FINAL REPORT

PART 1: SPORT FIELDS

Investigations on outdoor sports fields with synthetic turf systems to determine wear phenomena due to fibre abrasion related to the intensity of use

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1 Initial situation

The ILOS at the Osnabrück University of Applied Sciences, together with the EMEA Synthetic Turf Council (ESTC), is investigating outdoor sports facilities with synthetic turf systems throughout Europe to contribute to the estimation of the discharge quantities of secondary microplastics.

Following the current discussions about the ban on the marketing of primary microplastics for synthetic turf surfaces, it is to be expected that a similar discussion will also arise for secondary microplastics. To ensure that the discussion is not based on erroneous data, it is necessary to determine discharge quantities.

In the study presented here, the aim is to clarify which quantities are discharged from synthetic turf systems through abrasion and fibre wear.

2 Analysis of the literature

According to LASSEN et al. (2015), microplastics enter the environment along various pathways. The microplastics are discharged into surrounding soils and onto sealed surfaces. Drainage then causes the plastic particles to enter the sewage system. Discharge also takes place through clothing, as the filling material sticks to the clothing and later falls off. Microplastics can also be discharged through the drainage system built into the synthetic turf pitch.

Accordingly, LASSEN et al. estimate a discharge quantity of 1.5 - 2.5 t/year. However, it should be noted that this is a theoretical estimate and that this discharge quantity is not the result of rigorous scientific work. In addition, a theoretical calculation estimates the discharge of microplastics through fibre wear at 5 - 10 % per year. This calculation is based on a fibre quantity of 0.8 kg/m² and a football field size of 7,140 m² (KÄLLQUIST 2005). The total amount of fibre is thus 5,712 kg per pitch, whereby 5 - 10 % is lost through microplastic discharge. This means that between 285.6 kg and 571.2 kg per year and field. It should be noted that these numbers are estimates, which are likely overestimates. They refer to intensively used areas and are difficult to extrapolate to a complete field. Drainage is seen as the least important discharge route, except for the connection of the box gutters around the pitch to the drainage system. Surface discharge into adjacent soils is cited as the main discharge pathway, although discharge via players and their clothing is also relevant.

FLEMING et al. (2019) discuss the effect of maintenance on synthetic turf playing fields and analyse the deterioration of the usage characteristics of synthetic turf pitches over the years. The data for the research was collected between 2011 and 2018. The research project aims to build on the existing 'pitch degradation and maintenance model' and complement it with the change in scale factor.

FLEMING et. al. (2019) has studied pitches over years and comes to a loss of 0.5 - 0.9 t/ year x pitch microplastic fibres.

MÜLLER (2018) deals with the discharge of microplastics from synthetic turf from outdoor sports facilities. In addition to the rubber infill, turf fibres can be found in the drainage facilities and in the supplementary surfaces of outdoor sports facilities. It can be assumed, that these plastic particles damage the environment in the long term.

To obtain a comparable basis that can prove or disprove the thesis, only the synthetic turf fibres are examined as this wear out in both filled and unfilled synthetic turf surfaces thus leading to the discharge of synthetic particles. To investigate the thesis, the wear phenomena and the wear measurement variables are simulated in laboratory tests as well as in field tests. Furthermore, the amount of wear on the synthetic turf surface during use is unknown.

Another study which is frequently cited on the subject, but which has not conducted its own investigations, is Bertling et al. 2021. In their literature search, fibre losses of between 50 kg and 1000 kg were found. In addition, Bertling et al. 2021 converted the results of Flemming et al. 2020 to one pitch. The results obtained ranged from 55 kg to 280 kg of fibre loss per square per year.

3 Method

For this study, the results of preliminary, self-funded investigations that have already been carried out on playing fields in the Free and Hanseatic City of Hamburg by Osnabrück University of Applied Sciences and further investigations at 3 different locations in Europe on 10 football fields were combined.

The selection of the 25 pitches in Hamburg was made by the appropriate authority, Hamburg-Mitte. Only systems with a sand filling were investigated here.

The 10 pitches selected by the ESTC were in Great Britain, Italy and the Netherlands. The location of these sites is shown in figure 1.

The selection of the 10 pitches by the ESTC is subject to the requirement to represent average pitches in terms of infill, pile height, number of stiches and similar technical data and represent systems that were mostly installed within the last 10 years. According to the ESTC, the representative system is a synthetic turf for football with a smooth yarn monofilament, a pile height of 50 mm, an infill of sand and SBR. The systems studied on football pitches in Italy, Great Britain and the Netherlands were installed between the years 2011 and 2017.

Figure 1: Large-scale location of the study areas (Google Maps 2022, modified).

Table 1: Climate data of the study areas by region.

Country	Province/ Region (En)	Average annual mean temperature	Average annual precipitation
Great Britain	East Midlands	9,8 °C	712 mm
The Netherlands	Gelderland Utrecht	10,5 °C	824 mm
Italy	Trentino Südtirol	8,7 °C	1221 mm
Belgium	West Flandern	11,2 °C	792 mm

The following general data were included for the present study, as far as they could be obtained:

- Name of the site
- Address
- Synthetic turf system
- Synthetic turf type
- Age or year of construction
- Main use
- Infill system or type
- Photo documentation

In addition, the following measurement parameters were recorded for the study, as far as they could be determined:

- Pitch dimensions in m
- Area of the pitch in m²
- Pile height above the base fabric in accordance with FIFA TM 29
- Infill height of the infill material according to FIFA TM 21
- Stich spacing in stich rows according to FIFA TM 28
- Stich row spacing in accordance with FIFA TM 28
- Number of threads per nap
- Nap weight
- Total thread length per nap by estimation

These data are kept internally at ILOS and are only used in this study if significant differences or other assertions can be proven. Complete documentation is not provided here. This also ensures that no conclusions can be drawn about products or manufacturers.

3.1 Sampling and testing in the field

The collection of the individual samples from the pitches investigated was carried out in 4 steps.

Step 1: Documentation and pitch parameters

- Determination of the size of the pitch by means of a measuring wheel. The perimeter (distance from the Pitch’s outer line to the field's edge) was measured separately.
- The infill heights on the football pitches with synthetic turf system were measured according to the FIFA test method (FIFA TM 21) (cf. figure 2).
- Photo documentation of the pitch, the respective sampling point, the structure or shock pad as far as possible and the infill material where available.

Step 2: Determination of the test sites

Five sampling points were selected to sample the fibre bundles at each of the football pitches with synthetic turf systems in Great Britain, Italy and the Netherlands, as shown in figure 2. In addition, the sampling points were measured accordingly. The aim was to make visible possible use intensities and the resulting wear variations within a field.

Sampling points 1, 2 and 4 were used on the pitches in Hamburg.

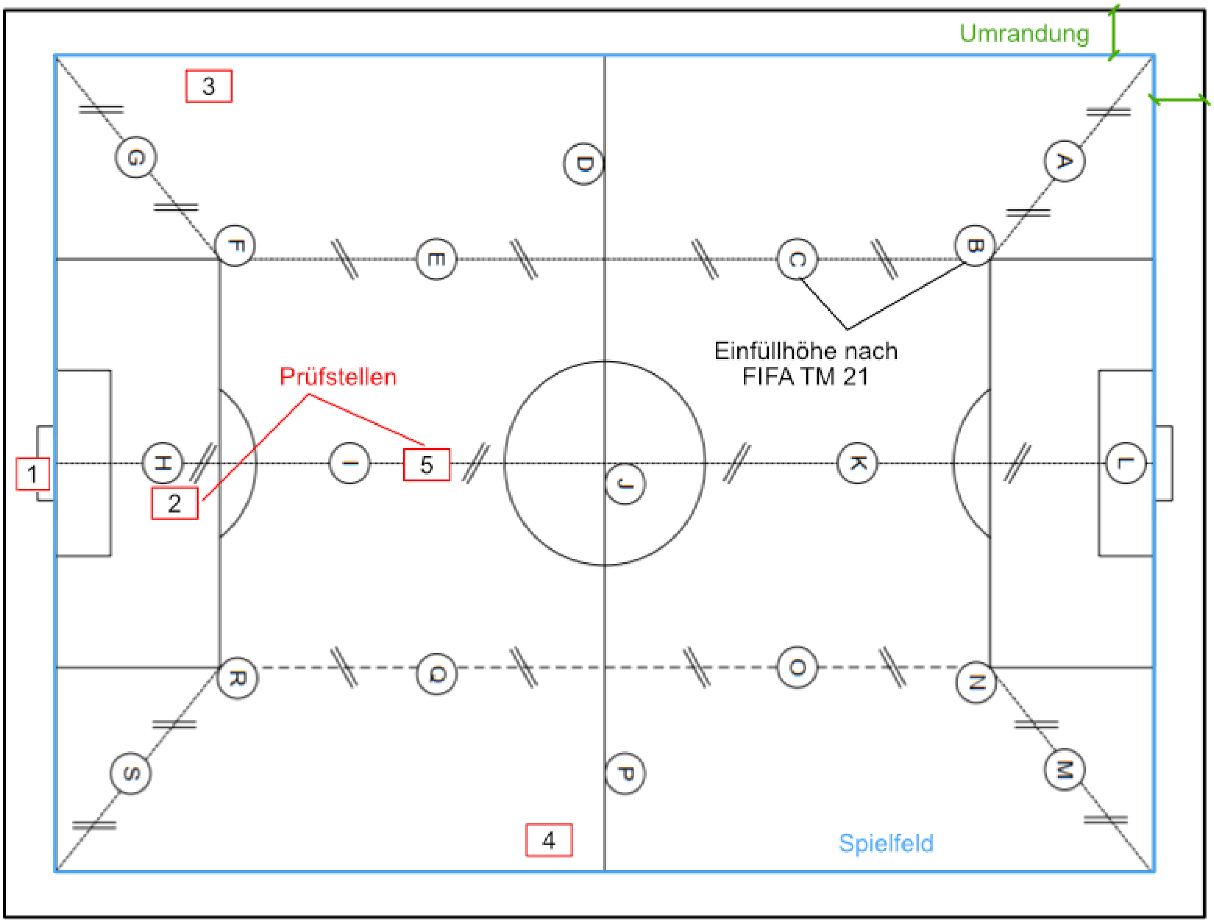

Figure 2: Overview of sampling and measuring points for football pitches (according to FIFA 2022, p. 23, modified).

Step 3: Vacuuming up the infill material

At each sampling point, the infill material was vacuumed up down to the base fabric to cut the fibre bundles directly above the backing fabric (see figure 3).

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Figure 3: Vacuuming the infill material

Step 4: Cutting off the fibre bundles

The exposed fibre bundles were cut directly above the backing fabric using nail scissors and bagged in reusable bags (see figure 4). 20 fibre bundles were taken per sampling site.

Figure 4: Fibre removal

3.2 Performance and measurement in the laboratory

The laboratory measurements were carried out for all fibre samples under constant conditions in the laboratory for soil mechanics at the Osnabrück University of Applied Sciences (see figure 5). To ensure uniform temperature and humidity, the fibres were conditioned beforehand. For this purpose, the fibres were stored in the laboratory and dried before weighing.

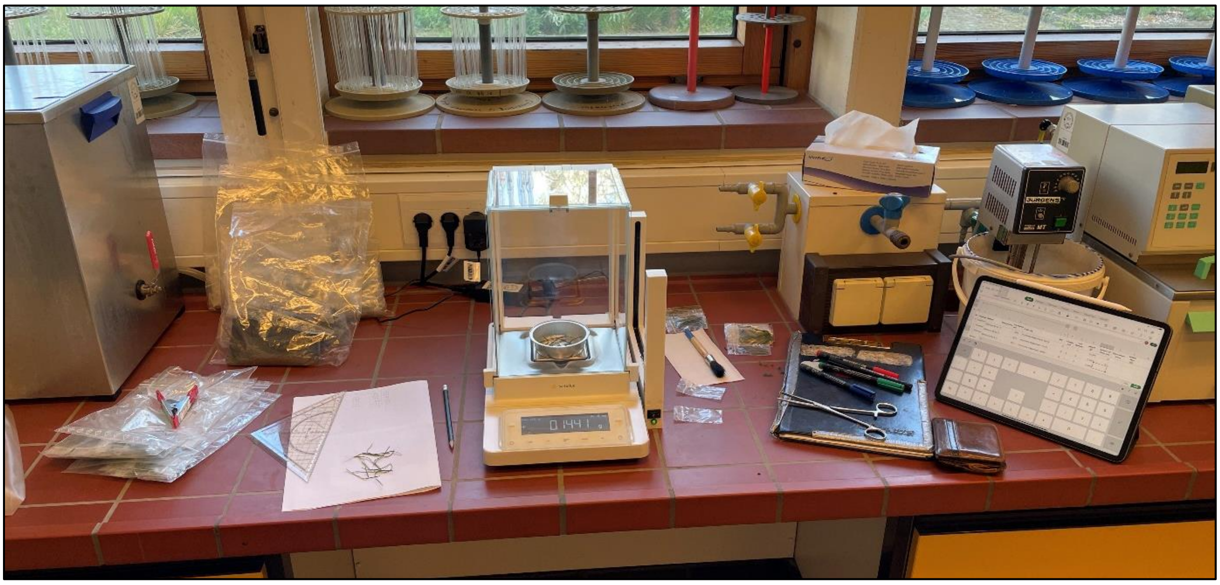

Figure 5: Work in the laboratory

Step 1: Removing the fibre

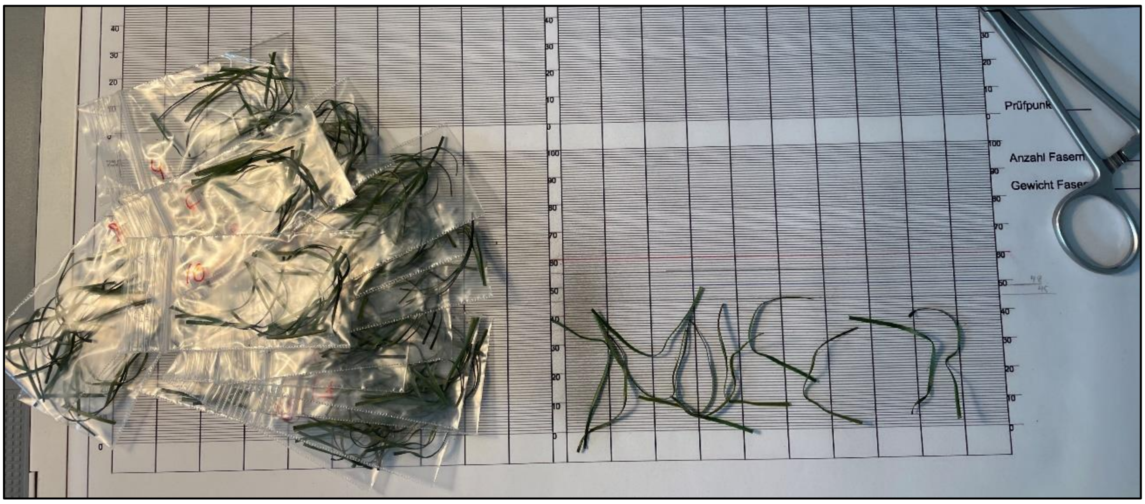

Figure 6: Removing the fibres

In the first step, the fibre bundles were removed from the reusable bags and checked for completeness (see figure 6). Subsequently, the fibres were cleaned of any residues and thus prepared for weighing.

Step 2: Checking the fibre for possible fibre breakage

In order to differentiate between fibre breakage and fibre wear, the fibres were also checked for possible fibre breakage. For this purpose, they were placed on an evaluation sheet as shown in figure 7.

Figure 7: Detection of possible fibre breakage

Step 3: Weighing with an analytical balance

The cleaned and conditioned fibre bundles were weighed with an analytical balance under laboratory conditions (see figure 8) and the results were documented.

Figure 8: Analytical balance

3.3 Evaluation of the data

The fibre wear was determined using the weight of the individual fibre samples. Assuming that the intensity of use influences fibre wear, the following intensities of use are assigned to the sampling points of the football pitches (see chapter 3.1 step 2):

Sampling point 1 → no/low use; control point, control area

Sampling point 2 → intensive use

Sampling point 3 - 5 → extensive use

Point 1 was defined as a control point, based on the assumption that no use takes place within the area of sampling point 1 and consequently no fibre wear/mass loss is to be expected at this point. Accordingly, the weights determined from sampling points 2 - 5 were always compared with this point.

The assumption that no mass loss occurs at sampling point 1, the control point, is not correct. Nevertheless, in order to obtain results that are as real as possible, the missing fibres were taken into account using the average value of the fibres found at the sampling point. The "correction" of the control point is used for the comparison of the measuring points. In the individual representations of the pitches, the boxplots, the uncorrected values are shown. A correction of the remaining measuring points is not carried out.

The wear percentage was modelled as a function of time with the best-fitting regression function.

3.4 Error analysis

To better classify the data obtained, it is important to mention possible sources of error and their evaluation.

In a preliminary investigation, random samples of one square meter of a new, unused synthetic turf were examined according to the method described. Within this, 1,500 fibre bundles were weighed. The coefficient of variation of the results of this preliminary investigation is 3.4% with an outlier rate of 4.2%. The already existing large scatter within a new synthetic turf reduces the statistical robustness of the obtained data of this study.

The assumption that there is no abrasion in sampling point 1, which serves as a control point, because it is located in the goal area and does not experience any use, is not correct. Broken and worn fibres are also found at sampling point 1. Even if the missing fibres in the control point are included, the calculated mass losses are lower than the real mass losses. The actual mass loss at the control point cannot be determined with this method. Using the manufacturer's data as a control point is not expedient, since these have a tolerance of +/- 10 %.

Another source of error is the cutting of the bundles above the backing fabric. Due to the tight tufting, some bundles may not be cut off completely horizontally directly at the backing fabric. Since this source of error exists at every sample point, it contributes to the increase in variance, but has very little influence on the calculated mass losses. Alternative methods, such as pulling the fibres, have greater sources of error because the loops underneath the backing fabric are different. Since the pile layer is cut at a uniform height above the backing fabric during production, cutting above the backing fabric is preferred.

Negative mass loss was measured for individual pitches. Since yarns cannot gain mass, this is due to measurement or product variables.

4 Evaluation of the sports fields

4.1 Fibre wear Hamburg

The results of the measurements taken at the pitches in Hamburg, Germany are shown in the following figures.

All the examined pitches in Hamburg were semi-filled with sand.

It should be noted that the method for investigating the Hamburg pitches was slightly modified. The number of sampling points was reduced from five to three. The control point in the goal area is sampling point 1. The extensively used sampling point is number 4 and the intensively used sampling point is number 2.

Furthermore, any missing fibres in control point 1 were not corrected and are therefore not included in the calculation of the total mass loss.

The box of the boxplot represents the range in which 50% of the determined fibre bundle weights lie. The median (value that bisects the data series sorted by size) is shown as a horizontal line within the box. The constrictions/notches of the box show the 95% confidence interval for the median. The antennas/whiskers show the maximum or minimum weight, as long as this is not more than 1.5 times the box height away from the box. Points above or below the antennas are likely to be outliers.

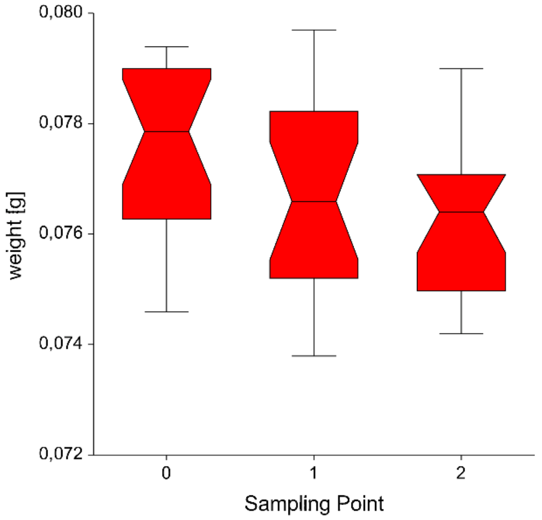

Figure 9: Distribution of the determined fibre bundle weights Hamburg 1

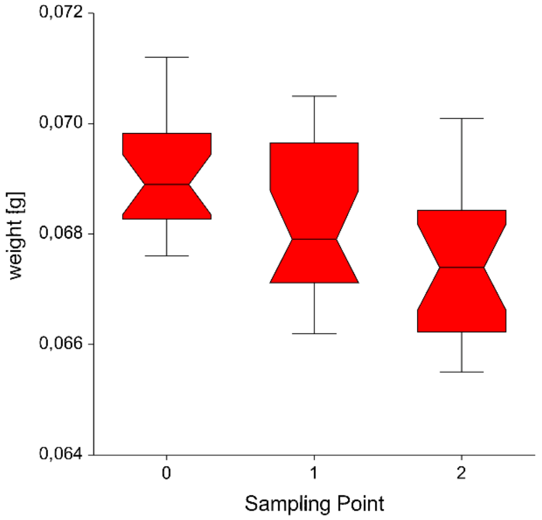

Figure 10: Distribution of the determined fibre bundle weights Hamburg 2

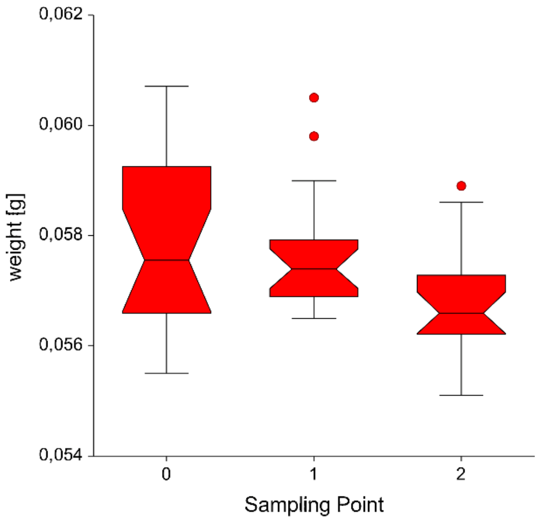

Figure 11: Distribution of the determined fibre bundle weights Hamburg 3

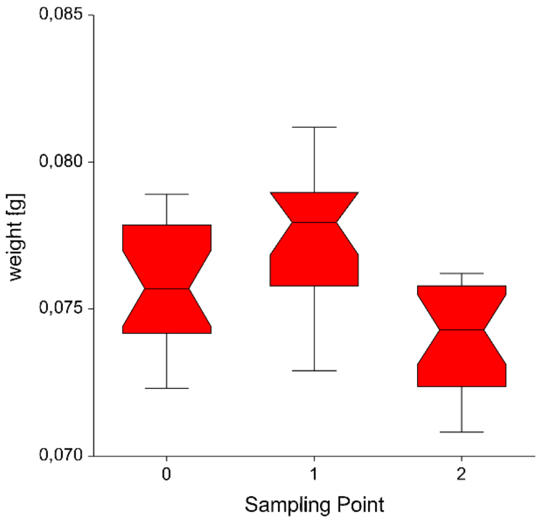

Figure 12: Distribution of the determined fibre bundle weights Hamburg 4

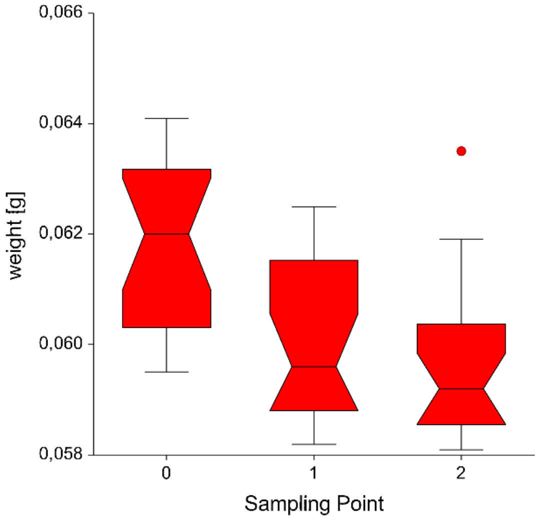

Figure 13: Distribution of the determined fibre bundle weights Hamburg 5

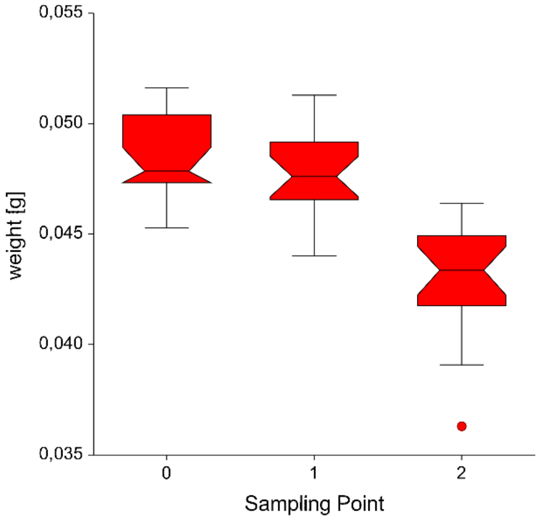

Figure 14: Distribution of the determined fibre bundle weights Hamburg 6

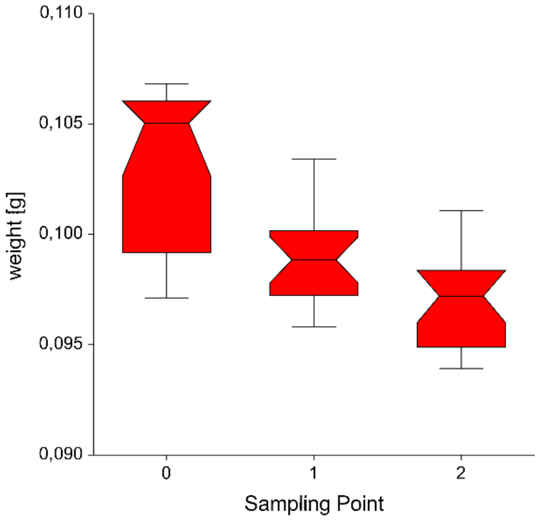

Figure 15: Distribution of the determined fibre bundle weights Hamburg 7

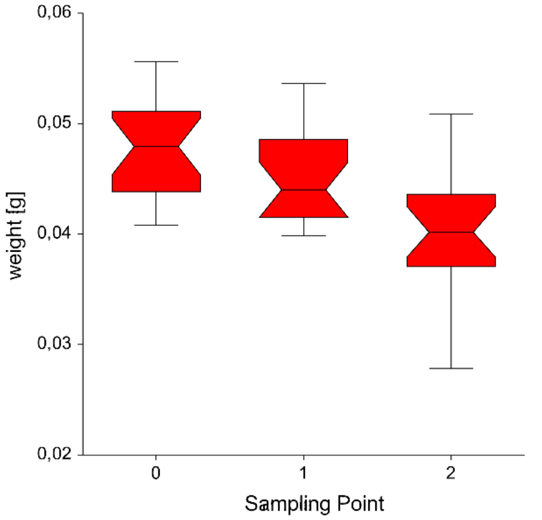

Figure 16: Distribution of the determined fibre bundle weights Hamburg 8

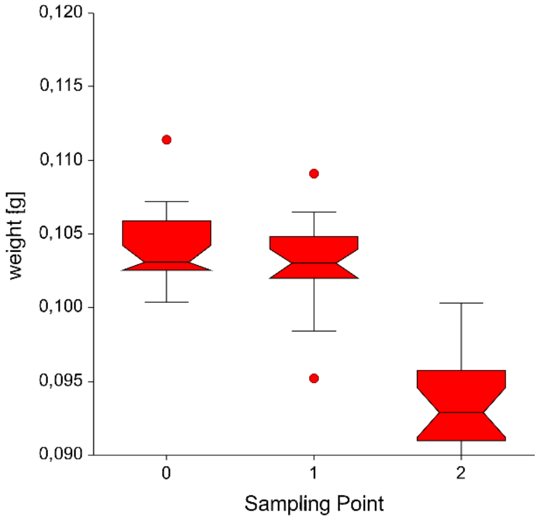

Figure 17: Distribution of the determined fibre bundle weights Hamburg 9

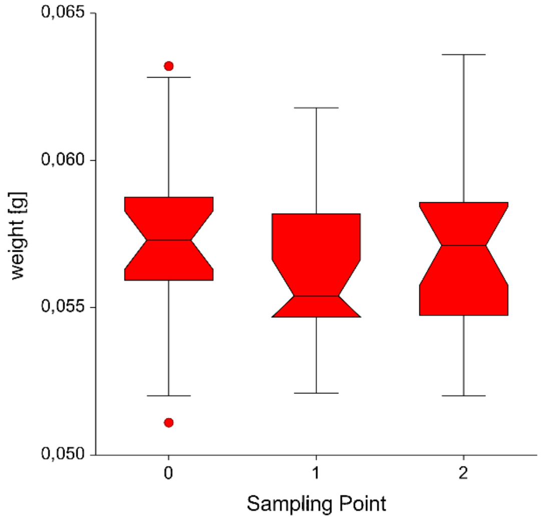

Figure 18: Distribution of the determined fibre bundle weights Hamburg 10

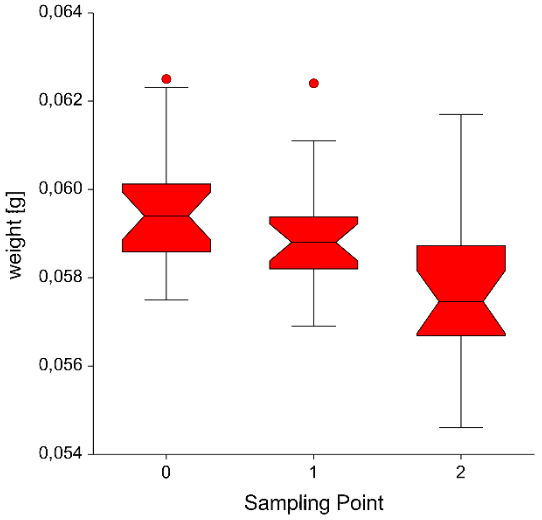

Figure 19: Distribution of the determined fibre bundle weights Hamburg 11

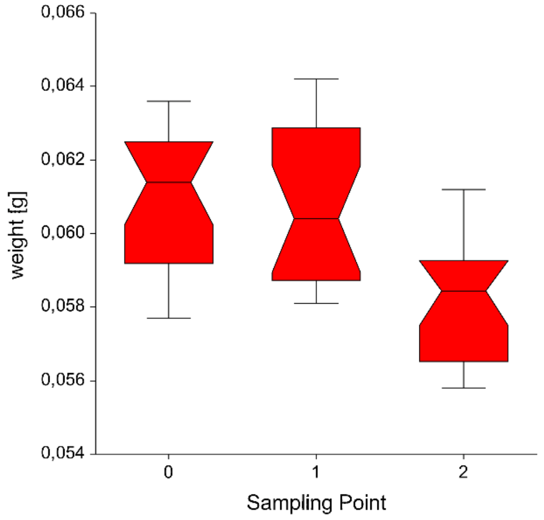

Figure 20: Distribution of the determined fibre bundle weights Hamburg 12

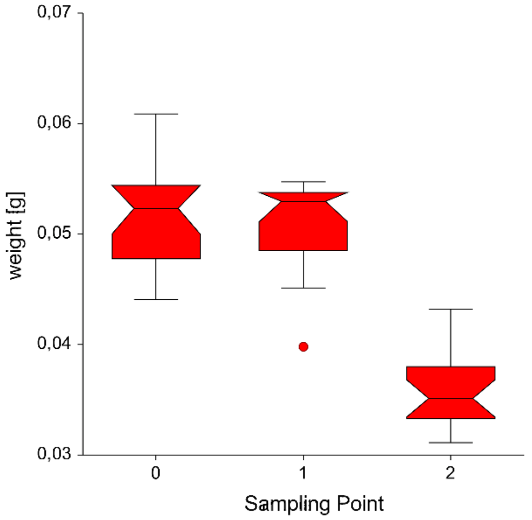

Figure 21: Distribution of the determined fibre bundle weights Hamburg 13

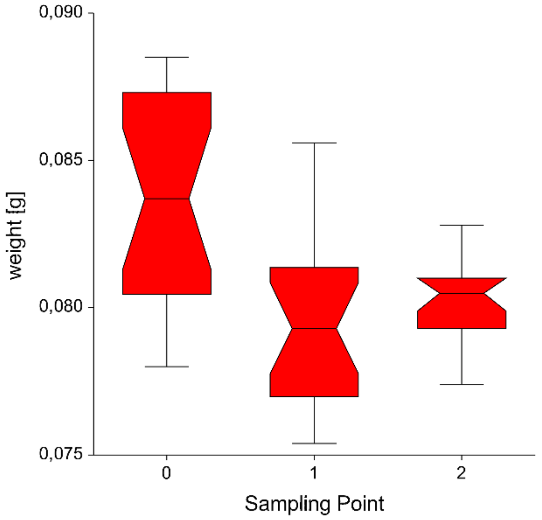

Figure 22: Distribution of the determined fibre bundle weights Hamburg 14

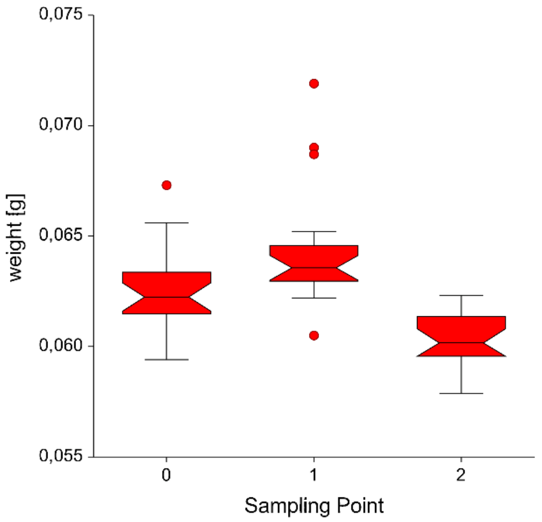

Figure 23: Distribution of the determined fibre bundle weights Hamburg 15

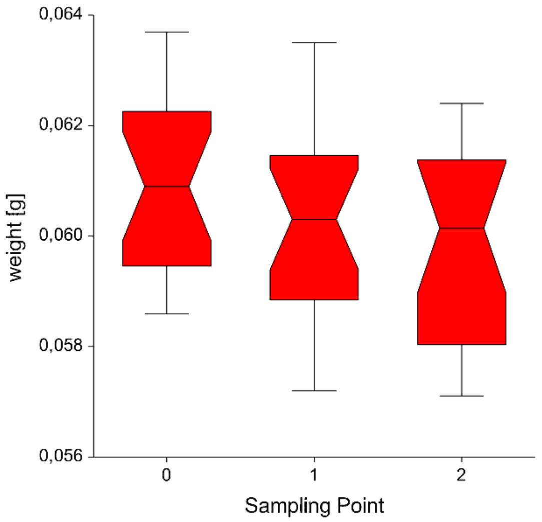

Figure 24: Distribution of the determined fibre bundle weights Hamburg 16

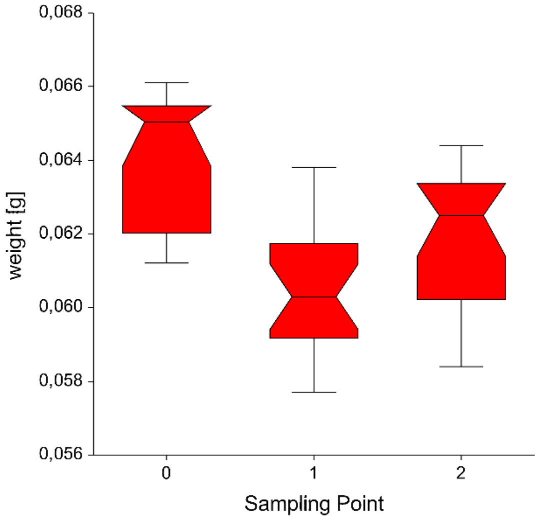

Figure 25: Distribution of the determined fibre bundle weights Hamburg 17

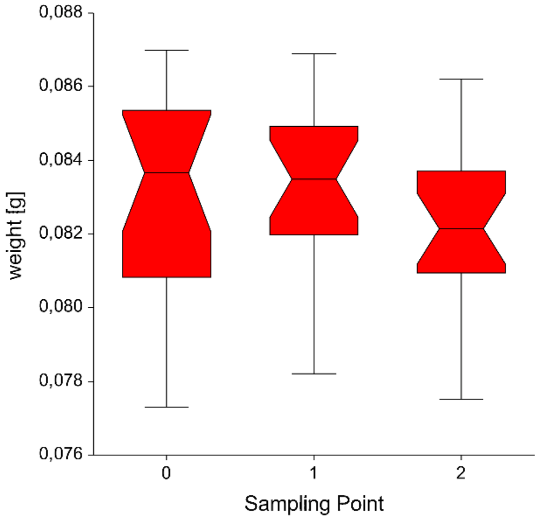

Figure 26: Distribution of the determined fibre bundle weights Hamburg 18

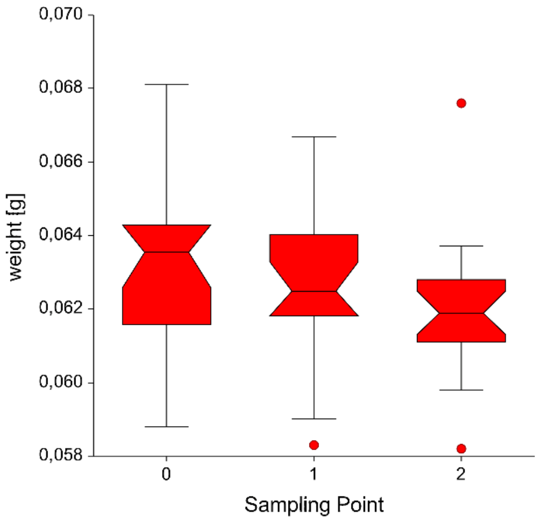

Figure 27: Distribution of the determined fibre bundle weights Hamburg 19

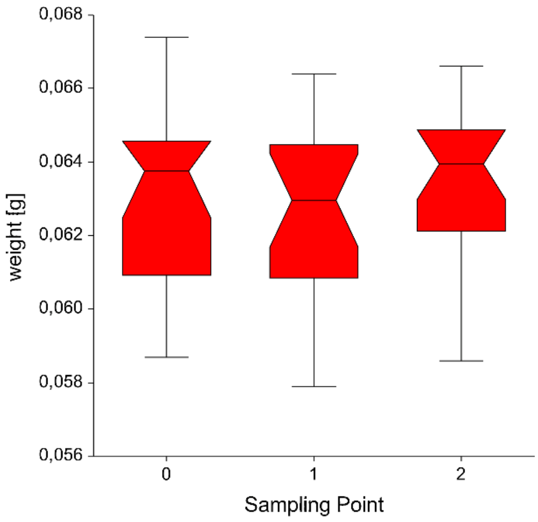

Figure 28: Distribution of the determined fibre bundle weights Hamburg 20

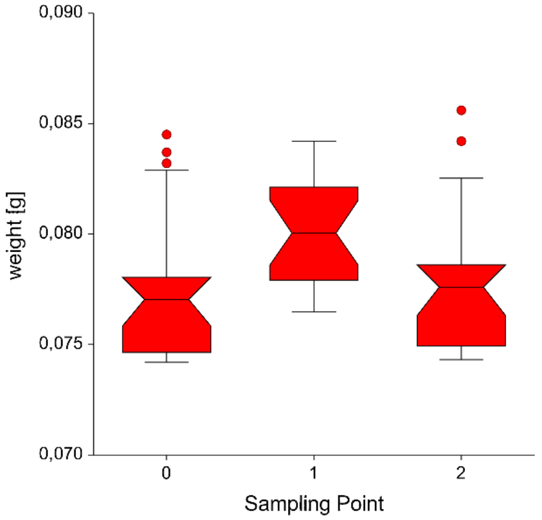

Figure 29: Distribution of the determined fibre bundle weights Hamburg 21

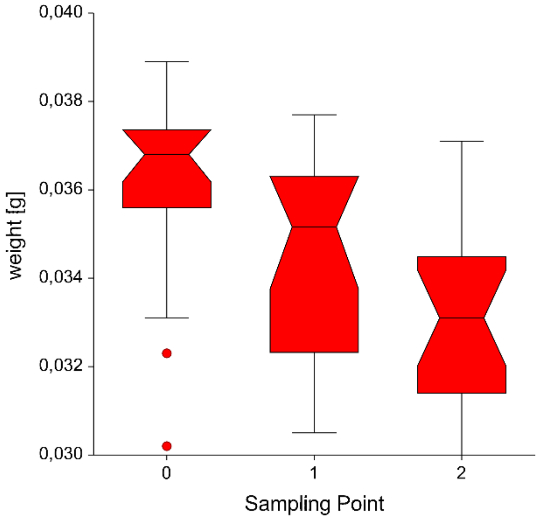

Figure 30: Distribution of the determined fibre bundle weights Hamburg 22

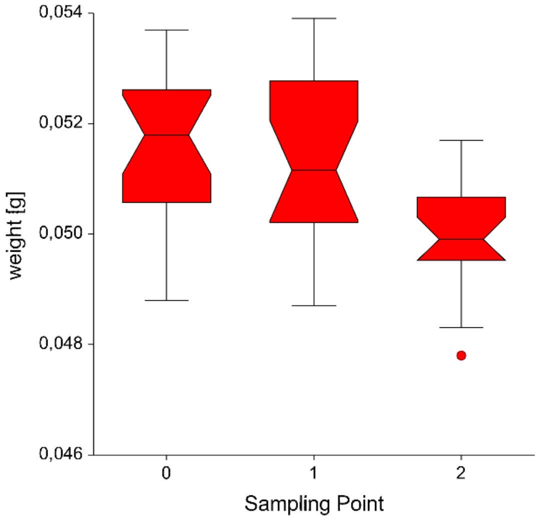

Figure 31: Distribution of the determined fibre bundle weights Hamburg 23

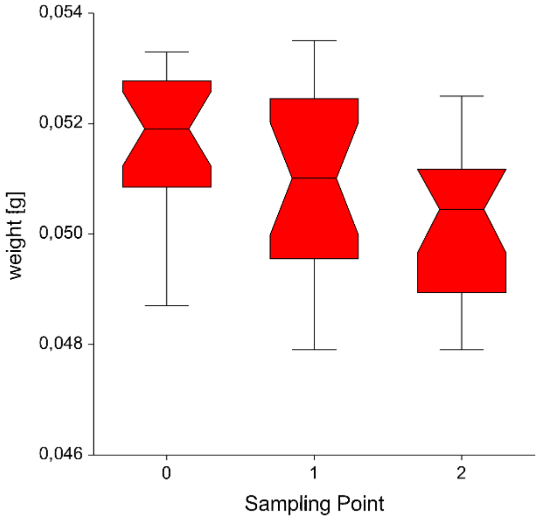

Figure 32: Distribution of the determined fibre bundle weights Hamburg 24

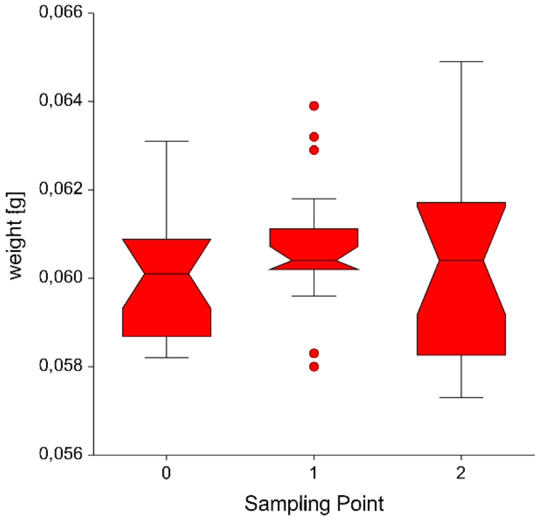

Figure 33: Distribution of the determined fibre bundle weights Hamburg 25

When looking at the measurements from Hamburg, it can be seen that the highest or greatest losses as a function of time were measured at sampling point 2 (see figure 34). Specifically, losses in the area of sampling point 2 were recorded at 22 pitches (see figure 34). The highest loss of approx. 30 % was recorded at a sixteen-year-old pit (see figure 34).

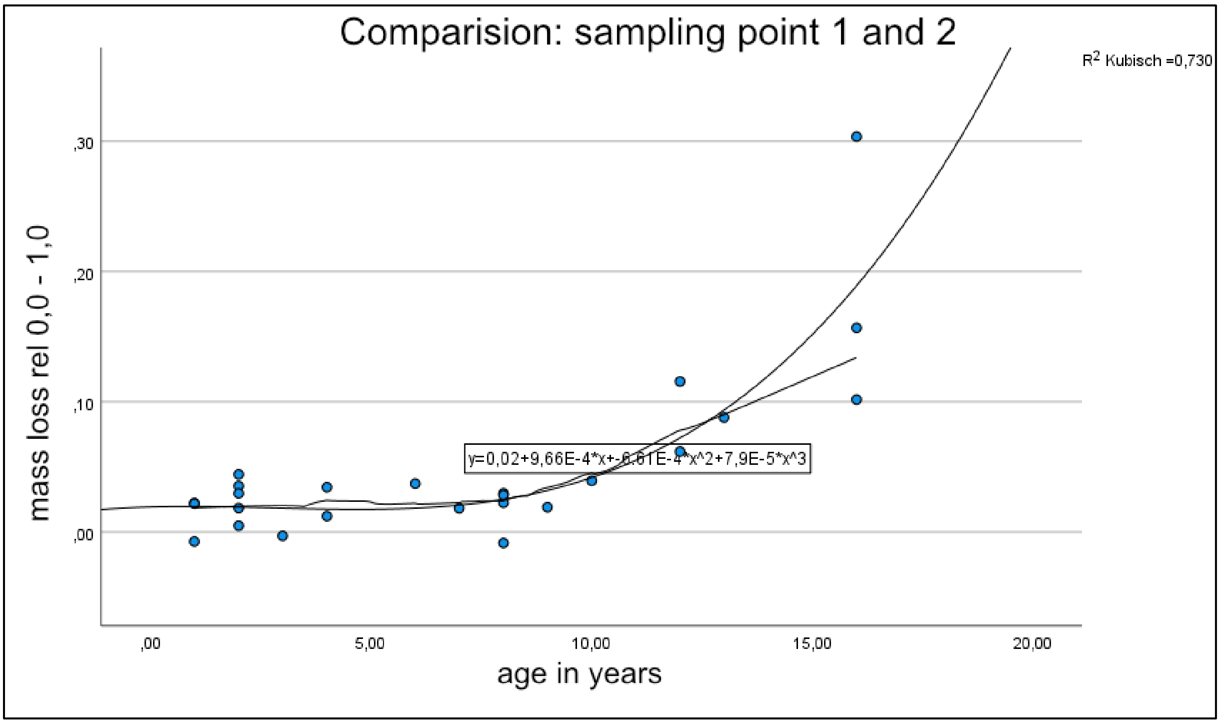

Figure 34:Total fibre wear on pitches in Hamburg at sampling point 2 in %.

With extensive use intensity, a percentage mass loss of 6 % is not exceeded (see figure 35). Overall, a loss of mass could only be determined for 20 of the 25 artificial turf pitches examined (see figure 35). The investigations revealed a negative loss of mass for 5 artificial turf pitches (see figure 35). It can only be assumed that this is due to fluctuations in fibre production.

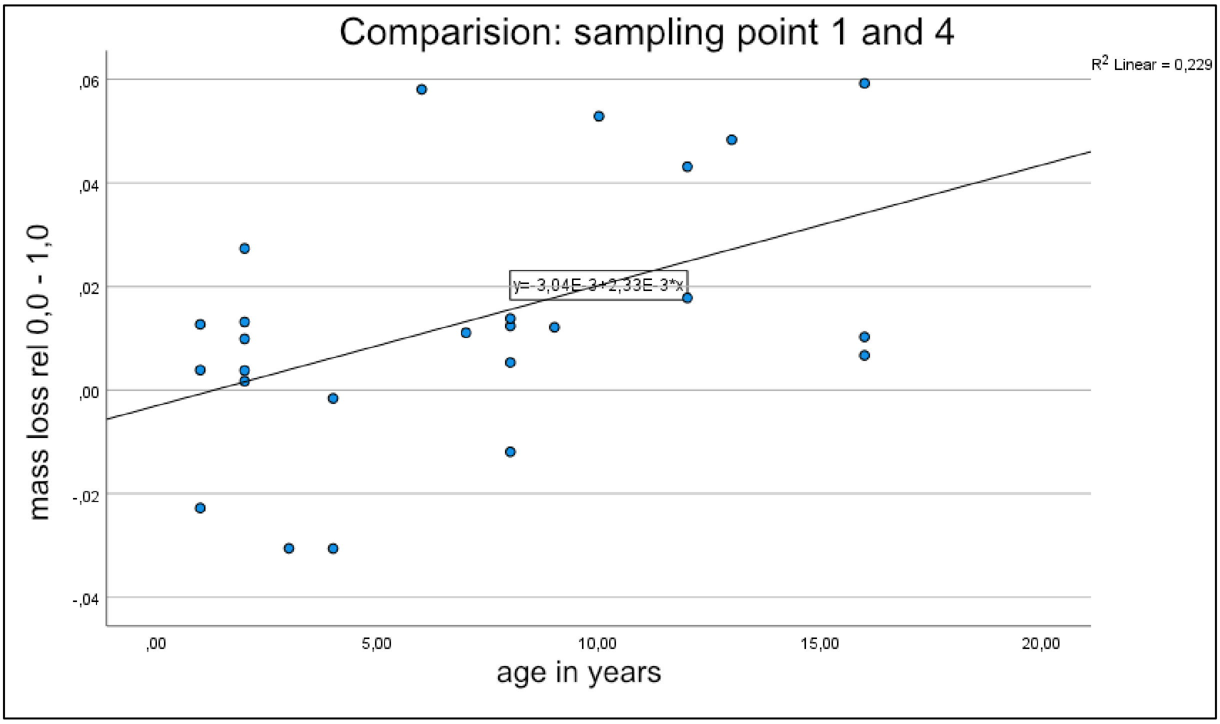

Figure 35:Total fibre wear on pitches in Hamburg at sampling point 4 in %.

It is noticeable when looking at the results, especially for Sampling Point 2, that in addition to old pitches, new pitches show a high mass loss in the first years (see figure 34). To clarify this observation, the results are presented in the following two figures in mass loss per year. The high mass loss in the first years can be explained by torn out fibres. It is likely that the absence of whole fibres in new pitches is explained by faulty bonding of these into the support fabric. As soon as all loose fibres are lost, the mass loss per year decreases to less than 1%. Towards the end of the lifetime, after 12 years, the mass loss increases sharply. This can be explained by embrittlement of the fibres, which have aged considerably. The effects described are more pronounced in intensively used areas than in extensively used areas.

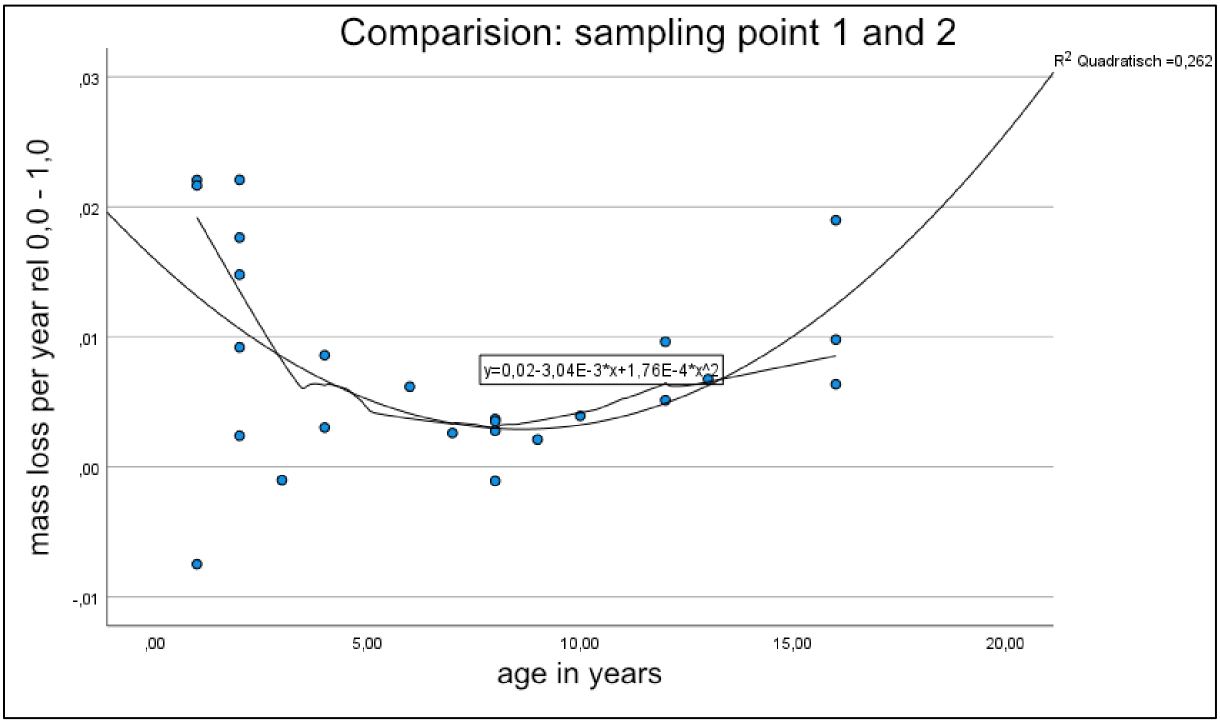

Figure 36: Fibre wear per year on pitches in Hamburg at sampling point 2 in %.

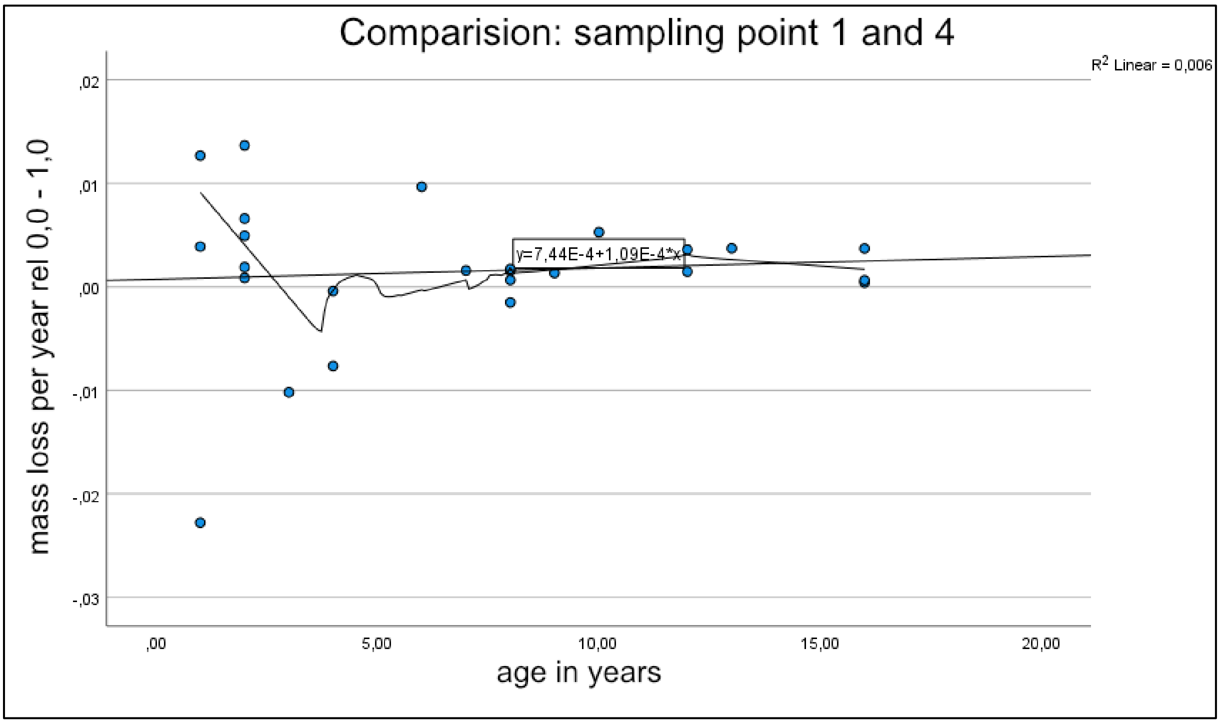

Figure 37: Fibre wear per year on pitches in Hamburg at sampling point 4 in %.

4.2 Fibre wear within the investigated pitches

The distribution of the values measured at the individual sampling points within the pitch under consideration can be seen in the following boxplots (notched).

Great Britain

Figures 38 to 40 show the surveys on the sites in Great Britain.

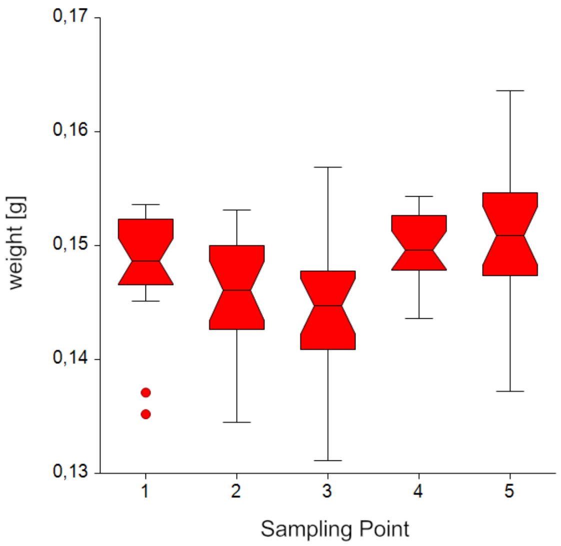

Figure 38: Distribution of the determined fibre bundle weights Great Britain 1

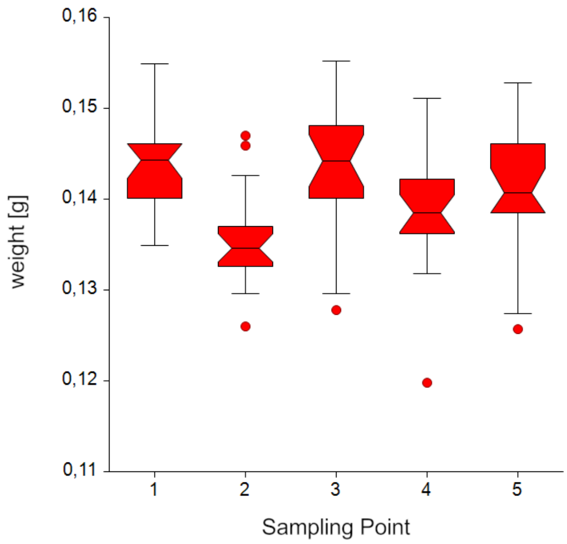

Figure 39: Distribution of the determined fibre bundle weights Great Britain 2

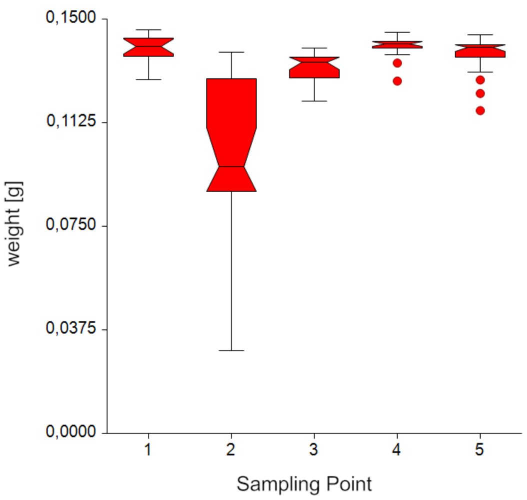

Figure 40: Distribution of the determined fibre bundle weights Great Britain 3

Italy

Figures 41 to 43 show the results from the pitches in Italy.

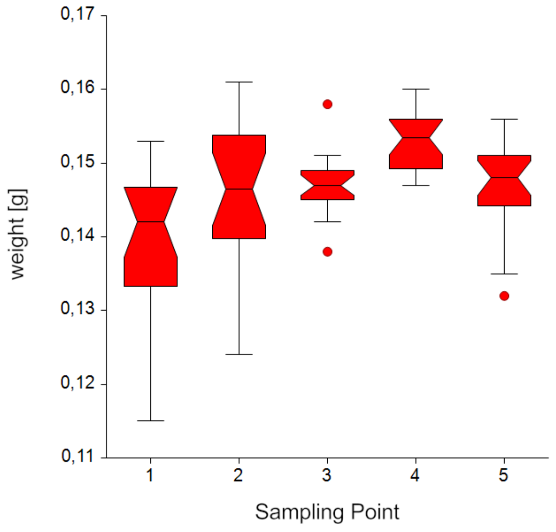

Figure 41: Distribution of the determined fibre bundle weights Italy 1

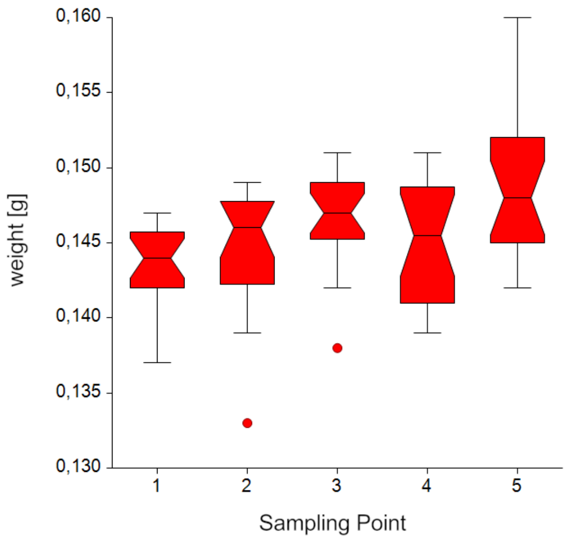

Figure 42: Distribution of the determined fibre bundle weights Italy 2

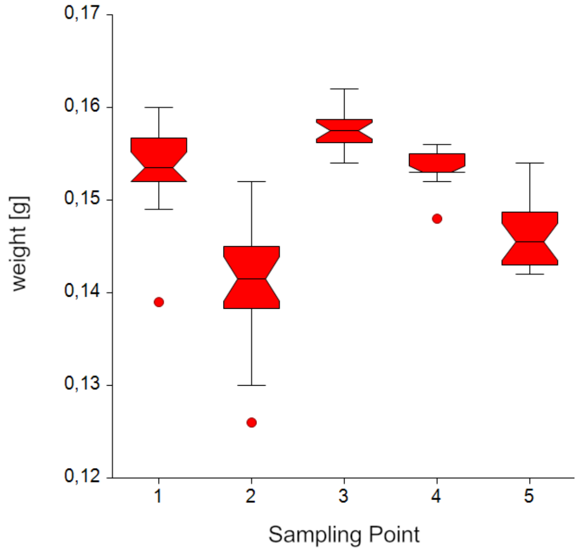

Figure 43: Distribution of the determined fibre bundle weights Italy 3

The Netherlands

Figures 44 to 47 show the results from the Netherlands.

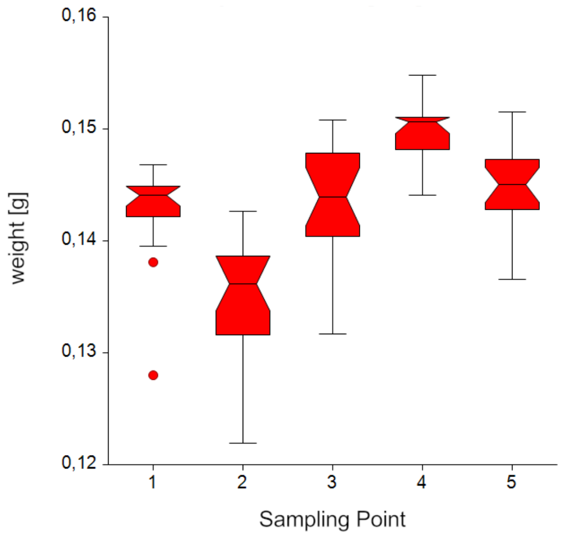

Figure 44: Distribution of the determined fibre bundle weights the Netherlands 1

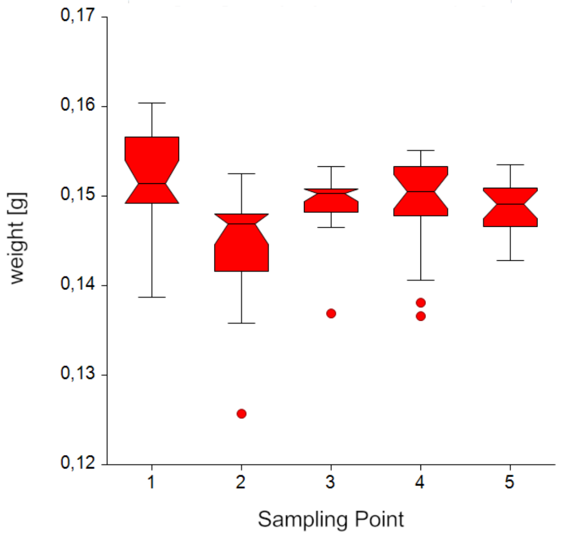

Figure 45: Distribution of the determined fibre bundle weights the Netherlands 2

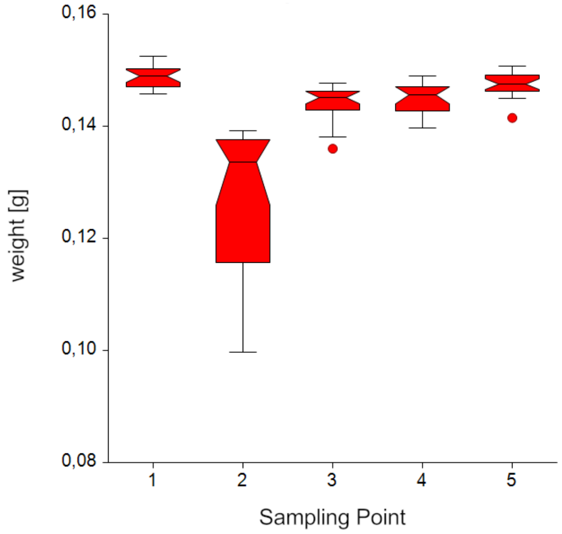

Figure 46: Distribution of the determined fibre bundle weights the Netherlands 3

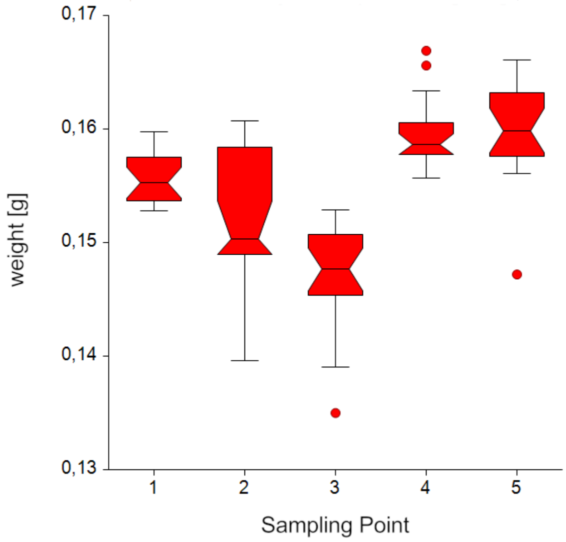

Figure 47: Distribution of the determined fibre bundle weights the Netherlands 4

4.3 Fibre loss

The number of fibres per sample bundle are counted before weighing. The absence of whole fibres can be explained by tearing out or breaking off. The average percentage of missing fibres in Great Britain, Italy and the Netherlands is 1.4% and thus makes up a significant share of the total mass loss. The fibre loss is particularly pronounced in the intensive area, sampling point 2. The largest mass differences, see Great Britain 3 and Netherlands 3, can be explained by missing fibres.

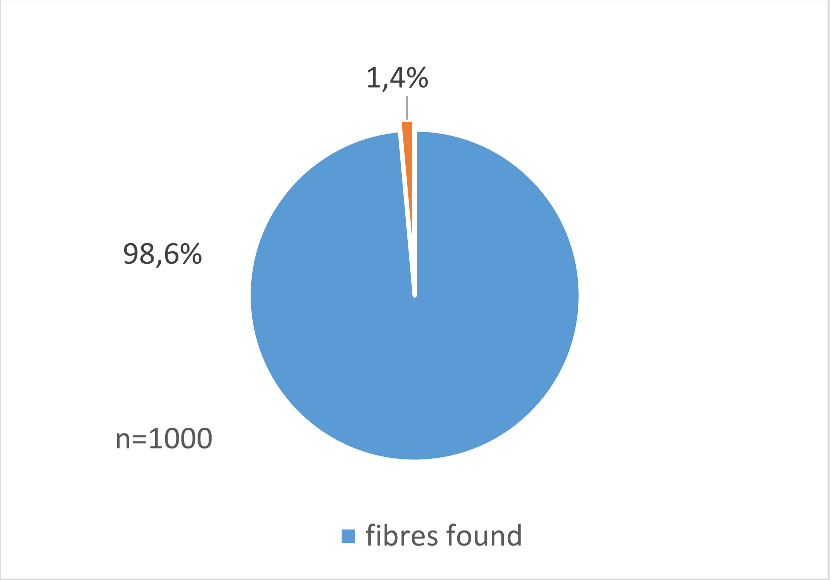

Figure 48: Distribution of whole and broken fibres found at sites in Great Britain, Italy and the Netherlands

4.4 Comparison of fibre wear at the sampling points excluding Hamburg

When examining all pitches regarding the different sampling points, it can be seen, the highest losses were determined for sampling point 2, measured both in terms of the number of fibres and in terms of the percentage share. Specifically, mass or fibre loss as a function of time was detected at sampling point 2 for 9 sites. An eleven-year-old pitch in Great Britain recorded the highest loss value of just under 30 %.

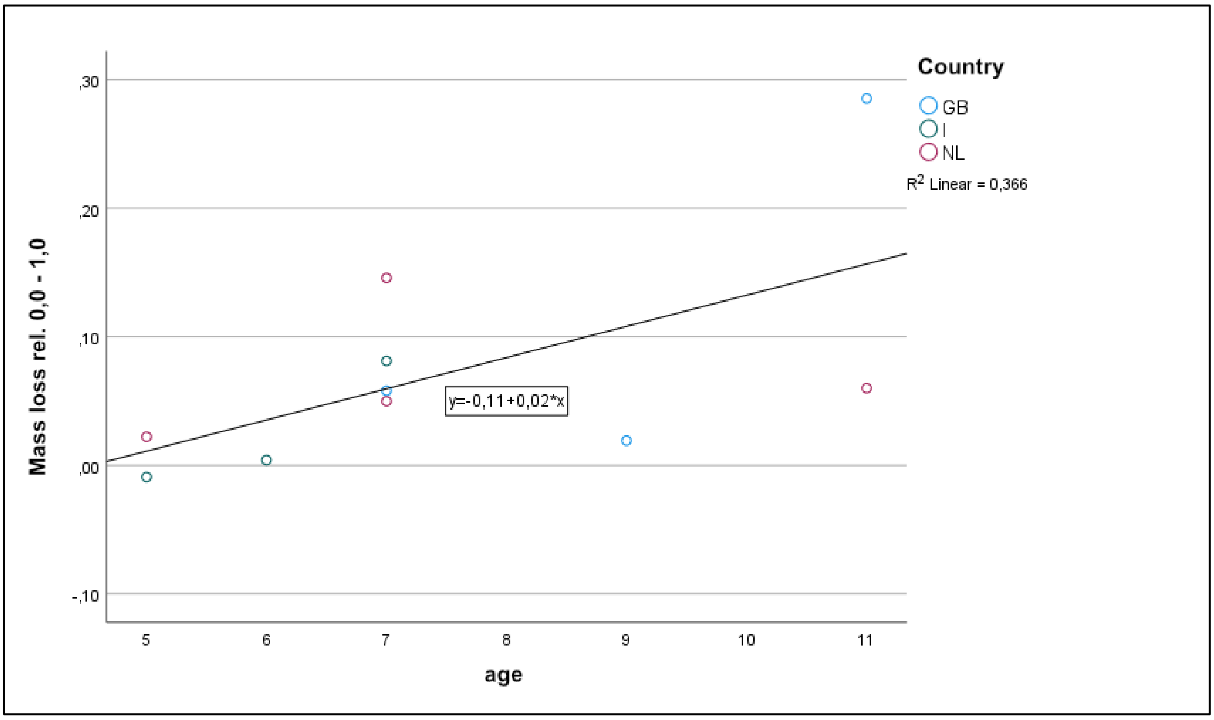

Figure 49: Total fibre wear on pitches in Great Britain, Italy and the Netherlands at sampling point 2 in %.

A similarly high value could only be measured at one of the other sampling point. The losses determined at the other sampling points range from just under 4 % to approx. 7 %. The highest value measured for sampling point 3 was approx. 7 %. This was determined within the same pitch as the highest value for sampling point 2. Overall, fibre losses could only be determined at sampling point 3 in 6 pitches. Italy is the only country with no fibre losses at this sampling point.

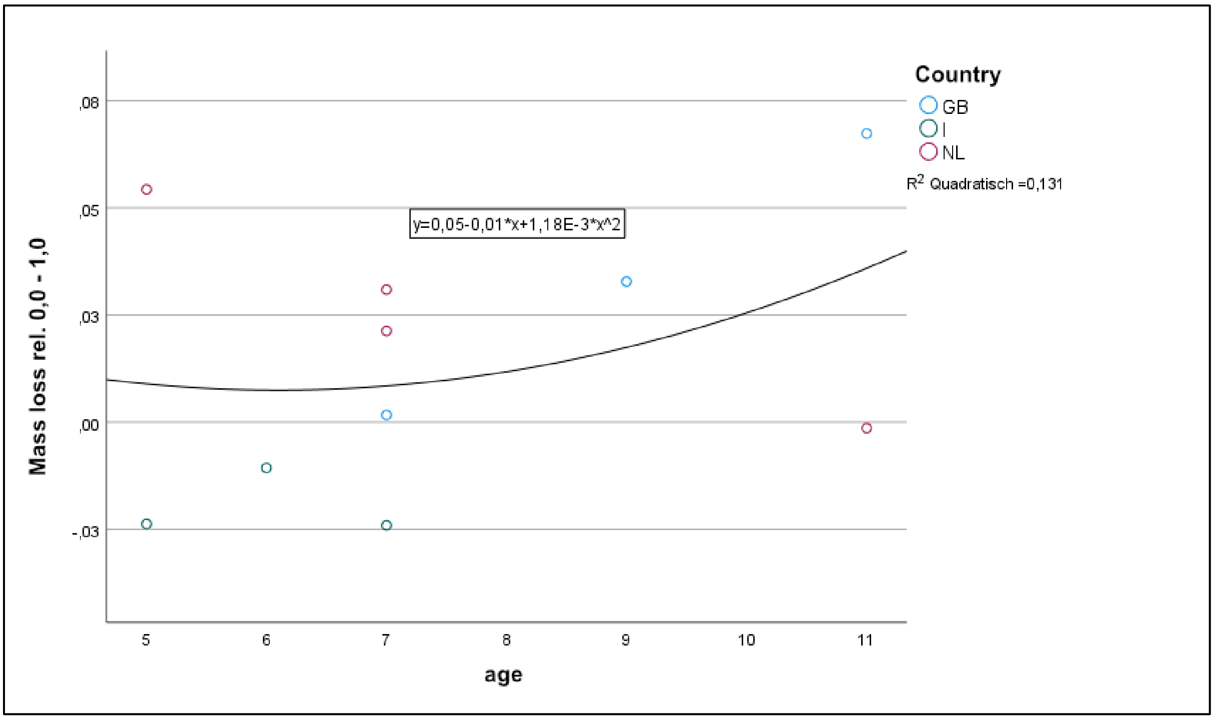

Figure 50: Total fibre loss on pitches in Great Britain, Italy and the Netherlands at sampling point 3 in %.

Within the remaining test sites, the highest loss was just under 4 % at sampling point 4 and approx. 5 % for sampling point 5. In contrast to the previous sampling points, the maximum values determined this time lie in the range of the seven-year-old pitches. The highest fibre losses for sampling point 4 can be assigned to a site in Great Britain.

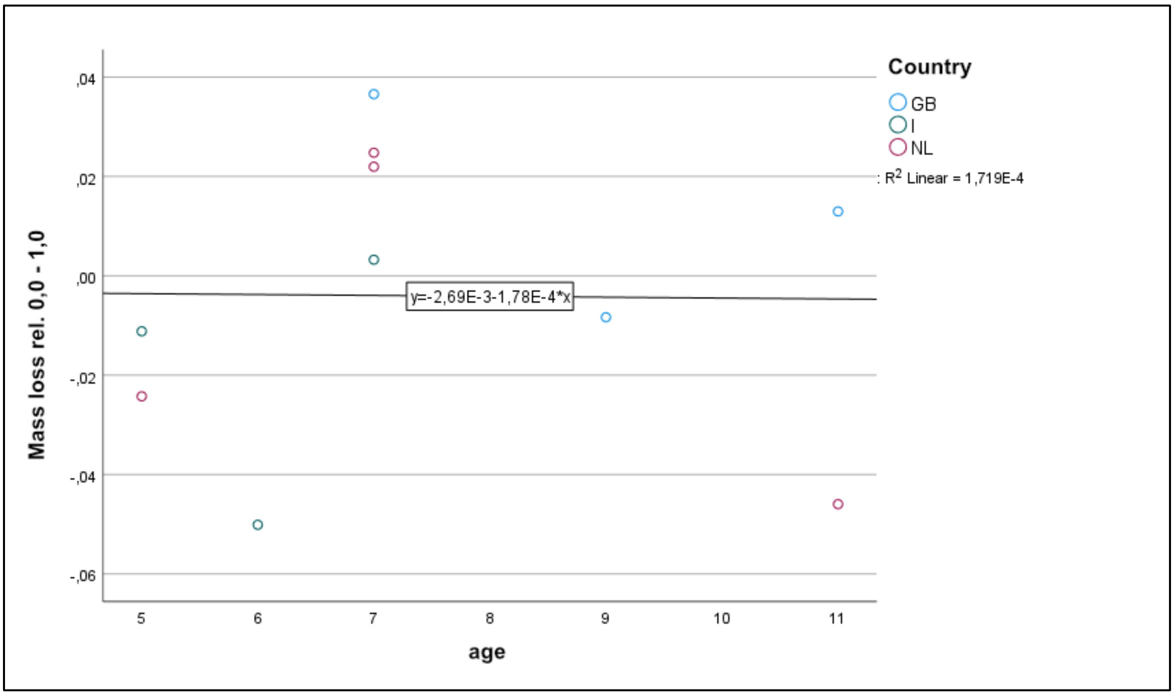

Figure 51: Total fibre loss on pitches in Great Britain, Italy and the Netherlands at sampling point 4 in %.

The highest fibre loss at sampling point 5 was determined on a pitch in Italy. Negative fibre losses could also be determined at all sampling points. However, there is the consideration that the synthetic turf fibres used in the construction of the facilities had a higher initial weight than the weight that was determined for the control area as a reference.

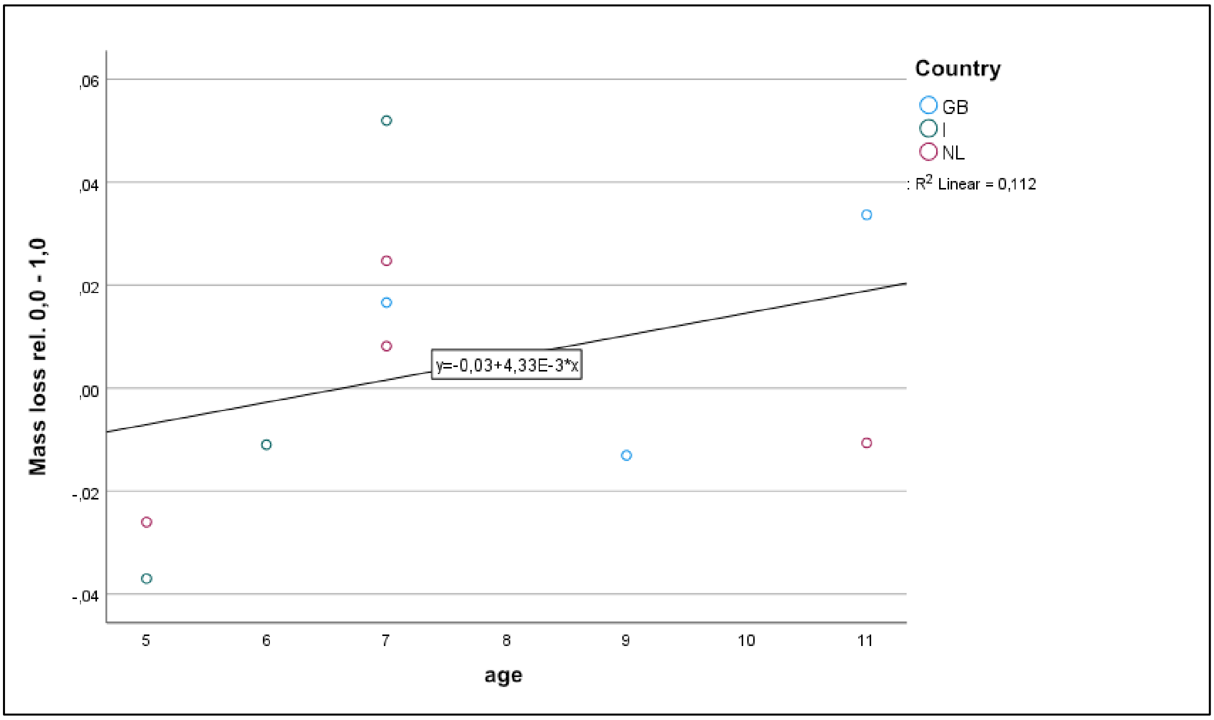

Figure 52: Total fibre wear on pitches in the UK, Italy and the Netherlands at sampling point 5 in %.

4.5 Fibre wear at the sampling points in comparison with the results from Hamburg

The sites listed above were all sites where a sand-rubber mixture was used as infill material. To determine the differences between sand-rubber filled and sand-filled pitches, an overall analysis of all sports facilities was carried out. It is noticeable when considering intensive use that the annual loss tends to be slightly higher in the first few years after filling and then decreases. When looking at the total loss during intensive use, it is noticeable that after 10 years the values increase significantly.

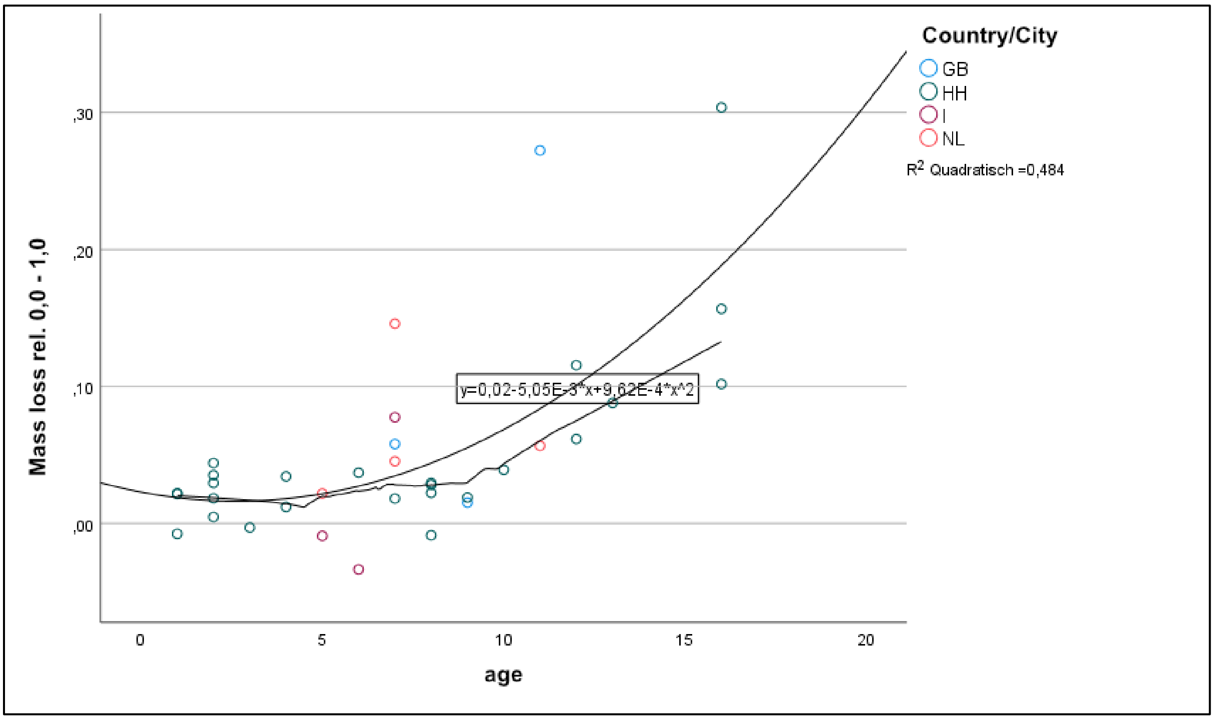

Figure 53: Total fibre wear on pitches in Great Britain, Italy, the Netherlands and Hamburg at sampling point 2 (intensive use) in %.

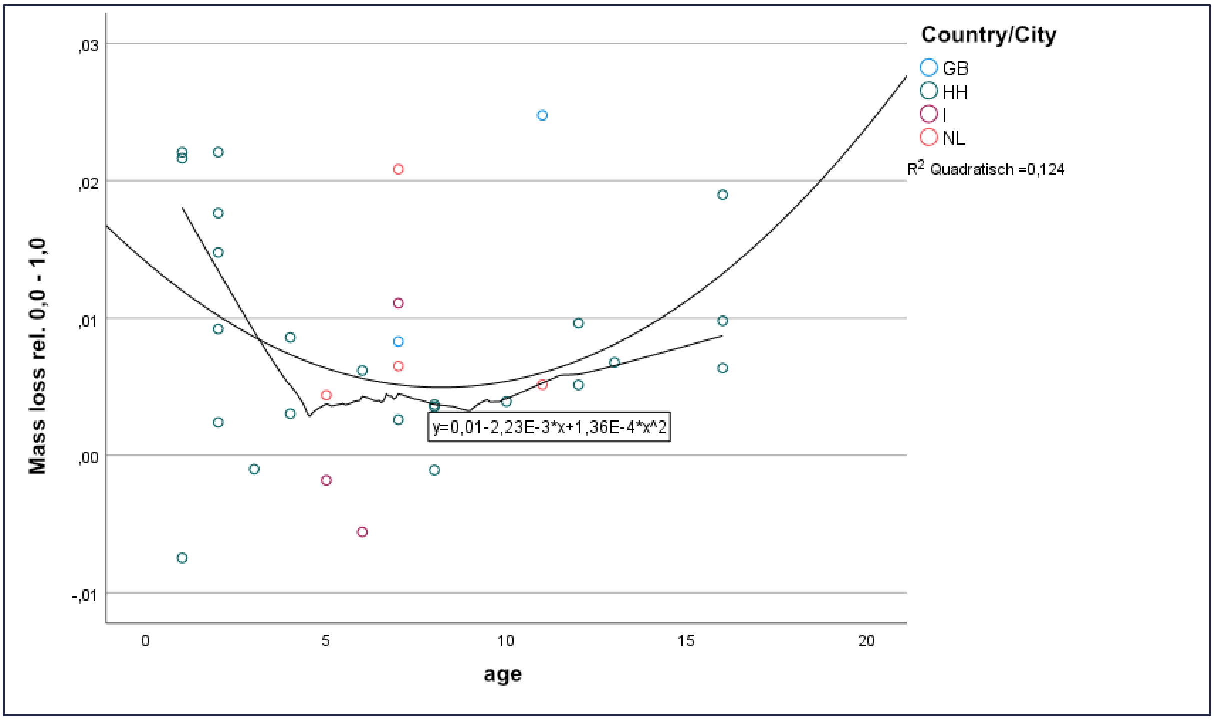

Figure 54: Fibre wear per year on pitches in Great Britain, Italy, the Netherlands and in Hamburg at sampling point 2 (intensive use) in %.

The expected difference between rubber-sand infill (Great Britain, Italy and the Netherlands) and infill with sand only (Hamburg) could not be proven. The two infill materials cannot be considered significantly different based on the 95% confidence intervals.

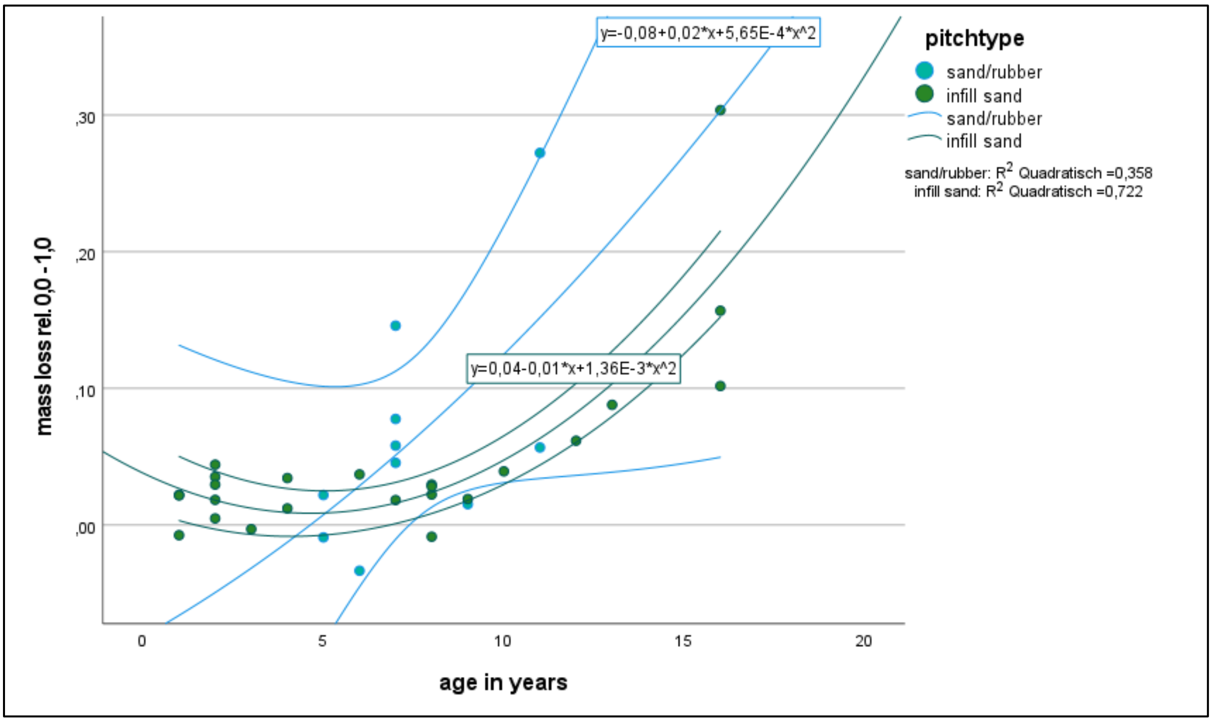

Figure 55: Comparison of fibre wear on pitches with sand-rubber infill and sand infill

5 Discussion of the results

The measurement results show a wide scatter. If sampling points 2 to 5 are compared with the control point, a significant loss of mass can be observed. Sampling point 2 shows the highest average mass losses. This is not surprising, since this point is located in the intensively used area.

The negative values are caused by the erroneous assumption that there is no mass loss in the control point, sampling point 1. This is amplified by statistical outliers due to the high variance.

A significant mass loss can be determined overall. However, since the measurement results show a high variance, no significant relationship between mass loss and place-specific properties, such as geographic location, infill type or fibre cubature, can be demonstrated. However, statistical trends can be observed. For example, the observed mass loss increases with increasing age of the pitch and with increasing intensity of use.

The high mass loss in the first years can be explained by torn out fibres. It is likely that the absence of whole fibres in new pitches is explained by faulty bonding of these into the support fabric.

The research to date provides a preliminary indication of the wear rates of artificial turf. The methodology appears sound and provides a means to objectively measure fibre loss on playing fields; however, more data is needed to improve the accuracy of the results and to understand the causes of yarn wear.

Further research should include measurements from many more pitches, uses, and geographic locations to improve confidence in the developed methods and findings. With a larger experimental matrix, other factors influencing wear, in addition to the age of the pitches, can be determined. This will provide better insight into attrition and is currently being planned.

It can be assumed that the secondary microplastic, which is created by abrasion and fibre breakage, enters the environment through the same pathways as the primary microplastic used as an infill. Due to the significantly smaller dimensions, it can be assumed that the fibre abrasion is more mobile than the infill and is discharged sooner by wind and rain.

6 Extrapolation of results

In the following calculation, we will try to transfer the results to a typical football pitch. However, due to the high variance of the measurement results and variable assumptions, the following extrapolation is only a rough estimate and should be treated with caution. A pitch size of 7,600 m² is assumed, which corresponds to the average size of large pitches used in Europe. Furthermore, it is assumed that 10% of the pitch is used intensively and 90% extensively. However, this assumption cannot be generalized, since the intensity of pitch use depends strongly on the duration of use as well as the performance level. High-fill synthetic turf systems typically have fibre weights between 1,000 g/m² and 1,600 g/m². From the measurement results presented above, neglecting the outliers, a mass loss in intensively used areas of 0.5 %/y to 2.0 %/y is obtained. For extensively used areas, the expected mass loss is 0.1 %/y to 0.6 %/y. From these assumptions, a best-case and a worst-case calculation for the expected mass loss from an entire pitch in one year is proposed.

Formula:

$$pitch\ size \cdot pole\ weight\ \cdot (10\%\ loss\ intensive\ area + 90\%\ loss\ extensive\ area) = totalloss\ per\ year$$

Best-case: $$7{,}600\ m^2 \cdot 1{,}000\ \frac{g}{m^2} \cdot (0.1\ \cdot 0.005 + 0.9\ \cdot 0.001)\ \frac{\%}{y} = 10{,}640\ \frac{g}{y}$$

Worst-case: $$7{,}600\ m^2 \cdot 1{,}600\ \frac{g}{m^2} \cdot (0.1\ \cdot 0.02 + 0.9\ \cdot 0.006)\ \frac{\%}{y}\ = 89{,}984\ \frac{g}{y}$$

A high-fill synthetic turf probably loses between 10 kg and 90 kg of microplastics per year through fibre loss and abrasion only, without considering infill loss.

7 Summary

The aim of the study is to determine the fibre wear of facilities with synthetic turf. For this purpose, pitches of different ages are sampled. Fibre bundles are taken from areas of the pitch with varying usage intensity and analysed. The methodology appears sound and provides a means to objectively measure fibre loss on playing fields.

Significant overall mass loss can be determined. However, since the measurement results show a high variance, no significant relationship between mass loss and pitch-specific properties, such as geographic location, infill type or fibre cubature, can be demonstrated. However, statistical trends can be observed. For example, the observed mass loss increases with increasing age of the pitch and with increasing intensity of use.

In intensive use areas, around the penalty spot, a fibre wear or fibre loss of 0.5 % to 2 % per year can be observed. In extensively used areas, mass loss ranges from 0.1 % to 0.6 %. Furthermore, fibre loss per year is highest within the first three years and after ten years. In contrast, the loss is lower in the middle years of a facility's life than in the first three years and after ten years.

Osnabrück, October 2023

Prof. Martin Thieme-Hack

8 Literature

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