiber breakage on pile fiber of artificial football turf: (a) broken fiber in artificial football turf and (b) type of breakage on pile fiber.

TABLE V
NUMBER AND PERCENTAGE OF BROKEN FIBERS IN SAMPLES WITH 20 MM RUBBER HEIGHT

Company	Free pile height (mm)	Number of broken fibers	Percentage of broken fibers
A	10	29	0.20
	20	43	0.30
B	10	39	0.27
	20	54	0.37

Statistical analysis of samples with 20 mm free pile height showed that wear had no significant effect on shock absorption, which could be attributed to the retention of fibers by the rubber infill.

But, fiber resistance to wear, as well as their static protection against wear, by proper storage of rubber, cause a decrease in shock absorption over longer periods. In other words, the lifetime of artificial football turf and the quality of the game depend on the fiber type, as well as the amount of infill and the free pile height.

As noted above, wear reduces shock absorption due to compression and loss of rubber.

By analyzing the obtained results, the rate of reduction of shock absorption due to wear after 20,000 cycles for samples with high rubber height (14% for company B and 12% for company A for samples with 30 mm rubber height) was higher than that for samples with low rubber height (4% for company B and 11% for company A for samples with 15 mm rubber height). The reason for this can be attributed to the compression of rubber at high rubber height.

IV. CONCLUSION

Shock absorption is one of the most important determinants of game quality and player safety. The experimentally obtained data in this research shows the following results:
1) Increasing rubber height increases shock absorption.
2) Wear reduces shock absorption.
3) The rate of decrease in shock absorption varies for different rubber heights.
4) Free pile height does not affect shock absorption. However, the free pile height can be effective due to the retention of rubber in reducing the rate of shock absorption reduction after wear.
5) The type of fibers (for tested 2 samples) does not affect the shock absorption, but it does affect the broken rate after wear and thus affects the life of the artificial football turf. Increasing knowledge about the effect of rubber height, free pile height, and wear effect on it, is a good guide for installers and consumers. This will help manufacturers and designers to develop alternatives that will improve the design and installation of artificial football turf on football fields. In addition to the above, the structure of the carpet may also affect the mechanical properties of artificial turf that we will discuss in future research.

A. Declaration of Conflicting Interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

REFERENCES

[1] A.S. McNitt, D.M. Petrunak, and T.J. Serensits, "Temperature amelioration of synthetic turf surfaces through irrigation", II International Conference on Turf Grass Science and Management for Sports Fields, Beijing (China), pp. 573-582, 2007. Doi: 10.17660/ActaHortic.2008.783.59

[2] J. Brito, P. Krustrup, and A. Rebelo, "The influence of the playing surface on the exercise intensity of small-sided recreational soccer games", *Hum. Mov. Sci.*, vol. 31, no. 4 , pp. 946–956, 2012.

[3] P. Fleming, "Artificial turf systems for sport surfaces: current knowledge and research needs", *Proc. Inst. Mech. Eng. P: J. Sport. Eng. Technol.*, vol. 225, no. 4, pp. 43-63, 2011.

[4] S. Williams, P.A. Hume, and S. Kara, "A review of football injuries on third and fourth generation artificial turfs compared with natural turf", *Sport. Med.*, vol. 41, no. 11, pp. 903-923, 2011.

[5] N.J. McLaren, P. Fleming, and S. Forrester, "Artificial grass, a longitudinal study on ball roll and free pile height", *Procedia Eng.*, vol. 72, pp. 871-876, 2014.

[6] E. Alcantara, J. Gamez, D. Rosa, and M. Sanchis, "Analysis of the influence of rubber infill morphology on the mechanical performance of artificial turf surfaces for soccer", *Proc. Inst. Mech. Eng. P: J. Sport. Eng. Technol.*, vol. 223, no. 1, pp. 1- 9, 2008.

[7] J. Sánchez-Sánchez, J. García-Unanue, A.M. Gallardo, L. Gallardo, P. Hexaire, and J.L. Felipe, "Effect of structural components, mechanical wear, and environmental conditions on the player–surface interaction on artificial turf football pitches", *Mater. Des.*, vol. 140, no. 15, pp. 172-178, 2018.

[8] S. Forrester and F. Tsui, "Spatial and temporal analysis of surface hardness across a third-generation artificial turf pitch over a year", *Proc. Inst. Mech. Eng. P: J. Sport. Eng. Technol.*, vol. 228, no. 3, pp. 213-220, 2012.

[9] A.E. Kerdok, A.A. Biewener, T.A. McMahon, P.G. Weyand, and H.M. Herr, "Energetics and mechanics of human running on surfaces of different stiffnesses", *J. Appl. Physiol.*, vol. 92, no. 2, pp. 469-478, 2012.

[10] E. Alcantara, J. Gamez, and D. Rosa, "Analysis of the influence of rubber infill morphology on the mechanical performance of artificial turf surfaces for soccer", *Proc. Inst. Mech. Eng. P: J. Sport. Eng. Technol.*, vol. 223, no. 1, pp. 1-9, 2009.

[11] J. Sanchez-Sa´nchez, P. Haxaire, J.G Unanue, J. Felipe, A. Gallardo, and L. AMGallardo, "Determination of mechanical properties of artificial turf football pitches according to structural components", *Proc. Inst. Mech. Eng. P: J. Sport. Eng. Technol.*, vol. 232, no. 2, pp. 1-9, 2017.

[12] J.Sanchez-Sa´nchez, J.L.Felipe, P.Burillo, J.Corral, and L.Gallardo, "Effect of the structural components of support on the loss of mechanical properties of football fields of artificial turf", *Proc. Inst. Mech. Eng. P: J. Sport. Eng. Technol.*, vol. 228, no. 3, pp. 155-164, 2014.

[13] N. McLaren, P. Fleming, and S. Forrester, "Artificial grass: a conceptual model for degradation in performance", *Procedia Eng.*, vol. 34, pp. 831–836, 2012.

[14] G. Kieft, "Quality monitoring of 50 artificial turf football fields: a study of the correlation between field properties", Sport Turf 7th workshop of Loughborough University, Loughborough, 2009.

[15] R. Harper, "Development of novel synthetic turf infill materials", Ph.D. thesis, Georgia Institute of Technology, USA, 2015.

[16] *FIFA Quality Program for Football Turf*, Handbook of Test Methods, 2012.

[17] K. Severn, P. Fleming, J. Clarke, and M.J. Carré, "Science of synthetic turf surfaces: investigating traction behavior", *Proc. Inst. Mech. Eng. Part P: J. Sport. Eng. Technol.*, vol. 147, no. 3, pp. 147–158, 2011.