Microplastic from cast rubber granulate and granulate-free artificial grass surfaces

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in collaboration with Sandmaster AB

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Foreword

Several problems need to be solved to achieve Sweden's long-term climate goals by 2045; to create a circular economy and to reduce the amount of plastic in our seas and in nature. Fossil based plastics need to be replaced by materials with a lower climate impact and we need to identify the value inherent in plastics to increase material recycling and reduce plastic leakage.

The Swedish EPA is responsible for the National Plastics Coordination, which aims to contribute to sustainable plastic use, through the gathering and dissemination of knowledge and supporting sustainable plastic use nationally. This knowledge also provides support for international collaborations in which Sweden participates. The aim of the National Plastics Coordination is also to improve collaboration between stakeholders, to identify and carry out activities to promote sustainable plastic use. Collaboration for a sustainable use is a mutual effort and process within and between county administrative boards, regions, municipalities, research, business and government agencies. The National Plastics Coordination strives to be a driver in this work.

By contributing to increased knowledge and collaboration, the National Plastics Coordination will facilitate and strengthen the work of stakeholders to contribute to environmental goals and the UN's Sustainable Development Goals (SDGs). This is done by creating measures for a sustainable use of plastic, where plastic is used in the right context, in resource- and climate-efficient, non-toxic and circular flows, without any leakage.

This report has been developed as a part of the work by the National Plastics Coordination.

Stockholm, 13 January 2022

Ingela Hiltula
Head of Department
Sustainable Society Department

Contents

Summary

This assignment, commissioned by the Swedish Environmental Protection Agency, focused on expanding knowledge about the dispersion of microplastics from cast rubber and granulate-free artificial grass surfaces by supplementing previous studies with new measurements and calculations. The goal was to improve estimates of how much these sources contribute to microplastics nationally and to identify strategies to better prevent leakage into the environment.

To our knowledge, this is the first time this method has been used. The method allowed us to quantify the leakage of microplastics from cast rubber surfaces and granulate-free artificial grass surfaces in wash water from cleaning machines specifically adapted for these types of surface. By analysing a well-mixed subset of wash water and using information on the size of cleaned surface areas, the leakage of microplastics from these materials per unit area was determined to be 0.4–20 g/m^2 per year for granulate-free artificial grass and 0.6–48 g/m^2 per year for rubber surfaces. The variation between different surfaces is, however, very high and the uncertainty in both measurements and analysis is high. This is a level of dispersion on par with a road surface with an annual mean daily traffic of 5,500–13,000 vehicles, which is estimated to be 56 g microplastic/m^2. Some artificial grass surfaces release their artificial grass much more easily than others (about 50 times easier). This is why standardised methods for identifying high-emission artificial grass surfaces should be developed. Well-designed and well-maintained granulate-free artificial grass surfaces are likely to meet the EU's proposed threshold limit for dispersion of microplastics at 7 g/m^2 per year.

Based on municipal surveys, supplier data and GIS analyses, Sweden's total area of cast rubber surface is estimated to be 1,200,000 m^2 in 2020, of which approx. 550,000 m^2 is on playgrounds and approx. 650,000 m^2 is on sports pitches. Previous studies looked at Sweden's total area of granulate-free artificial grass in 15 cities, which this project estimates, based on population, to total about 447,000 m^2.

Based on the estimated rubber area on playgrounds and sports pitches combined with the measured microplastic emissions per year and square metre, total emissions from Sweden's rubber surfaces are estimated to be about 16 tonnes/year. The equivalent estimate for artificial grass surfaces without granulates is about 2 tonnes/year. These are thus considerably smaller sources of emissions than such sources as road traffic (8,190 tonnes/year) and artificial grass with infill (676 tonnes/year), and in line with estimated microplastic emissions from fishing nets and other fishing implements (4–46 tonnes/year). The relatively low values are attributable to the total area of these surfaces being significantly smaller compared with the total area of roads in Sweden. Measures to reduce microplastic emissions from car traffic can thus reduce Swedish microplastic emissions more than measures for rubber surfaces. However, the latter measures are also important because they are relatively easy and cost-efficient to implement.

The project developed technical specifications to limit the leakage of microplastics from surfaces with cast rubber granules. These include making good material choices, such as recycled SBR (styrene-butadiene rubber), choosing European tyres newer than 2010 which do not contain hazardous HA oils, and

using 10–20 % PUR binder if casting occurs outdoors. Always consider the use of natural materials, which do not generate microplastics, such as grass, wood chips or sand. Available cork products on the market have the same function and appearance as rubber materials. Though these still contain PUR binders, they are considered a more environmental-friendly alternative from a microplastic perspective and probably from a climate perspective as well.

Construction (environment, substrate and design) is another important aspect for reducing the leakage of microplastics from rubber surfaces and artificial grass surfaces. Open street drains near these surfaces should be avoided, and in exposed places these should be fitted with filters. Good drainage should be ensured by using stable draining substrate, such as crushed stones and stone dust. Sand on granular surfaces increases wear and should be avoided by separating with edges and spacing. Trees, particularly fruit trees, and berry bushes should be avoided next to rubber surfaces due to bird droppings and troublesome soiling that can require expensive maintenance.

Maintenance is crucial for long lifespan and reduced leakage of microplastics from rubber materials. Prepare a maintenance plan together with the supplier and the maintenance contractor. Check the surfaces regularly (approx. 3–10 times/season) and repair damage as soon as possible so that it does not worsen. Pick, vacuum, brush and/or blow off debris and leaves from the surfaces regularly (3–10 times/season). Do not plough and clear snow on granulate surfaces and avoid using the surfaces for dumping snow. Empty any microplastic filters regularly, at least once a season and more often as needed. Do a deep clean with a cleaning machine if necessary, about once per every 1–4 years, depending on how dirty the surface becomes. It is important that the wash water be treated properly, so that it does not contribute to emissions of microplastics. Standardised methods for identifying and addressing high-emission artificial grass pitches and rubber surfaces should be developed to cost-effectively reduce the dispersion of microplastics from these surfaces.

Sammanfattning

Detta uppdrag, beställt av Naturvårdsverket, syftade till att öka kunskapen om spridningen av mikroplaster från gjutna gummiytor och granulatfria konstgräsytor genom att komplettera tidigare studier med nya mätningar och beräkningar. Ett mål var att komma närmare en kvantifiering av dessa källors bidrag till mikroplaster nationellt, samt att få en bättre förståelse för hur man kan förhindra att spridning av mikroplaster från dessa ytor sker.

Metoden som projektet använde för att kvantifiera spridningen av mikroplast från gjutna gummi-ytor och granulatfria konstgräsytor, och som oss veterligen inte använts tidigare, var att analysera tvättvatten från rengöringsmaskiner specialanpassade för denna typ av ytor. Genom att analysera en väl blandad delmängd av detta vatten, och med information om hur stor yta som rengjorts, bestämdes spridningen av mikroplast från dessa material per ytenhet till 0,4–20 g/m² per år för konstgräs utan granulat och 0,6–48 g/m² per år för gummiytor. Variationen mellan olika ytor är mycket stor och osäkerheten i både mätningar och analys hög. Detta är en spridning i samma nivå som en vägyta med en årsmedeldygnstrafik på 5 500–13 000 fordon, som beräknas sprida 56 g mikroplast/m². Vissa konstgräsplaner släpper sina konstgräsfibrer betydligt lättare än andra (ca 50 ggr lättare) och av denna anledning bör standardiserade metoder för att identifiera högutsläppande konstgräsplaner utvecklas. Välkonstruerade och välskötta granulatfria konstgräsytor har goda möjligheter att klara EUs kommande gränsvärde för spridning av mikroplast på 7 g/m² per år.

Utifrån kommunenkäter, leverantörsdata och GIS-analyser har Sveriges totala area platsgjutet gummi uppskattats till 1 200 000 m² år 2020, varav ca 550 000 m² på lekplatser + ca 650 000 m² på idrottsplatser. Sveriges totala yta konstgräs utan granulat har i tidigare studie undersökts i 15 städer och har i detta projekt utifrån befolkning uppskattats till totalt ca 447 000 m².

Med utgångspunkt från den beräknade gummiarean på lekplatser och idrottsplatser kombinerat med de uppmätta mikroplastutsläppen per år och kvadratmeter uppskattas de totala årliga utsläppen från Sveriges gummiytor till ca 16 ton/år. Motsvarande beräkning för konstgräsytor utan granulat ger ca 2 ton/år. Detta är sålunda avsevärt mindre utsläppskällor än t ex vägtrafiken (8 190 ton/år) eller konstgräsplaner med infill (676 ton/år) och ligger snarare i nivå med uppskattade mikroplastutsläpp från fiskenät och andra fiskeredskap (4–46 ton/år). De jämförelsevis låga värdena beror på att den totala arean gummi och konstgräs utan granulat i Sverige än så länge är liten jämfört med bilvägsarean. Åtgärder för att minska mikroplastutsläppen från biltrafiken kan därför reducera de svenska mikroplastutsläppen mer än åtgärder för dessa ytor. De senare åtgärderna är dock också viktiga eftersom de är relativt lätta och kostnadseffektiva att genomföra.

Projektet tog också fram tekniska specifikationer för att begränsa spridningen av mikroplaster från ytor med gummigranulat. Dessa inkluderar bra materialval, som att när återvunnet SBR-gummi används välja europiska däck nyare än 2010 som inte innehåller hälsofarliga HA-oljor och använda ca 10–20 % PUR-bindemedel om gjutning sker utomhus. Beakta alltid om naturmaterial, som inte generar några mikroplaster alls som gräs, flis eller sand, kan användas. Det finns även korkprodukter på marknaden med samma funktion och utseende som gummimaterialen. Dessa

innehåller dock fortsatt PUR-bindemedel men bedöms ändå som ett miljövänligare alternativ ur ett mikroplastperspektiv och sannolikt även ur ett klimatperspektiv.

Konstruktion (omgivning, underlag och utformning) är en annan viktig aspekt för att minska spridningen av mikroplast från gummiytor och konstgräsytor. Öppna gatubrunnar nära dessa ytor bör undvikas, och på utsatta ställen bör dessa förses med filter. God dränering bör säkerställas mha stabilt dränerande underlag, t ex stenkross och stendamm. Sand på granulatytor ökar slitaget och bör undvikas genom separering med sarg och avstånd. Träd, speciellt bär- och fruktträd, bör undvikas vid gummiytor pga. fågelspillning, besvärlig nedsmutsning och därmed fördyrat underhåll.

Underhåll är centralt för lång livslängd och liten spridning av mikroplast från gummimaterial. Utarbeta en underhållsplan tillsammans med leverantören och underhållsentreprenören. Kontrollera ytorna regelbundet (ca 3–10 ggr/säsong) och åtgärda skador snarast så att de inte förvärras. Plocka, sug, borsta och/eller blås regelbundet bort skräp och löv från ytorna (3–10 ggr/säsong). Ploga och snöröj helst inte granulatytor, och undvik att använda dem som snötipp. Töm eventuella mikroplastfilter regelbundet, minst varje säsong och vid behov oftare än så. Djuprengöring med tvättmaskin kan göras vid behov, ca 1 ggr/1–4 år, beroende på nedsmutsningsgrad. Viktigt är då att tvättvattnet hanteras säkert, så att det inte bidrar till spridningen av mikroplast. Standardiserade metoder för att identifiera och åtgärda högutsläppande konstgräsplaner och gummiytor bör utvecklas för att spridningen av mikroplaster från dessa ska kunna reduceras kostnadseffektivt.

Introduction

Through the framework agreement "Follow-up & evaluation of chemical substances in the environment – Sub-area 1 Measurements in the environment", the Swedish Environmental Protection Agency commissioned IVL Swedish Environmental Research Institute to conduct this assignment with case number NV-00173-16.

IVL contracted two sub-consultants, KTH and Sandmaster, to ensure the best possible potential and expertise for the project. KTH has leading research expertise in polymer materials, and the company Sandmaster has cleaning machines for the relevant surfaces, which have been used in the project when taking samples. Sandmaster has also contributed with its extensive practical experience in cleaning and maintaining rubberised surfaces and artificial grass pitches.

Finally, we would like to thank all facility owners, suppliers and other stakeholders who answered our questions or participated in the project's two meetings held together with the Artificial Grass Pre-purchase Procurement Group (BEKOGR) for input primarily on material specifications and care routines for rubber surfaces. The views and discussions presented at these meetings were very interesting and valuable for the final compilation of our proposals for reducing the dispersal of microplastics from rubberised surfaces and artificial grass pitches without granulate.

Background

Microplastics are usually defined as plastics and rubber particles with a diameter between 1 µm and 5 mm (Gigault, et al. 2018). Nanoplastic is the name for plastic/rubber particles that are even smaller. In recent years, the proliferation of micro- and nanoplastics has begun to receive attention, partly due to a growing awareness of the large amounts of plastic that accumulate annually in nature (Zhou, et al. 2020), (Galafassi et al. 2019), (Geyer, Jambeck, & Lavender Law, 2017), (Eriksen, et al. 2014), and partly due to a growing insight that nanoplastics, in particular, can cause significant damage to living organisms (Jiang, et al. 2020), (Wang, et al. 2021), (Chae, Kim, & An, 2019).

Nanoplastics are smaller than the eye can see, but increasingly advanced methods are being developed to detect their presence in the environment (Fu et al. 2020). Most plastics and rubbers are inert and marginally toxic in macroscopic form (Ekvall, et al. 2019), (Hamid, 2020), (Kutz, 2018), but if they are broken down or produced as microscopic particles, the potential risks increase for living organisms (Kögel, et al. 2020). Health risks are affected by such aspects as particle size, particle concentration, exposure time, particle characteristics (e.g., shape), particle material and surrounding environmental factors (Kögel, et al. 2020). At least some nanoplastics can accumulate in biological tissue (Sökmen, et al. 2020), (Ding et al. 2018), (Deng et al. 2017).

Living organisms that ingest sufficient amounts of micro- or nanoplastics can have stomach problems, impaired growth, impaired reproductive capacity, inflammation, damage to the immune system, altered metabolism and neurological changes (Kögel et al. 2020), (Barría et al. 2020), (Stapleton, 2019), (Büks et al. 2020), (Rochman, et al. 2017), (Yong et al. 2020), (Sana et al. 2020), (Lehner et al. 2019), (Prüst et al. 2020). Scientific studies of the health effects of micro- and nanoplastics have mainly studied fish, snails, shellfish and human cells, but the effects on humans, mice and other animals have also been examined (Wang et al. 2020), (Yong et al. 2020), (Lehner et al. 2019). Today's levels of micro- and nanoplastics in Sweden's drinking water are so low that they are probably not directly harmful to human health (Swedish Food Agency, 2020), but there are still significant knowledge gaps in this area (Horton et al. 2017), (Ogonowski, Gerdes, & Gorokhova, 2018), (Bouwmeester, Hollman, & Peters, 2015). The amount of microplastics, knowledge about microplastics and regulations related to microplastics are also expected to increase over time.

To limit the presence of microplastics, Sweden has drawn up a roadmap for sustainable plastic use to determine the main sources of Swedish microplastic emissions and to propose limiting measures. The Government has tasked the Swedish Environmental Protection Agency (Swedish EPA) with overall responsibility for national plastic coordination. This assignment includes "gathering and building objective and fact-based knowledge about microplastics, disseminating this knowledge to relevant actors, and coordinating and pursuing issues with a view to achieving sustainable plastic use" (The Swedish EPA, 2020). Swedish EPA presented a previous study on microplastics in 2019 (The Swedish EPA, 2019), on which this current work is based. This previous study included a compilation of estimated coverage area in Sweden's largest municipalities using cast rubber granulate. The study, however, did not report an estimate of total microplastic emissions from Sweden's rubberised surfaces.

Plastic flows in Sweden have recently been documented in SMED[1]'s report: "Mapping Plastic Flows in Sweden" (SMED, 2019). The two primary quantifiable sources of microplastics in Sweden are judged to be rubber particles from vehicle tyres from road traffic and rubber granules from artificial grass pitches with infill, although non-quantified sources, such as littering and degradation of macroplastics to microplastics, could be just as important (Magnusson, et al. 2016), (Magnusson, et al. 2019). Unlike plastics, such as polyethylene and polypropylene, tyre rubber is heavier than water and sinks to the bottom sediment if it ends up in lakes, rivers or other watercourses (Lenaker, et al. 2019). The amount of rubber particles that reach sewage treatment plants in Stockholm, Gothenburg and Malmö is therefore relatively limited (Tumlin & Bertholds, 2020). The concentration of rubber particles in surface water is also comparatively low in other countries' rivers and lakes (Xu, et al. 2020). Several studies have analysed aquatic dispersal pathways for microplastics (Horton et al. 2017), (Baresel & Olshammar, 2019), (Baensch-Baltruschat et al. 2020), (Bergmann et al. 2015) and on land (Zhang, et al. 2020), and preventive measures have been proposed (Ogunola, Onada, & Falaye, 2018), (Ejhed et al. 2018), (Peng, Wang, & Cai, 2017), (Auta, Emenike, & Fauziah, 2017).

The current IVL report ("Microplastics from cast rubber granulate and granulate-free artificial grass surfaces") is a follow-up of the IVL report "Sammanställning av kunskap och åtgärdsförslag för att minska spridning av mikroplast från konstgräsplaner och andra utomhusanläggningar för idrott och lek" [Survey of knowledge and proposals for measures to reduce the dispersion of microplastics from artificial grass and other outdoor sports and play facilities] (Krång, et al. 2019). The report is part of Swedish EPA's assignment as national plastic coordinator and aims to quantify microplastic emissions from surfaces with cast rubber granulate and infill-free artificial grass in Sweden. Surfaces with cast rubber granulate and infill-free artificial grass are expected to produce relatively limited microplastic emissions, but the amounts are not quantified and are probably not negligible.

Playgrounds, schoolyards, sports facilities and outdoor gymnastics areas are examples of outdoor areas where cast rubber granulate and granulate-free artificial grass are used. During the 2010s, these types of materials increased sharply in popularity, mainly because of State requirements that playgrounds and other public spaces be adapted for accessibility for the disabled. When constructing fall protection surfaces, emissions of microplastics are only one of several parameters to be considered. Characteristics, such as wear resistance, good cushioning ability, low price, high play value, good accessibility, low greenhouse gas emissions and limited chemical content are also important, so the desired characteristics must be balanced.

[1] Svenska Miljöemissionsdata

Purpose and goal

The assignment had the following objectives:

1. Build on the studies of cast rubber surfaces and granulate-free artificial grass surfaces described in the IVL report “Sammanställning av kunskap och åtgärdsförslag för att minska spridning av mikroplast från konstgräsplaner och andra utomhusanläggningar för idrott och lek” (Krång, et al. 2019).
2. Develop technical specifications to limit dispersal of microplastics from surfaces with rubber granulate through better design of facilities, materials and maintenance.
3. Measure and calculate microplastic emissions from surfaces with cast rubber granulate and granulate-free artificial grass pitches.
4. Identify dispersal pathways for microplastic emissions from surfaces with cast rubber granulate and granulate-free artificial grass pitches.

The goal of the assignment was to better understand the importance of surfaces with cast rubber granulate and granulate-free artificial grass surfaces as sources of microplastics and to evaluate the dispersal of microplastics from these surfaces.

Another goal was to improve quantification of these sources in the dispersal of microplastics nationally and to identify strategies for improved prevention of microplastic dispersal from these surfaces.

Implementation

The assignment was carried out in the form of the three work packages described below.

Specifications for reduced dispersal of microplastics from surfaces with cast rubber granulate

The assignment

KTH led this part of the assignment, which developed specifications for installing surfaces with cast rubber granulate that clearly defined installation and maintenance that reduces emissions of microplastics to the environment.

This work package consisted of three main activities:

- **a Description of materials currently used, their extent of use and what requirements apply to these rubber surfaces.**
- **b Proposals for material specifications for installing durable surfaces with cast granulate, including care instructions.**
- **c Estimation of total area nationally with cast rubber.**

Implementation

Activity A (**Description of currently used materials, their extent of use, and what requirements apply to these rubber surfaces)** took the form of literature studies, analysis of suppliers' websites and contacts with material manufacturers, suppliers, contractors and facility owners.

Activity B (**Proposal for material specification for installing durable surfaces with cast granulate, including care instructions**) took the form of literature studies and discussions with material manufacturers, suppliers, contractors and facility owners. Two well-attended zoom workshops were arranged, together with the Pre-purchase Procurement Group for Artificial Grass (BEKOGR), aimed at hearing from municipalities, manufacturers and other stakeholders. We received valuable feedback through discussions with stakeholders, and we could build support for proposed specifications. We have sought to define functional requirements since technical and specific material requirements can be an obstacle for technology development and competition.

Activity C (**Estimation of total area nationally with cast rubber**) was conducted to more easily quantify the amount of potential microplastic emissions from surfaces with cast rubber granulate in Sweden. Since Work Package 2 in this study measures microplastic emissions as a function of surface area and time for representative fall protection surfaces, the total area with cast rubber can be used to estimate total annual microplastic emissions from such surfaces in Sweden.

Three parallel strategies were used to estimate the total outdoor surface area in Sweden covered in cast fall protection rubber and rubber fall protection tiles. Using Geographic Information System (GIS) data, aerial images were analysed where size and position were labelled for all rubber surfaces identified in Sweden's largest cities. Additionally, about 10 of the leading suppliers of playground fall protection rubber in Sweden were asked the amount of rubber they install annually and how much they think they have installed in total over the years. In addition, data from a previous study was used that asked Sweden's municipalities to estimate of the size of large rubber areas within their municipal boundaries (Krång, et al. 2019). We used two parallel strategies for rubber at sports facilities (running tracks, athletics arenas, multi-sports fields, etc.): GIS and the previous survey study with the municipalities.

The map study was mainly carried out in GIS map software "My map" from Lantmäteriet (the Swedish mapping, cadastral and land registration authority), which is freely available at https://www.lantmateriet.se/en/maps-and-geographic-information/maps/min-karta/. High-resolution aerial images were used as basic layers in the map analysis. Manual visual inspection of the aerial images was used to locate and identify all potential rubber surfaces. The area of each separate rubber surface was automatically calculated as the area of the polygon formed when the corner coordinates of the surface are linked together. Usually the polygon was a rectangle (Figure 1), but more complex shapes also emerged. For each area, the centre coordinates were calculated to facilitate further analysis. The surfaces were temporarily saved in a map layer, and the centre coordinates and areas of all surfaces were then saved permanently as tables. The sum of the surfaces' areas was calculated and compared with the corresponding total areas from the municipalities' and from supplier data.

Figure 1. Example of a map image from the GIS analysis.

Eleven of the dominant playground contractors in the fall protection industry provided information how much rubber surface area they have installed. This included the companies Lekplatskonsulten, Trygglek, Nordic Surface, Lappset, Tress, Unisport, Söve, Gårda Johan, Kompan, Hags and Turfs. At least a dozen other smaller suppliers also offer fall protection tiles and/or rubber asphalt on the Swedish market, but it is still reasonable to assume that the large suppliers providing this information represent about 80 % of today's Swedish market for rubber fall protection outdoors, and probably significantly more. Note that rubber granulate substrate for sports facilities is not included in the supplier study. Instead, the study only includes fall protection rubber for playgrounds and similar. The suppliers could provide comparatively reliable data for the current year, but estimates of total rubber installations over the years by each company are very uncertain. Cast rubber granulate fall protection was introduced in Sweden just before 2000, but only began to be used on a larger scale a few years later once the National Board of Housing, Building and Planning's regulations (BFS 2004: 15 ALM 1) stipulated that playgrounds must be made accessible for people with reduced physical mobility. From that point, the use of fall protection rubber increased steadily, especially from 2012, to about 2018, when the new installations began to decline due to initial concerns about microplastics. The total area continues to increase annually, but the rate of increase has declined. When the supplier could not provide an exact figure on the company's total installed rubber area over the years, a qualified estimate was made based on the supplier's information.

Area data for municipally procured rubber surfaces have been taken from the March 2019 IVL study (Krång, et al. 2019). Additional granulate surfaces have been installed since then, so it can be expected that these figures are slightly lower than if the corresponding information for 2021 had been used. The municipalities included in the study and this report are Stockholm, Gothenburg, Malmö, Uppsala, Linköping, Lund, Borås, Örebro, Helsingborg and Umeå. These municipalities correspond to 28.9 percent of Sweden's 2020 population of 10,373,225 (Statistics Sweden, 2020), which has been included in the calculations.

Dispersal of microplastics from surfaces with cast rubber granulate

The assignment

IVL conducted this part of the assignment. The goal was to estimate how much rubber granulate disappears from these facilities by both taking samples from different facilities and from the facility to see the variation within and between sites. It also examined the dispersal of microplastics over time and estimated the transport of microplastics from the facilities to recipients. The measurements were from cast granulate substrates with different degrees of wear and use level and different ages, sizes and geographical locations.

The measurements were made on a sufficient number of occasions to provide a good picture of variation over time between the different surfaces and to provide a picture of the variation for each of the surfaces. The selected surfaces were to be of comparable material, in terms of the expected emissions of microplastics. To the extent possible, a reported estimate of emissions from these areas was included. The measurements were collected regularly during the period autumn 2020 and spring 2021.

Implementation

(Krång, et al. 2019) reported how IVL demonstrated in previous assignments the dispersal of microplastics from playgrounds by sampling and analysing microplastics in sediment taken from stormwater drains near play areas and sports surfaces with cast rubber. However, this method did not quantify the dispersal of microplastics from these surfaces. Far from all rubber that travels from the surfaces ends up in stormwater drains and some of the particles that initially ended up there may then have been transported further in the system to the nearest water recipient or treatment plant through combined sewage systems.

In this project, IVL worked with the company Sandmaster, leading experts in cleaning artificial grass pitches and rubber surfaces, to develop a sampling methodology from a previous study. This collaboration has allowed us to test, analyse and quantify the dispersal of microplastics from these surfaces in a standardised way by gaining access to mixed collection samples from Sandmaster's cleaning machines that perform deep cleaning of the rubber surfaces with water (Figure 2). Broken off rubber material is flushed into the washing water, and laboratory analyses allow us to estimate the amount of microplastic losses per square metre of rubber surface.

Figure 2. Sandmaster's internally produced machine for wet cleaning of rubber surfaces, which was used in the project.

Similar measurement methods have been used to investigate the dispersal of microplastics from roads (Järlskog, et al. 2020). During cleaning, Sandmaster took photos of the surfaces before and after cleaning and noted the location of the surface, its age and its wear level when possible. Any quantitative information on the use of the rubber surface has also been documented. See the below examples of sampling data (Table 1).

Table 1. Examples of sampling data.

Site name	**Nytorpsvägen 32, Breviksskolan**
Site designation	G7
Surface type	Buddy swing cast rubber
Coordinates (lat./long. WGS 84)	59.1346, 18.201
Surface area [m²]	37.5
Age of surface [years]	?
Most recent cleaning [date]	14 April 2021
Wear level	Normal wear, a little damage, very loose granules on the surface and around the entire play area
Demonstrated dispersal of microplastic	
Utilisation	Frequently used by children during school hours.
Closest storm drain	1.7 m. Only hard surface in between.
Sampling date	26 May 2021
Sample taken by	Mats Svensson, Sandmaster Skandinavien AB
Sampling conditions	
The cleaned surface area [m²]	37.5
Cleaning pressure	200
Sample volume [l]	5
Total water volume when taking sampling volume [l]	250
Sample label	Brevikskolan buddy swing

Since the project must be able to judge losses over time, which requires multiple sampling, some rubber surfaces were chosen that were cleaned several times during the project. To attain a good range of different materials, wear level and other properties and a broad statistical basis, we also examined additional rubber surfaces a single time, see Table 2.

Table 2. Number and type of samples.

Artificial grass surface	**Autumn sampling**	**Spring sampling**	**Total**
K_Surface1	2		2
K_ Surface 2	2	2	4
K_ Surface 3	2	2	4
K_ Surface 4	2	2 + filter	4
K_ Surface 5	2 + filter	2 + filter	4
	10	**8**	**18**
Rubber surface			
G_ Surface 1	1	1	2
G_ Surface 2	1		1
G_ Surface 3	1		1
G_ Surface 4	1		1
G_ Surface 5	1		1
G_ Surface 6	2	1	3
G_ Surface 7	2 + filter	1 + filter	3
G_ Surface 8	1	1	2
G_ Surface 9	1	1	2
G_ Surface 10	1	1	2
G_ Surface 11	1		1
G_ Surface 12	1		1
	14	**6**	**20**

Figure 3 below shows a map of the different sampling sites. Detailed descriptions of the various sampling sites are presented in annexes 1 and 2.

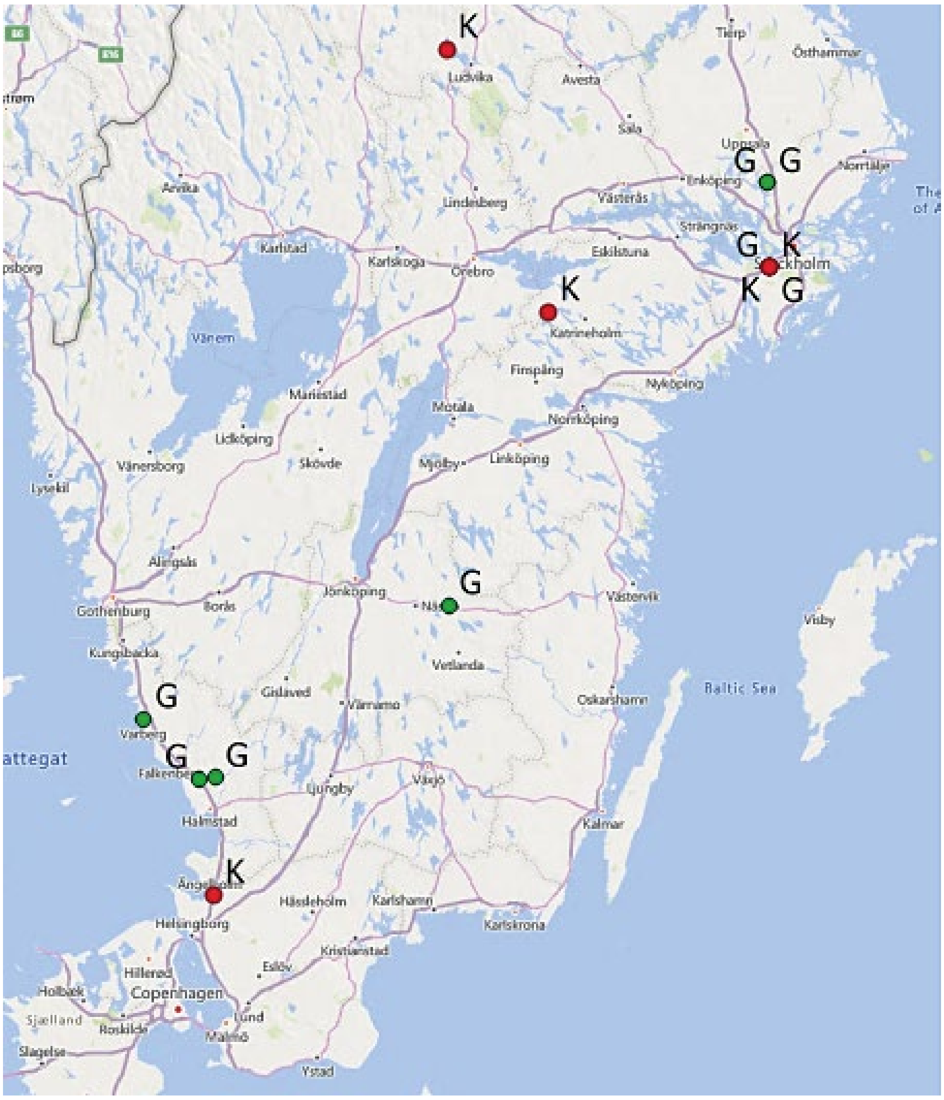


Figure 3. Map of all sampling sites. K = artificial grass, G = rubber surface.

For surfaces repeatedly sampled as part of the project and where possible, drain filters (Figure 4) were installed in nearby stormwater drains to capture microplastics from stormwater to gain a better understanding of the various transport pathways. Two filter bags with 200 µm and 50 µm filters, respectively, were placed in the filter holders.

The material in the 200 µm filter was first sieved through a 2 mm metal sieve with MQ water. The filtrate was saved and sieved down on a 100 µm nylon filter. The material stuck to the metal sieve was filtered down on a 300 µm nylon filter using water suction. The material in the granulate trap's 50 µm filter was filtered down on a 50 µm nylon filter. Each granulate trap thus results in three size categories of microplastics: > 2 mm, 2 mm – 200 µm and 200 µm – 50 µm.

Figure 4. Well filters from SEKA Miljöteknik with two surface-mounted filter bags (200 and 50 µm mesh size) were used in the project to quantify microplastics in stormwater.

Dispersion of microplastics from granulate-free artificial grass surfaces

Assignment

IVL conducted this work package. In addition to measurements and calculations of microplastic emissions from granulate-free artificial grass pitches, it also attempted to quantify and describe microplastic dispersal pathways into the environment. The measurements were done from artificial grass surfaces with different degrees of wear and use level and different ages, sizes and geographical ranges. The measurements were made on multiple occasions to provide a good picture of variation over time. An estimate of the total volume of microplastic emissions nationally from artificial grass without granulate was reported where possible. The measurements were collected regularly during the period autumn 2020 and spring 2021.

Implementation

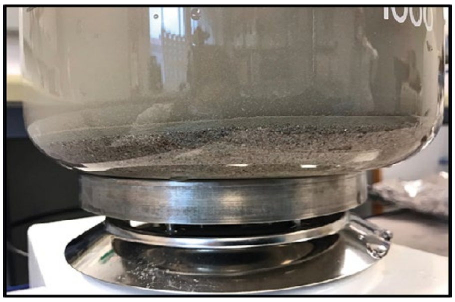
This work package also used a sampling methodology based around Sandmaster cleaning granulate-free artificial grass surfaces with its purpose-built machines (Figure 5). IVL was given access to collection samples of washing water from a known area of the examined pitch for extraction and analysis of the amount of microplastics. The procedure for sampling, documentation and analysis was the same as for rubber surfaces, although the machine was different. In this work package, a total of 18 samplings and analyses were performed on five multisport pitches to enable follow-up of microplastics dispersion during the sampling period, see Table 2 previously in this report.

Figure 5. Sandmaster's internally produced machine for wet cleaning of artificial grass pitches with or without granulate and the collected washing water analysed by IVL.

Sample processing and analyses

The project's water samples and drain filters were transported to IVL's microplastic laboratory in Stockholm, where the samples were processed (Figure 6). After careful homogenisation using a magnetic stirrer, one or more subsamples were taken from each water sample to determine the quantity of microplastic particles. The volume of the subsamples varied between 1–1,140 ml. The subsamples were then filtered through a 300 µm and then a 50 µm nylon filter using water suction. The assignment originally only included analyses of 300 µm filters. Previous experience from similar assignments at IVL, e.g., analyses of Sandmaster's washing water carried out in 2018, had shown an increase in particle content/L for smaller fractions sizes. This, in combination with analysing the granulate traps' collection of particles at both 200 and 50 µm, resulted in extending the assignment to include analyses of both 300 and 50 µm for the washing water.

A)



B)

C)

D)

Figure 6. A) Incoming water samples with clearly different microplastic contents. B) Examples of samples with lots of sediment that are difficult to homogenise. C) Selection of homogenised subsamples for analysis. D) Filtration through two filter stages using water suction.

The filters with their particles were then placed in clean petri dishes for analysis in a stereomicroscope (Figure 7). The stereomicroscopes used in this study were Nikon SMZ18 with a 7.5–135 magnification and Nikon SMZ745T with a 13–100 magnification. Between each filtration, the equipment was thoroughly cleaned.

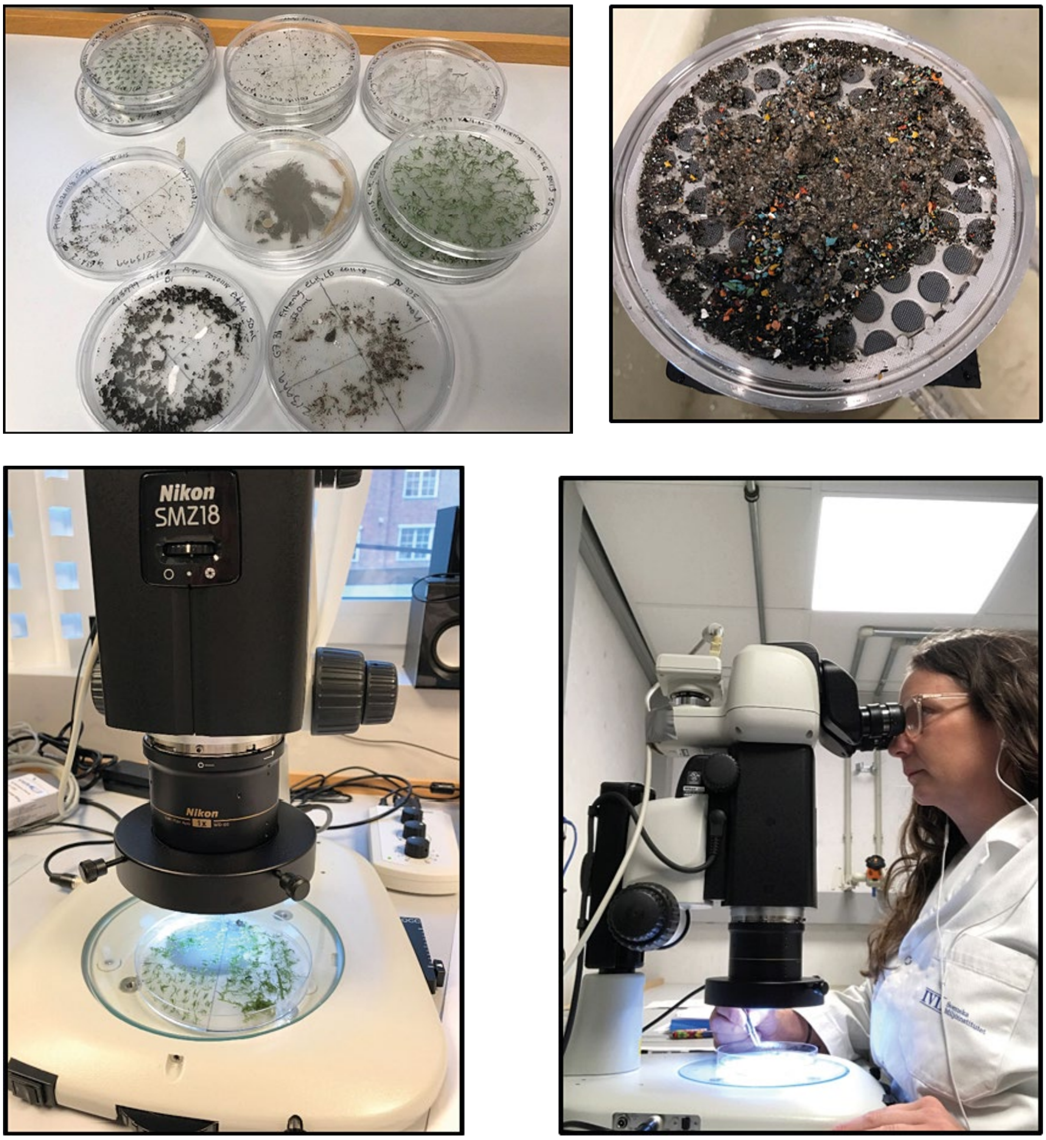


Figure 7. Petri dishes for analysis in a stereomicroscope.

Each granulate trap consisted of two nylon filters: an outer one with a mesh density of 50 µm and an inner one with a mesh density of 200 µm. From each filter, three subsamples were taken to determine the dry weight:wet weight ratio. The subsamples were weighed and then dried in a convection oven at 105 °C until constant weight was reached. In this way, the water content and dry weight:wet weight ratio of the samples could be calculated. Two to three subsamples (between 0.05 and 7.7 g) were then taken from each drain filter to analyse the amount of microplastic particles. The sediment samples from the 200 µm filter were first sieved through a 2 mm metal sieve with MQ water. The particles settling on the sieve were suspended in MQ water and filtered down on a 300 µm nylon filter using water suction. The filtrate from the sieve was saved and was filtered in turn through a 100 µm nylon filter using water suction. The sediment sample from the 50 µm filter was suspended in MQ water before being filtered down on a 50 µm nylon filter using water suction. Each filter with these particles was moved to clean petri dishes for analysis in a stereomicroscope.

Each sample was analysed optically in a stereomicroscope, where all microplastic particles from artificial grass pitches and rubber granulate surfaces captured on each filter were quantified with respect to particle type, number and colour. This analysis used systematic examination at both higher and lower magnification, where each individual particle was assessed visually (colour, shape and structure) and based on its firmness. Melt tests were also performed from time to time to determine the origin of the particles.

In all parts of sampling, process and analysis work, precautionary measures were taken to minimise contamination of microplastic particles from the surrounding environment. This was done even though this type of contamination normally consists of airborne fibres, which cannot be confused with particles coming from rubber surfaces and artificial grass pitches. By also analysing blank samples with deionized water, any contamination can be quantified and managed. The microscope was connected to a camera and computer, where the samples were further analysed and documented.

Calculation methodology

The calculation of microplastic dispersion in grams per square metre and year depends on assumptions about washing water consumption per area, weight estimate for the microplastic particles and the time interval between sampling occasions.

Area estimate

Data for determining area is based on Sandmaster's water consumption in the washing process. Washing of granulate surfaces uses 10 litres per m^2. Sample water was taken from a full 250 litre wash water tank, which corresponds to 25 m^2. For granulate-free artificial grass surfaces, 1.25 litres per m^2 is used and the sample water was taken from a 350 and 400 litre wash water tank, respectively, which corresponds to 280 and 320 m^2 for each machine.

Weight estimate

To calculate a corresponding weight for a number of microplastic particles per litre of wash water, we assumed spherical particles with a diameter of 300 µm and 175 µm for each particle in the 300 µm and 50 µm filter, respectively. A density of 1 g/cm^3 was used for the granulate particles at the bottom of the sample water. This resulted in an estimated weight of 1.41372E−05 and 2.80616E−06 g/particle for the rubber granules, respectively.

The weight estimate for artificial grass fibre is a little more complicated due to their ray-like shape. The shape was described as a measurement block with the sides 0.1 x 0.25 x 3.1 mm for the particles that stuck to the 300 µm filter (Figure 8). The particles stuck to the 50 µm filter were described as 0.1 x 0.25 x 0.3 mm. Artificial grass fibre floats on the test water, and the density 0.93 g/cm^3 for LDPE (Low-density polyethylene) was used, resulting in an estimated weight of 7.20750E−05 and 6.97500E−06 g/particle for artificial grass fibres, respectively.

Figure 8. Size of some artificial grass fibres that are separated after count.

The weight estimate was calibrated by weighing counted artificial grass fibres from two subsamples K4A and K4B, giving a mean value of 7.30693E−05 g/particle for artificial grass fibres stuck to the 300 µm filter. In addition, all artificial grass fibres from sub-sample K4C were weighed when high concentrations of grass blades were detected (Figure 9). The total weight of dried artificial grass fibres was 21.8 g. The theoretical weight was calculated based on the analysed concentration of 88,182 fibres/litre and the average weight per above particle to 31.2 grams. The difference between the two weights points to the uncertainty in the methodology.

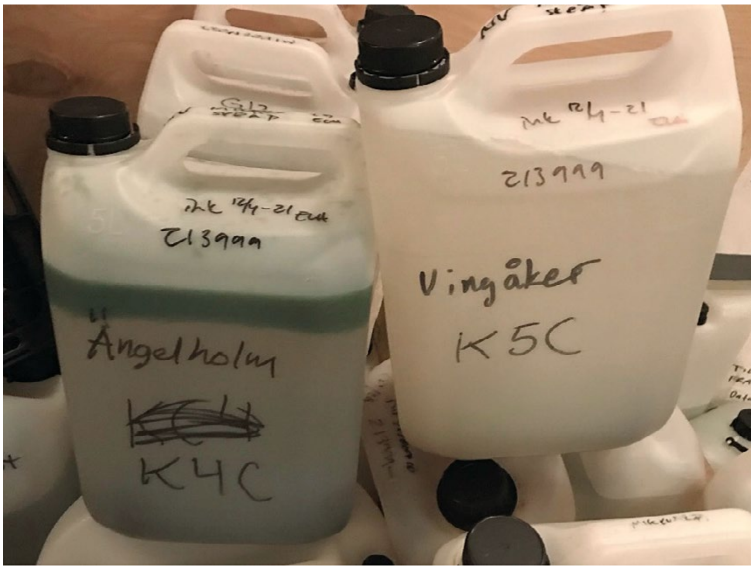


Figure 9. Container with sampling water from station K4C containing high levels of artificial grass fibres.

Results

Specifications for reduced dispersal of microplastics from surfaces with cast rubber granulate

The purpose of this part of the study is to: (1) summarise the regulations for fall protection surfaces, (2) describe how surfaces with cast rubber granulate are usually constructed, (3) describe the materials used in surfaces of cast rubber granulate, (4) describe the properties of existing materials, (5) develop specifications and care instructions for sustainable surfaces with cast granulate, and, finally, (6) determine the current total size of all areas of cast rubber granulate.

Regulations for fall protection surfaces

When constructing and managing fall protection surfaces, there are several national and international regulations to comply with, both regarding fall protection safety, accessibility for people with reduced mobility and the environment.

The European standards SS-EN 1176 (Swedish Institute for Standards, 2018) and SS-EN 1177 (Swedish Institute for Standards, 2019) for play equipment and shock-absorbing substrate regulate minimum requirements for fall protection safety for shock-absorbing surfaces for play equipment. The standards describe test methodology, calculation algorithms and requirement specifications for fall protection materials. Impact measurements are taken by dropping a heavy, well-defined aluminium ball from a series of heights against the fall protection surface. The acceleration of the ball is recorded digitally as a function of time, the maximum acceleration is noted and the HIC (Head Injury Criterion) number is calculated and compared with the threshold values. By repeating the test for different thicknesses of fall protection material, the minimum permissible material thickness can be calculated and tabulated as a function of fall height. Higher play equipment requires thicker fall protection layers and a larger safety radius covered in fall protection material around the equipment.

The Planning and Building Act (PBL) (Government Offices of Sweden, 2010) regulates outdoor environment in built-up areas in Sweden. These regulations specify that there are to be areas for play and outdoor activities in residential areas, that they be constructed and maintained to minimise the risk of accidents and that, if possible, public places and plots be designed to provide accessibility to people with reduced mobility (SFS 2010:900).

The Product Safety Act (PSL) (Government Offices of Sweden, 2004) stipulates that all goods and services offered to Swedish consumers by commercial providers and public enterprises must be safe (SFS 2004:451). PSL also applies when municipalities and tenant-owner associations provide play equipment on playgrounds, regardless of the age of the equipment. The Swedish Consumer Agency ensures adherence to PSL.

The National Board of Housing, Building and Planning’s collection of statutes (BFS) (The National Board of Housing, Building and Planning, 2011) includes “The

National Board of Housing, Building and Planning's regulations and general advice on accessibility and usability for people with reduced mobility or orientation in public places" (BFS 2004:15 ALM 1, BFS 2011:5 ALM 2). This specifies that newly built playgrounds must be usable by children and parents with reduced mobility or orientation, but that not all play equipment must necessarily be made available. The National Board of Housing, Building and Planning's regulations on easily removed barriers (BFS 2013:9 HIN 3) strive to adapt existing public places, including playgrounds, to provide increased accessibility.

The BFS also includes the National Board of Housing, Building and Planning's building regulations (BBR), which regulate the design of fixed play equipment, such as swings and jungle gyms, to minimise the risk of accidents and injuries. Surfaces under play equipment must be shock-absorbing and designed to minimise injury (BBR 8:93). BBR applies to both new construction and renovated playgrounds. The wording of BFS was updated in 2020.

The EU chemicals legislation REACH (EU, 2006) regulates the use of chemicals within the EU. In Sweden, these regulations are included in the Environmental Code. The Swedish EPA, the Swedish Chemicals Agency and the Swedish Work Environment Authority have supervisory responsibility for ensuring that REACH is complied with in Sweden.

CE marking according to the EU Toy Safety Directive (2009/48/EC) (EU, 2009) is required for fall protection and play equipment for individual use to show that it meets the EU criteria for environment, health and safety. The Toy Safety Directive regulates how much heavy metals and chemicals are allowed in toys and play surfaces and other aspects. The standards in the SS-EN 71:2005 series are relevant in this context, in particular Part 1 and Part 9 (Swedish Institute for Standards, 2005), (Swedish Institute for Standards, 2005b). The chemical requirements are implemented in Swedish legislation through laws (2011:579), ordinances (2011:703) on the safety of toys and in the Swedish Chemicals Agency's regulations (Swedish Chemicals Agency, 2019). The Swedish Consumer Agency is responsible for toy safety in general in Sweden, the Swedish Institute of Standards is responsible for preparing standards and the Swedish Chemicals Agency ensures compliance with the chemical rules for toys.

The Paris Agreement (UN, 2015), which entered into force in 2016, declares that global warming must be kept well below two degrees compared with the reference year 1990 and that a limit of 1.5 degrees warming is preferable. Sweden's long-term climate goals within the framework of the Paris Agreement are to end net emissions of greenhouse gases into the atmosphere by 2045 (EU, 2009). This requires that all organisations minimise their climate impact, including construction companies and municipalities that build, order and manage sports facilities and playgrounds, respectively. Consequently, climate-smart material choices should be used when installing such surfaces.

Structural overview for surfaces with cast rubber material and artificial grass

Outdoor-use fall protection from cast rubber granulate can either consist of cast rubber (rubber asphalt) or prefabricated fall protection tiles made of rubber. An advantage of cast rubber is that it can be used to create surfaces with complex geometries and a variety of colour combinations, while fall protection tiles have the advantage that they do not require as advanced technology to be installed. Both options can offer effective, accessible fall protection where wheelchairs and prams can be used. All rubber surfaces also have comparatively low maintenance needs, even if not completely maintenance-free. Surfaces with cast rubber granulate, however, risk releasing microplastics, often use at least partly newly made synthetic rubber, which makes them less than ideal from a climate perspective, and may in some cases contain higher levels of heavy metals and chemicals than allowed by the EU Toy Safety Directive (2009/48/EC) (EU, 2009), which regulates the chemical content of play products for children. There are also preliminary indications that the incidence of torsion-induced knee joint injuries increases on surfaces with rubber granulate compared with, e.g., fall protection sand, but this has not yet been systematically investigated.

Prefabricated fall protection tiles for outdoor use are normally made of rubber granulate (approx. 5–15 mm in diameter) in either newly manufactured EPDM (ethylene-propylene-diene) rubber or in recycled SBR (styrene-butadiene) rubber from old tyres. The granules are bonded together with polyurethane-based adhesive. The same type of rubber is often used throughout the tile, but it is also common for the tiles to consist of two layers of material with different structures. For example, the lower layer may have a regular granulate structure while the upper layer has a grass-like mulch structure. The tiles are often approximately rectangular with a side length of about 50–100 cm and a thickness of about 3–9 cm. Cushioning in fall protection increases with the thickness of the tile, so a thicker tile provides better protection and should be used for higher fall heights. Several plates can be linked together with connecting dowels to create a larger continuous rubber surface and individual broken tiles can easily be replaced.

Fall protection surfaces of cast rubber granulate are usually manufactured in two layers: an abrasion-resistant surface layer and a shock-absorbing bottom layer (Figure 10). The thickness of the lower layer largely determines its fall protection properties, i.e., a thicker bottom layer enables a higher fall height. At low fall heights, a single surface layer may be sufficient. The granulate in the surface layer usually consist of newly produced EPDM, but recycled EPDM (from, e.g., sports shoe rubber soles) is also used at times. The granulate in the bottom layer traditionally consist of recycled SBR from tyres, but newer cushioning materials for the bottom layer also occur, for example, expanded thermoplastic polyurethane (E-TPU). Polyurethane-based adhesives are used to bind the granulate, as is also the case in fall protection tiles. Several Swedish manufacturers in this study have stated that the proportion of binder in relation to the proportion of granulate is about 5–10 % in the bottom layer and 5–20 % in the surface layer. Increasing the proportion of binder improves granulate binding, but unfortunately this also increases the cost and the hardness of the material. An excessively low amount of binder risks reducing the service life of the surface, while an excessively high amount of binder risks diminishing fall protection. Cast fall protection materials can also be made of cork granulate, which is held together using polyurethane binders in the same way as rubber granulate.

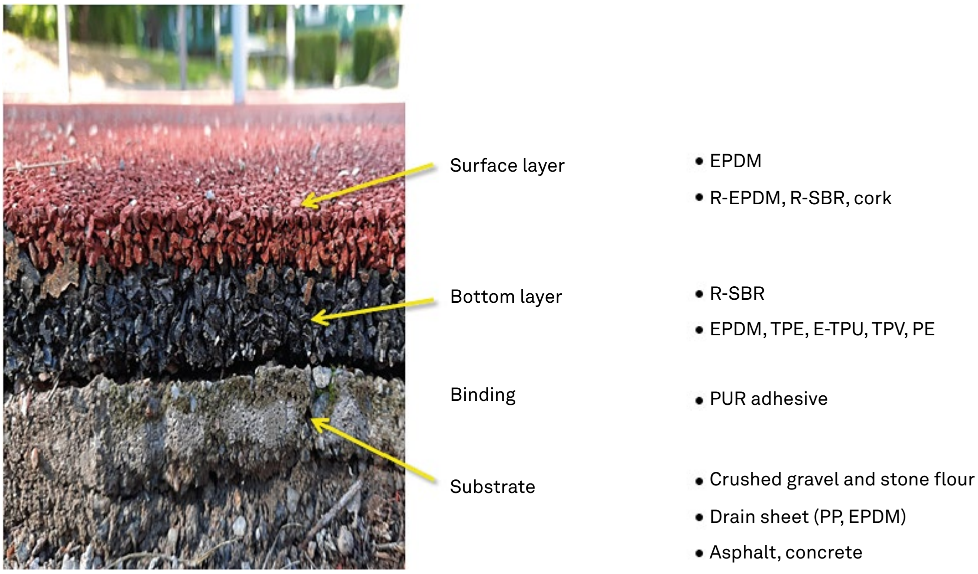
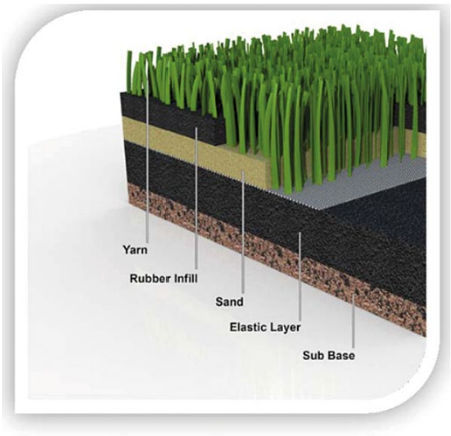


Figure 10. Design of fall protection surfaces with cast rubber (this study).

Cast rubber granulate are also used on running tracks and other sports facilities needing a shock-absorbing substrate. The principle is the same as for fall protection rubber, but as a rule a much thinner shock-absorbing bottom layer is used, usually of recycled tyres ("SBR" rubber). The surface layer usually consists of either EPDM or polyurethane (PUR), both of which are abrasion and weather resistant soft materials. Figure 11 shows an example with the trade name Tartan gold. www.polytan.se/produkter/syntetiska-belaeggningar/loeparbanor/tartan-gold/

Figure 11. Design of rubber substrate for running tracks. The top layer is usually made of coloured polyurethane (PUR) or EPDM and the bottom layer of black SBR (recycled tyres). This photo shows a common running track material with the product name Tartan Gold.

Artificial grass pitches consist of artificial grass fibre made of plastic, a backing mat that the grass fibres are attached to, a shock pad made of rubber, and possibly granulate infill in the form of small rubber granulate (Figure 12). Infill-free artificial pitches by definition have no rubber granulate infill. The infill increases the cushioning characteristics of the artificial grass, makes the grass fibres stand up straight and makes it more comfortable to play football on the surface. For this reason, it is often used on football pitches. Playgrounds, on the other hand, rarely need infill.



Grass fibre	• PE, PP, PET, PA6
Granulate infill	• None • SBR, EPDM, TPE, sand, cork, others
Backing	• PUR, Latex, PE, PP, PET, PA6
Shock layer	• SBR, PUR, E-PP
Substrate	• Crushed gravel and stone flour • Drain sheet (PP, EPDM)

Figure 12. Structural overview of artificial grass with and without granulate infill (Genan rubber surfaces – granulate for artificial turfs, https://www.genan.eu/applications/sport-and-leisure/).

Description of currently used materials

Polymer-based shock-absorbing materials and fall protection materials, including fall protection rubber and artificial grass, can consist of many types of rubbers and plastics. The diversity of materials can be expected to continue increasing once more alternatives are developed for the current dominant material solutions.

Playgrounds and primary schools often have rubber granulate-based fall protection surfaces consisting of cast rubber or prefabricated fall protection tiles. Rubber granulate made of durable EPDM rubber is often used for surface layers and rubber granulate made of recycled tyres (R-SBR) for shock-absorbing bottom layers. Polyurethane-based adhesives are used to bind the granulate, as is also the case in fall protection tiles. Sometimes expanded polyethylene (PE), polypropylene (PP), cork or thermoplastic elastomer (TPE) are used as shock absorption, such as expanded thermoplastic polyurethane (E-TPU).

Running tracks and sports arenas often have a thin, cushioning surface layer with cast rubber granulate consisting of EPDM or PUR, sometimes in combination with textile materials. Examples of trade names are Tartan, Sorbitan, Chevron, Rekortan, Eurotan, Plexitracs and Mondotrack. When the running tracks are constructed with granular technology, PUR adhesives are often used, but latex-based adhesives can also be found. Cast rubber granulate is also found in other sports facilities.

Outdoor tennis courts, however, usually do not use rubber granulate. Instead, they use asphalt covered with a shock-absorbing layer of cross-linked acrylic plastic or red gravel, although from a distance it often looks like the tennis courts consist of rubber granulate.

Artificial grass consists of artificial grass fibres made of PE, PP, Nylon (PA6), Polyester (e.g., PET) attached to a backing of, e.g., PP, PE, PA6, PUR or natural rubber (latex) (NTNU SIAT, 2018). The artificial grass can possibly be filled with granulate of, e.g., R-SBR, EPDM or sand (Wallberg, 2016). A shock-absorbing layer of, e.g., R-SBR or PUR is often placed under the artificial grass (shock pad). Table 3 shows an overview of which materials are used for fall protection.

Table 3. Rubber and plastic materials used as fall protection.

Materials	Areas of use (in fall protection)
Polyethylene (PE), including low density polyethylene (LDPE), high density polyethylene (HDPE) etc.	Artificial grass fibres (most common materials for artificial grass) Backing for artificial grass (less common) Expanded PE: Bottom part of cast rubber fall protection (unusual but increasing)
Polypropylene (PP)	Artificial grass fibres (common) Backing for artificial grass (uncommon but increasing) Expanded PP (EPP): Fall protection tiles, shock layer in artificial grass pitches (uncommon but increasing)
Polyamide (PA6, PA66, i.e. Nylon)	Artificial grass fibres (less common, decreasing in use)
Polyester (textile fibres of, e.g., PET)	Artificial grass fibres (less common, increasing) Backing for artificial grass (less common)
Polyurethane (PUR)	Binder between rubber granulate in cast fall protection and fall protection tiles (always) Backing in artificial grass (quite common) Expanded PUR (E-TPU): Bottom part of cast rubber fall protection (unusual)
Recycled tyres with styrene-butadiene rubber (SBR). (Often also contains natural rubber (NR) and/or butadiene rubber (BR) and other material.)	Granulate infill in artificial grass (common but decreasing) Granulate in the bottom part of cast rubber fall protection. (Common but decreasing) Prefabricated rubber tiles (fairly common) Lower shock layer of artificial grass (common) (Pure natural rubber (latex) is often used as a backing in artificial grass.)
Ethylene propylene rubber (EPDM) (usually new production)	Granulate in the outer part of cast rubber fall protection. (Very common) Granulates in fall protection tiles (common) Granulate infill in artificial grass (quite common)
Thermoplastic elastomers (TPE), such as dynamic thermoplastic vulcanisate (TPV) or expanded thermoplastic polyurethane (E-TPU)	Granulate infill in artificial grass (unusual, increasing) Cast rubber fall protection (unusual)
Polystyrene (PS), including expanded polystyrene (EPS = Styrofoam)	Not currently found in fall protection. However, the chemical structure of PS is reminiscent of SBR and many microplastic studies have been done on PS.
Cork	Granulates in cast fall protection (unusual, unknown) Granulate infill in artificial grass (unusual, increasing) Non-cast fall protection areas (unusual, unknown)

Detailed information on polymeric materials is presented in Annex 3.

Specifications and care instructions for durable surfaces with cast granulate

Designing a playground, a sports facility or an outdoor gym with fall protection of cast rubber granulate or of fall protection tiles requires consideration of many aspects. The surface must provide good fall protection, allow operation of a wheelchair on it, be inexpensive, abrasion resistant, climate-smart, microplastic-free, chemical-free, and recyclable, and require little maintenance. It is often difficult to optimise all of these factors simultaneously, but with good planning and a well-thought-out strategy, it is possible to improve opportunities for achieving a good balance. Several stakeholders, including municipalities, have previously developed recommendations for dealing with microplastics for surfaces with cast granulate and artificial grass (Stockholm Stad, 2018), (Stockholms Stad , 2019a), (Stockholms stad, 2018b), (Goodpoint, 2016), the Swedish Environmental Protection Agency (The Swedish EPA, 2019), IVL Swedish Environmental Research Institute (Krång, et al. 2019) and the Swedish Football Association (SvFF, 2017). A new technical report from Ecoloop indicates that the leakage of microplastics (> 10 µm) from artificial grass pitches with SBR granulate infill can be significantly reduced if the facility is well designed and includes all effective protection measures and if the care instructions are followed (Regnell, 2019).

GRANULATE MATERIAL

The granulate material must provide adequate fall protection and ensure that the surface is accessible by individuals in wheelchairs and others with reduced mobility. The choice of granulate material is also central to the facility's environmental profile in terms of microplastics, chemicals, climate effects and recycling opportunities.

All forms of cast rubber granulate generate and disperse microplastics from their surface over time, although the amounts are likely to be relatively limited compared with artificial grass surfaces with rubber or plastic granulate. From a microplastic perspective, analysis is needed of whether natural materials, like sand, bark or wood chips, can be used as an alternative to cast granulate, at least on parts of the fall protection surface. However, accessibility requirements must be considered.

Recycled "SBR" rubber from old car tyres often contains high levels of zinc (a heavy metal) and may also contain hazardous chemicals, such as polyaromatic hydrocarbons (PAHs) and phthalates, especially if the tyres are older than 2010 or come from outside the EU (Anderson et al. 2016), (Bocca et al. 2009), (Menichini, et al. 2011), (Janes et al. 2018), (van Kleunen et al. 2020), (Massey et al. 2020), (EU, 2011). Even if the acute health risks of activities on SBR surfaces are limited, SBR should still be avoided as a top layer of fall protection surfaces, especially if it is intended for use by children. These types of surfaces are covered by the Toy Safety Directive (EU, 2009), and SBR often exceeds the directive's threshold values. The problem of high chemical content can be avoided by using, e.g., EPDM (either newly manufactured or recycled), for the top layer. Cork granulate (Bauer, Egebaek, & Aare, 2018) can also be used as a chemical-free alternative to rubber in cast fall protection surfaces.

The size and shape of the rubber granulate affect how easily they can be joined by the binder. The specific area of the granulate, i.e., their area divided by their volume, increases as their average size decreases. In theory, at least, small granulate should lead to a more durable surface. Some suppliers state that they have also noted this phenomenon in practice.

Recycled materials generally have a lower climate impact than newly manufactured materials from a life cycle analysis (LCA) perspective. This means that recycled SBR (or EPDM) has a significantly lower climate footprint than, for example, newly manufactured SBR, EPDM or TPE (Skenhall, et al. 2012) and even slightly lower than the natural material cork (Ragnsells, 2018). Cast fall protection in two layers, where the lower part consists of recycled SBR and the upper part of newly manufactured EPDM, should reasonably have a higher climate impact than cork but clearly lower than newly manufactured rubbers and plastics. LCA has also been made from newly manufactured tyres. In that case, the climate effects will of course be significantly higher (Shanbag & Manjare, 2020), (Piotrowska, et al. 2019).

Newly produced natural rubber is usually estimated to have a lower climate impact than newly produced SBR (approx. 0.7 CO^2 equivalents/kg rubber vs 2–3 kg CO^2 equivalents/kg), provided that no rainforest is cut down to make room for rubber trees. Doing so would result in effective emissions that would be considerably higher (approx. 13 kg CO^2 equivalents/kg) (Jawjit, Kroeze, & Rattanapan, 2010). If renewable energy is used to dry the natural rubber, its climate impact will be even lower (approx. 0.25 CO^2 equivalents/kg rubber) (Dunuwila, Rodrigo, & Goto, 2018). However, some studies claim that the real emissions from natural rubber are higher than that, e.g., 1.16–1.53 kg CO^2 equivalents/kg (Dayaratne & Gunawardana, 2015) or more (Soratana et al. 2017), (Pyay et al. 2019).

When recycling discarded fall protection materials, it is easiest to recycle thermoelastic plastics, such as polyethylene (PE, LDPE, HDPE) and polypropylene (PP), as they are easy to melt and reshape while reasonably retaining their properties. Thermoelastic plastics can also be melted and shaped while rubber is more difficult due to stable cross-links. Energy recovery, however, is always an option, and it is sometimes possible to find new areas of use for discarded materials without having to melt them down and reshape them, for example, in asphalt or concrete.

BINDERS

Currently, polyurethane-based binders made from isocyanates and polyols are used to bind rubber (or cork) granulate into granulate-based fall protection materials. Since free isocyanates are hazardous, it is important to carefully follow current work environment regulations when casting rubber granulate surfaces. The finished polyurethane polymer is not toxic but burning polyurethane can result in hazardous isocyanate vapours.

Increasing the content of binder improves bonding between the granulate grains but reduces the shock-absorbing characteristics of the surface. To maximise the life of the surface, it is recommended to use a relatively high proportion of binder in the top layer of the surface, at least at specific points where the wear is expected to be greatest. However, a higher proportion of binder must be compensated with a slightly thicker shock-absorbing layer. If the granulate is made of cork, however, a slightly lower content of PUR binder is recommended, as the binder can generate more microplastics, contains more chemicals and has a greater climate impact than pure cork.

The temperature must be well above zero (at least about 5 °C) as the binder hardens. If the temperature is too low, the binder between the granulate will deteriorate, shortening the life of the surface. The ground must be properly heated up for several days. If the granulate surface is prefabricated indoors under controlled conditions, the risk of poor curing decreases and a slightly lower content of binder can be used.

Polyurethane degrades more quickly at high temperatures and in prolonged contact with water, so good drainage is needed and it is recommended that the surface be positioned to avoid constant exposure to strong sunlight.

SUBSTRATE

The ground under a surface of rubber granulate must be stable and well-drained to reduce the risk of cracks forming and frost damage but also to extend the life of the binder. A thick layer of crushed stone and stone dust flour according to industry standards is ideal. However, other hardened substrates, such as asphalt and cement, are also potential candidates if good drainage is ensured and if the thickness of the fall protection surface is dimensioned to compensate for the harder substrate. The edge material that delimits the granulate surface should also be stable and well anchored in the ground to stabilise the surface, exposing it to fewer mechanical stresses and wear.

A drainage cloth of, e.g., polypropylene (PP) or EPDM, can be laid under new granulate surfaces for new installations. This layer collects rainwater and leads it, including any waterborne microplastics, from the granulate surface to a stormwater drain with microplastic filters. Further studies are needed to control how much of the microplastic is captured by the drainage layer after prolonged use, but there is much to suggest that this type of construction is best for new installations of shock-absorbing granulate surfaces. However, this construction approach is relatively new, so the long-term properties have not yet been fully clarified.

SURROUNDINGS

The surroundings of the fall protection surface must be designed to achieve a pleasant and creative environment with good accessibility, so that it is easy to access the surface even in a wheelchair. There may be trees at the playground/sports facility, but the need for maintenance increases when a granulate surface is subjected to lots of leaves, berries and bird droppings. Bright sunlight and high temperatures can shorten the life of surfaces but so can moss and other organic growth that thrives best in the shade. So, finding the right balance is best.

If there are stormwater drains in the vicinity of larger rubber surfaces, these can be fitted with microplastic filters that need to be cleaned at regular intervals. The interval is based on such things as the position and wear of the surface. This is probably not necessary for small rubber surfaces, but it may be appropriate for large ones. Streams, lakes and other watercourses in direct proximity to the rubber surface increase the site’s recreational value considerably while increasing the risk of microplastics dispersing with the water and being carried further out into nature.

Sand on rubber granulate surfaces can partly clog the air pores between the rubber granulate grains, reducing the surface’s shock-absorbing properties and increasing friction between shoe soles and the surface. This, in turn, can accelerate the release of microplastics from the rubber. For this reason, granulate surfaces should be well separated from sandboxes and surfaces with fall protection sand. The horizontal distance should be several metres and some form of sand barrier is strongly recommended, e.g., in the form of a raised hard wood edge and/or in the form of a wide grass surface to catch sand grains. Separating rubber and sand surfaces vertically is another option, so that the rubber surface is at least a few decimetres higher than the sand surface. In this way, the amount of sand moved to the rubber surface decreases.

DESIGN

When designing the facility, it is important to find a good balance between the desired properties, including function, safety, fall protection, the environment, inspiration, creativity and accessibility. One of the great advantages of fall protection made from cast-rubber granulate is that it can be manufactured in many interesting colours, shapes and geometries that are stimulating for children, athletes and other users. Unfortunately, surfaces with complex geometries are more difficult to maintain than flat and solid-coloured surfaces. In multicoloured surfaces, the boundary layers between different colours can be particularly sensitive. To generalise, it can be said that the flatter and "duller" a rubber surface looks, the easier it is to maintain and reduce microplastic emissions.

As long as a granulate surface is intact, its emissions of microplastics is probably relatively limited, but when it begins to be damaged, granulate can more easily disperse to stormwater and nature. The edges of the rubber protection are critical points that are easily damaged, making it important that they are well covered and anchored with a stable separating divider made of a hard material that is firmly attached to the ground. These types of edges must, of course, be designed so that they do not increase the risk of tripping injuries and that they do not make wheelchair access impossible. Since the edges of the granulate surface are exposure points, efforts should be made to limit the total edge length at the site. From a microplastic perspective, it is therefore better with a slightly larger granulate surface than with several smaller ones. Small, irregular surfaces can also be difficult to access with cleaning machines. However, fall protection tiles have other advantages, e.g., they are easy to replace when broken, they can be prefabricated indoors under ideal conditions, and they can be designed for easy recycling.

The surface should be designed to discourage intentional damage and unnecessary wear, but vandalism, fire, moped riding, ice spikes and the like are difficult to prevent with building approaches alone. Damage, however, should be repaired quickly so that it does not worsen, as people tend to be less careful with objects and environments that are already damaged and in disrepair. This is why fall protection surfaces should be designed to be repaired quickly, e.g., by using prefabricated rubber tiles where individual parts can be easily replaced or purchasing kits for repairing smaller holes in cast rubber granulate surfaces.

The National Board of Housing, Building and Planning's regulations stipulate that newly constructed playgrounds and recreational areas are be made accessible to persons with limited mobility whenever possible, but that it is not necessary for all play equipment to be adapted for accessibility. It is often appropriate to use cast rubber granulate (or cast cork) in playground areas most in need of accessibility, e.g., around swing sets, and to use natural materials, such as sand, bark or wood chips, on other fall protection surfaces.

Play equipment with a large drop height requires a thicker fall protection that extends further out from the equipment. EU standards SS-EN 1176 and 1177 are used to calculate the minimum dimensions.

Rubber granulate surfaces have a high coefficient of friction, which can increase the risk of torsional injuries in knees and ankles. For this reason, materials with slightly lower friction are recommended for surfaces intended for activities involving fast rotations, such as floorball and folk dancing. High friction, however, also reduces the risk of slip injuries.

Granulate surfaces should not be under water for long periods, which can be avoided with smart planning in combination with good design of the supporting layer and proper drainage. The location, slope, geometry and distance to the nearest stormwater drain should be considered before construction begins.

MAINTENANCE

Maintenance is essential for extending the life of a rubber granulate surface and for reducing its wear and emissions of microplastics. A maintenance plan should be prepared, preferably in consultation with the supplier and maintenance company. Table 4 shows examples of reasonable maintenance intervals.

Regular inspections of surfaces should be carried out frequently to ensure that no damage has occurred that could lead to an increased risk of accidents for children, athletes and other users. If material has been damaged, it should be repaired as soon as possible to avoid injuries and to prevent the damage from worsening. The recommended intervals between inspections and between other maintenance are largely governed by the intensity of wear on the facility, which in turn is affected by how it is designed, how many people use it per day and what the surroundings look like. The more sand, debris, cigarettes, berries, leaves, bird droppings, dog droppings, moisture and moss that end up on the surface, the more often it needs to be cleaned.

If filters for microplastics have been installed in nearby stormwater drains, these must also be inspected and, if necessary, emptied.

At regular intervals, debris and leaves should be removed from the surfaces. Sand should also be brushed off regularly so that it does not clog the pores in the granulate surface, as this reduces the effectiveness of the fall protection. Sand also acts like sandpaper that increases abrasion and wear, shortens the life of the material and increases emissions of microplastics. Sand and leaves can also be blown off, but the disadvantage of this strategy is that doing so also blows off all free microplastics so that they end up in nature instead of being captured in the microplastic filters that are hopefully installed in nearby stormwater drains. If granulate are loose along the edges of the surface, it must be swept up and disposed of as combustible waste.

Granulate surfaces should occasionally also be washed and thoroughly cleaned to remove bird droppings and sand in the pores between the granulate. The water pressure during rinsing must be reasonably high. If it is too low, the cleaning effect decreases, and if it is too high, the surface risks damage. The rinse water can contain quite high levels of microplastic and must be collected and filtered from microplastics to avoid the microplastics being dispersed untreated into the environment. The frequency of deep cleaning depends on the wear, but between once a year and once every three years is often appropriate.

Ploughing and snow removal can damage granulate surfaces and should therefore be avoided. If nearby surfaces must be cleared of snow, the boundaries between the surfaces should be clearly marked with dividers, logs or markers. If possible, surfaces with rubber granules should not be used as snow tips as this may increase wear.

From the very beginning, the maintenance plan should specify how the materials are to be recycled when they eventually need to be replaced. If several materials are included in the design, it is advantageous if they can be easily separated to facilitate recycling. Strive for recyclable materials with a long service life, as they are generally best both for the climate and financially. Cheap natural materials with a low climate footprint but with a short lifespan can sometimes be competitive from an environmental point of view. LCA is used to examine this.

A compilation of proposed measures to reduce microplastic dispersal from surfaces with cast rubber granulate is presented in Table 4.

Table 4. Measures to reduce microplastic dispersal from surfaces with cast rubber granulate.

Material selection (granulate and binders)
• Always consider the use of natural materials which do not generate microplastics, such as grass, wood chips or sand. • Cork granulate can be used as an alternative for accessibility-adapted fall protection surfaces. • When recycled SBR is used, choose European tyres newer than 2010. • Avoid SBR from recycled tyres in the surface layer for fall protection, especially on playgrounds. • Use small and evenly sized rubber granulate to maximize surface durability. • Use about 10–20 % PUR binder if casting occurs outdoors. • If casting occurs indoors, slightly less binder can be used. • Ensure that the temperature at which the PUR binder hardens is stable above 5 °C. • From a climate perspective, easily recyclable materials should be chosen, such as PE, PP, or natural materials. • Keep in mind that recycled materials usually generate lower greenhouse gas emissions than completely new ones.
Construction (surroundings, substrate and design)
• Ensure good drainage using a stable draining substrate, such as crushed stones and stone dust. • Avoid submersion of rubber surfaces for long periods, e.g., using drainage, levelling and tilting. • A drainage cloth can be laid under the surface for horizontal drainage and collection of microplastics. • Use a stable divider that surrounds the granulate surface to reduce the mechanical stresses. • The edges of the rubber surface should be protected and well anchored in a solid surface. • Sand on granular surfaces increases wear and should be avoided by separating with edges and spacing. • Berry bushes and fruit trees next to rubber surfaces should be avoided, due to bird droppings and increased need for maintenance. • Stormwater drains near large rubber surfaces can be equipped with granulate traps. • It is better to install flat, "boring" but easy-to-clean fall protection surfaces rather than small and inspiring ones. • Plan the facility so that it is easy to repair any damage to surfaces. • Take advantage of the fact that not all play equipment needs to be installed so high that it requires fall protection. • Note that accessibility is achieved even if only certain play equipment is adapted for accessibility.
Maintenance
• Prepare a maintenance plan together with the supplier and the maintenance contractor. • Check the surfaces regularly (approx. 3–10 times/season). • Repair damage as soon as possible so that it does not worsen. • Regularly pick up, sweep off and/or blow off debris and leaves from the surface (3–10 times/season). • Empty any microplastic filters regularly, at least once a season but likely more often. • Do not plough and clear snow on granulate surfaces and avoid using them to dump snow on. • Deep cleaning with a cleaning machine can be done when necessary, about 1 time/1–4 years, depending on the wear.

Estimate of Sweden's total area of rubber granulate (2021)

Surfaces with rubber granulate can be found on playgrounds, at schools and at sports facilities like running tracks, sports arenas and multi-sports pitches. Playgrounds often have a thick fall protection rubber layer, while sports pitches are often lined with a thin rubber layer to provide shock absorption and good grip in almost any weather. From a distance, tennis courts can also appear to be rubber coated but usually have other coatings than rubber.

Three complementary strategies were used to estimate Sweden's total area of rubber granulate: aerial image analysis, municipal data and interviews with suppliers. The first two strategies were applied to both playgrounds (including other outdoor surfaces with fall protection rubber) and sports surfaces (running tracks, sports arenas, multisport pitches, etc.), while the third strategy was only applied to playgrounds.

Aerial image analysis of rubber surfaces (playgrounds and sports grounds) in ten of Sweden's largest municipalities (Stockholm, Gothenburg, Malmö, Uppsala, Linköping, Lund, Borås, Örebro, Helsingborg and Umeå), corresponding to 28.9 per cent of Sweden's population, was conducted to determine area and position of these surfaces. These 10 municipalities have previously reported their estimated rubber surface area, as reported in a previous IVL study (Krång, et al. 2019). Table 5 summarises the size of rubber surfaces identified in these 10 municipalities, both with map analysis and with the municipalities' own estimates.

Table 5. Area fall protection rubber and fall protection tiles in studied municipalities [m²]. Based partly on 2019 survey (Krång et al. 2019), partly on the GIS analysis in the present study.

Municipalities 2019	Playgrounds (m²) Survey (2019)	Sports (m²) Survey (2019)	Playgrounds (m²) GIS (2021)	Sports (m²) GIS (2021)	Population (number of persons)
Stockholm	125,424*	0*	50,400	89,000	979,799
Gothenburg	40,469	18,000	46,900	24,600	507,330
Malmö	20,308	0	23,900	21,000	347,322
Uppsala	650	0	8,300	12,000	177,074
Linköping	4,599	3,500	5,800	9,200	164,473
Örebro	3,040	0	4,400	3,800	304,976
Helsingborg	4,310	0	3,600	9,400	148,248
Umeå	4,350	0	4,400	9,400	129,231
Lund:	8,478	3,500	7,900	12,000	126,025
Borås	6,407	3,500	7,300	11,700	113,637
TOTAL*	**218,035**	**28,500**	**162,900**	**202,100**	**2,998,115**
TOTAL – corrected**	**149,000**	**98,000**	**162,900**	**202,100**	**2,998,115**

* Stockholm reported playgrounds and sports facilities combined.

**The same data but adjusted so that Stockholm's area is distributed in the same proportion between playgrounds and sports facilities as the results from the aerial photo analysis, i.e., 45 % and 55 % respectively.

Stockholm did not report the granulate areas for playgrounds and sports facilities separately, which makes the comparison somewhat difficult. For Stockholm, the total rubber area for sports facilities and playgrounds is 139,000 m² (GIS) and 125,000 m² (municipal data), respectively. Excluding Stockholm, the playground area is 113,000 m² (GIS) and 93,000 m² (municipal data), respectively. If Stockholm's total area is divided between playgrounds and sports facilities with the same distribution as in the GIS analysis (45 % vs 55 %), the 10 municipalities' total playground rubber area is 163,000 m^2 (GIS) and 149,000 m^2 (municipal data), respectively. For sports facilities, the areas are 202,000 m^2 (GIS) and 98,000 m^2 (municipal data), respectively.

For the playgrounds, the values generally correspond very well between the GIS analysis and municipal data, both for the total sum and for the individual municipalities, with Uppsala as the only exception. The aerial photo analysis indicates an approximately 14,000 m^2 larger area than municipal data, but nearly the entire difference (8,000 m^2) can be explained by Uppsala seemingly not reporting most of its playgrounds.

For sports facilities, the area differences are significantly larger. The GIS analysis gives almost twice as high values as municipal data, primarily because of the lack of municipal data for sports facilities for half of the 10 municipalities analysed. For this reason, the GIS analysis area totals are judged significantly more reliable than municipal data.

The ten municipalities included in the study have a population corresponding to 28.9 per cent of Sweden's total population. If we assume the same per capita area for playground rubber for the rest of the country, the total area in Sweden would be approximately 560,000 m^2 (GIS) and 510,000 m^2 (municipal data), respectively. However, this is likely a somewhat overestimation of the true area, as the presence of rubber surfaces is greater in cities than in rural areas. Residential areas and farms usually lack fall protection rubber, while it is relatively common in neighbourhoods of flats, especially newly built ones. Fall protection rubber is more common in southern Sweden than in the central and northern parts of the country, and it is much more common in densely populated areas. Using the same extrapolation approach with GIS data for sports facilities gives a total sports rubber area for all of Sweden of approximately 700,000 m^2. This is likely a somewhat overestimation as it is more common with this type of sports arena in large cities than in rural areas, even per capita.

Interviews with suppliers of fall protection rubber were used as a third approach for estimating the total area of fall protection rubber on playgrounds in Sweden. Eleven of the largest suppliers of fall protection rubber in Sweden (Lekplatskonsulten, Trygglek, Nordic Surface, Lappset, Tress, Unisport, Söve, Gårda Johan, Kompan, Hags and Turfs) were interviewed and reported that they now (2021) annually install about 65,000 m^2 of fall protection rubber in total, but that this number has fallen in the last 1–2 years. A rough estimate of the total amount of playground rubber installed by these suppliers over the years is about 426,000 m^2. If it is assumed that these suppliers account for roughly 80 % of the total fall protection rubber market in country, this leads to a total area of about 530,000 m^2 of rubber granulate on playgrounds in Sweden, which is on the same order of magnitude as calculated with the GIS map analysis and the municipal survey, Table 5. However, the supplier estimates have a large degree of uncertainty. Note that indoor playgrounds and restored outdoor rubber surfaces are included in the suppliers' figures but not in GIS data.

In total, the three analysis methods show that the total area of outdoor rubber granulate in Sweden is approximately 550,000 m^2 in playgrounds and approximately 650,000 m^2 in sports facilities, see Table 6. The current total amount of rubber granulate in Sweden is approximately 1.20 ± 0.20 km^2. For playgrounds, the three methods gave very similar results. For sports facilities, only aerial photo analysis is reasonably reliable.

Table 6. Total rubber area for playgrounds and sports facilities in Sweden.

Measurement method	Playgrounds (m^2 rubber) Sweden total	Sports facilities (m^2 rubber) Sweden in total
GIS (2021)*	560,000	700,000
Municipal data survey (2019)**	540,000	340,000
Supplier data (2020)	520,000	-
Best estimate	550,000	650,000

*Extrapolation from Sweden's ten largest municipalities.

**Extrapolation from Sweden's ten largest municipalities. There is no data for sports pitches for half of the municipalities. The area for Stockholm municipality has been divided as in the GIS analysis (i.e., 45 % vs 55 %) between playgrounds and sports facilities.

All three methods for determining Sweden's total area of rubber granulate (GIS, municipal data and supplier data) were negatively impacted with source errors, which is described in detail below.

Aerial photo analysis (GIS) can be negatively affected by sometimes difficulty in distinguishing between sand and sand-coloured rubber, although it can usually be determined using nuance differences, the presence/absence of sharp colour edges and complementary ground-level photos, such as Google Streetview. There is also some measurement uncertainty about the areas of individual objects, but since many surfaces are measured, the total should be reasonably reliable, assuming there are no systematic sources of error. Sports surfaces were generally larger but fewer, which made them easier to measure with good accuracy. Lantmäteriet's map images are 0–3 years old, so newly constructed surfaces that are not included in the aerial photos risk being absent. Since large areas of the landscape have been analysed manually, some rubber surfaces could potentially also have been missed due to human error. The extrapolation from Sweden's 10 largest municipalities (29 % of the population) to the whole country also creates some uncertainty, as the proportion of rubber surface per capita is not necessarily the same in the rest of the country as in these municipalities.

Municipal data for playgrounds are probably quite reliable, except that they are from 2019, that municipalities greatly underestimate their playground areas and that Stockholm municipality has only reported its total area for playgrounds and sports facilities combined. The division of Stockholm's rubber areas between playgrounds and sports pitches generates an error, but it is probably fairly limited. The extrapolation from 10 municipalities to the whole country introduces the same error as in the GIS analysis. For the sports facilities, the municipalities' aggregated data are not very reliable as data are lacking for half of the 10 municipalities analysed.

Extrapolating the areas for the 10 municipalities included in the study for all of Sweden also introduces some uncertainty, as it is not obvious that all Swedish municipalities have as large a rubber area per capita as these 10 municipalities with 29 % of Sweden's population. For example, residential areas and rural communities tend to have fewer rubber surfaces than urban areas with many flats. The municipal data analysis gave a total of 540,000 m^2 of fall protection rubber on playgrounds in Sweden (plus at least 320,000 m^2 on sports surfaces).

Information for playground facilities also contains several potential sources of error. Most of the 11 companies had reasonably reliable data for the past year/years, but very few had thorough calculations of how much material had been installed in total over the years. Qualified estimates based on available information were used to approximate the total amount for the remaining companies. It is also uncertain whether these 11 companies have had 80 % of the Swedish market for fall protection rubber over the years, but this error should be reasonably small.

Analysis of microplastics from surfaces with cast rubber granulate

Water samples from surfaces with cast rubber granulate have been analysed for the presence of rubber granulate and plastic fragments, including flakes larger than 300 and 50 µm. See Figure 13–Figure 16. The sample designation "G" stands for rubber granulate surface, the numbers denote different sampling locations and A–C denote different sampling occasions. The sample from the first cleaning occasion from G1:A has been excluded due to issues with the sampling technique. Additional information for each sample site is provided in Annex 1.

The predominant type of microplastic particles shed from surfaces with cast rubber granulate is, not unexpectedly, rubber granulate (Figure 13 and Figure 14). At the first cleaning occasion (A) for sample site G6, there was a concentration of 7,795 rubber granulates/L of cleaning water. The concentration of microplastic particles/L of cleaning water was significantly less (154 pcs/L) at the second cleaning time (B) and 180 pcs/L at the time of cleaning (C) for the 300 µm filter. There were fewer microplastic particles at sample site G7 at the second cleaning (B) compared with the first (A). These then increased again at the next cleaning time (C), which is expected since the first measurements were taken close in time and (C) occurred after winter.

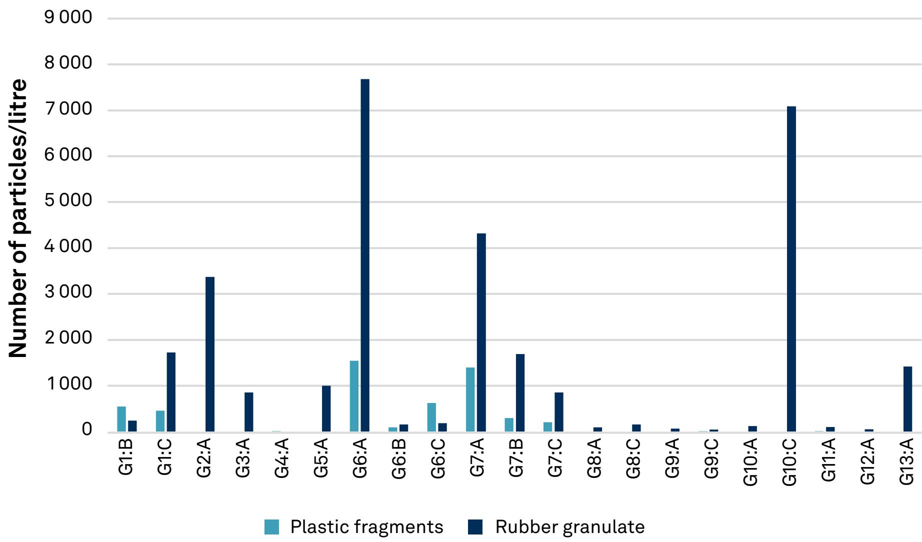


Figure 13. Microplastic dispersion from granulate surfaces 300 µm filter.

The number of smaller microplastic particles (50 µm filters) is significantly more per litre than on the larger 300 µm filters, on the order of two powers of ten, and rubber particles dominate significantly among these particles.

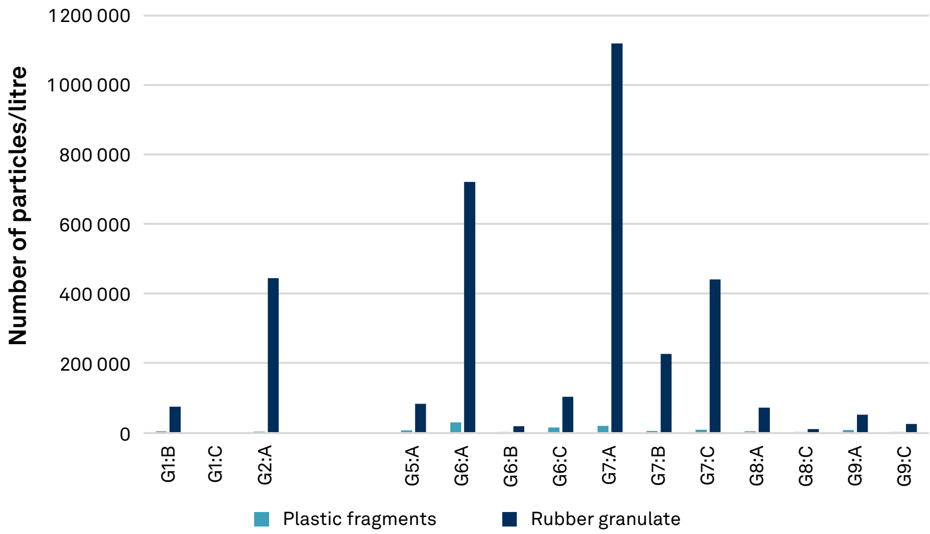


Figure 14. Microplastic dispersion from granulate surfaces 50 µm filter.

Figure 15 and Figure 16 show the distribution of different colours of rubber granulate and the proportion of unknown material in the washing water for the surfaces with cast rubber granulate that have been cleaned. The category "unknown material" includes particles that are obviously anthropogenic (e.g., based on colour, shape, structure and/or firmness), but which cannot be included in any of the plastic or rubber categories. These may be, e.g., paint residues or particles where the material could not be identified.

The colours correspond well with the expectations from the examined surfaces, according to the photo documentation, which proves that we have identified the right kind of particles.

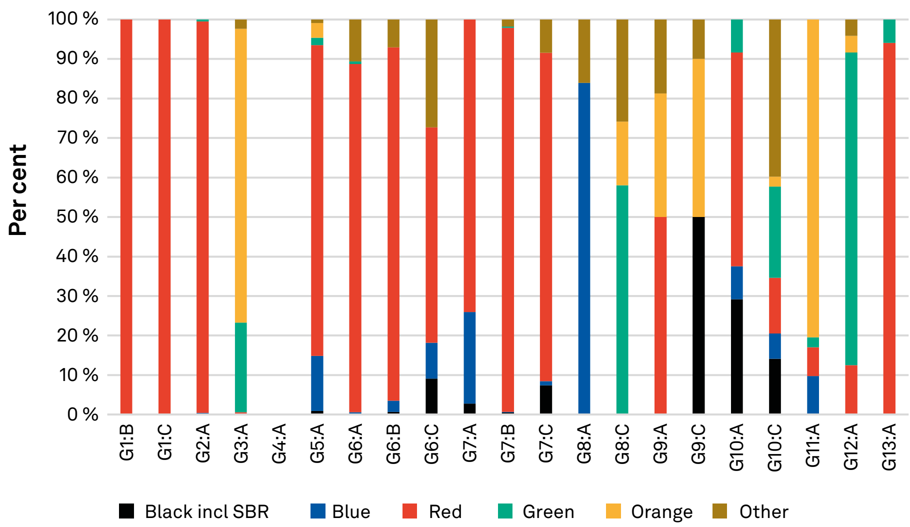


Figure 15. Granulate particles from granulate surfaces 300 µm filter.

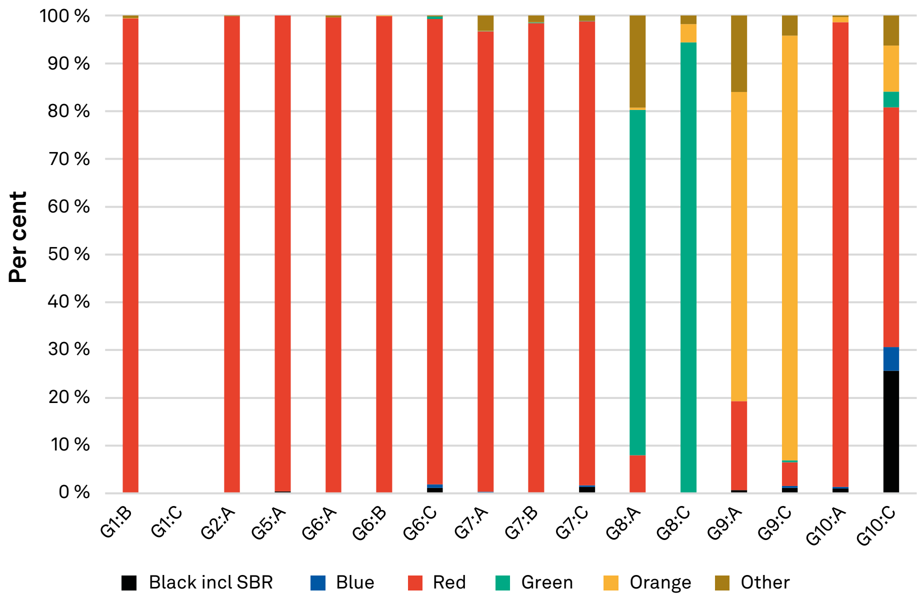


Figure 16. Granulate particles from granulate surfaces 50 µm filter.

Analysis of microplastics from granulate-free artificial grass surfaces

Five sites (K1–K5), see Annex 2, with granulate-free artificial grass surfaces have been sampled for analysis of microplastics in the form of residues of artificial grass, other plastic particles and rubber granulate. Each site except K1 has been sampled on four occasions (A–D), as was done for surfaces with rubber granulate, to calculate the amount of microplastic that sheds from the surface per time unit.

As can be seen from Figure 17, significantly more microplastic (300 µm filter) was dispersed from artificial grass area K4 than from the other sample sites. In the washing water at the first cleaning (A), 23,580 plastic fragments per litre were counted, at the second cleaning (B) 45,600 were counted, and at the third (C) 88,727 plastic fragments per litre. Onsite photo documentation also verifies extensive fibre shedding, see Figure 18.

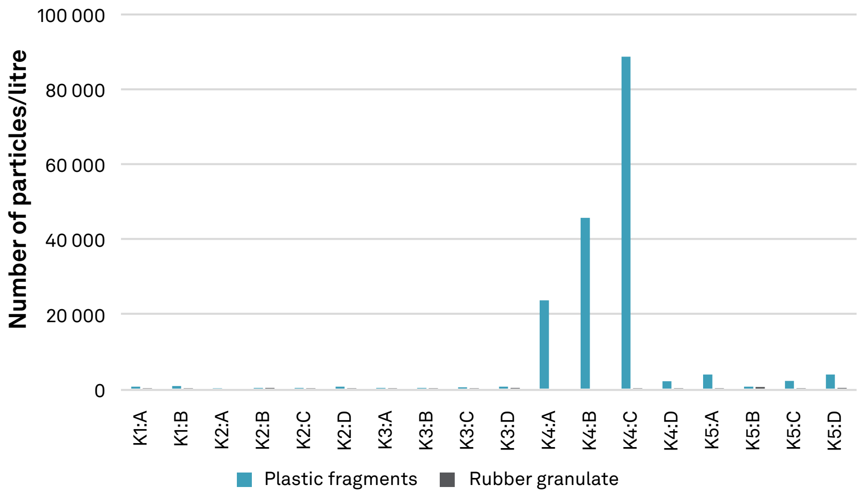


Figure 17. Microplastic dispersion from all investigated artificial grass pitches, 300 µm.

Figure 18. Extensive fibre shedding from artificial grass surface K4.

To more clearly illustrate the emission of microplastics at other sampling sites, test site K4 has been excluded from Figure 19.

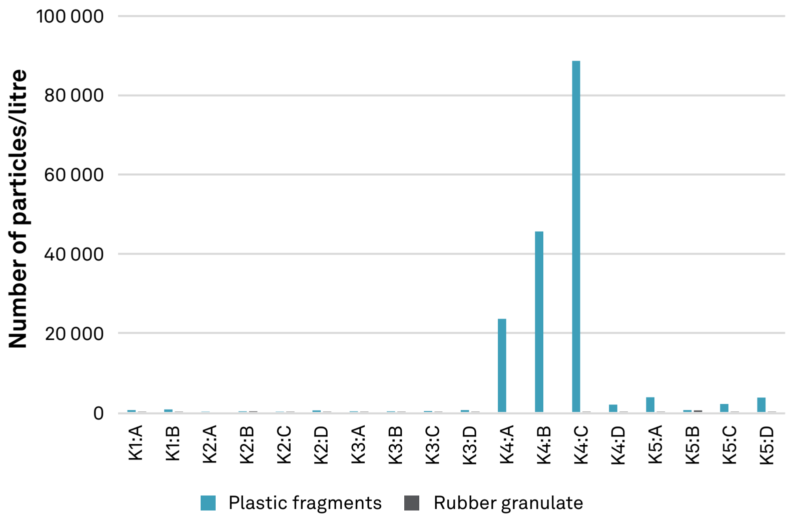


Figure 19. Artificial grass pitch K1, K2, K3 and K5, 300 µm.

Figure 20 shows that K4 does not deviate as much in the dispersion of smaller particles (50 µm filter) and that at the third examination, K5 shows high levels of rubber granulate.

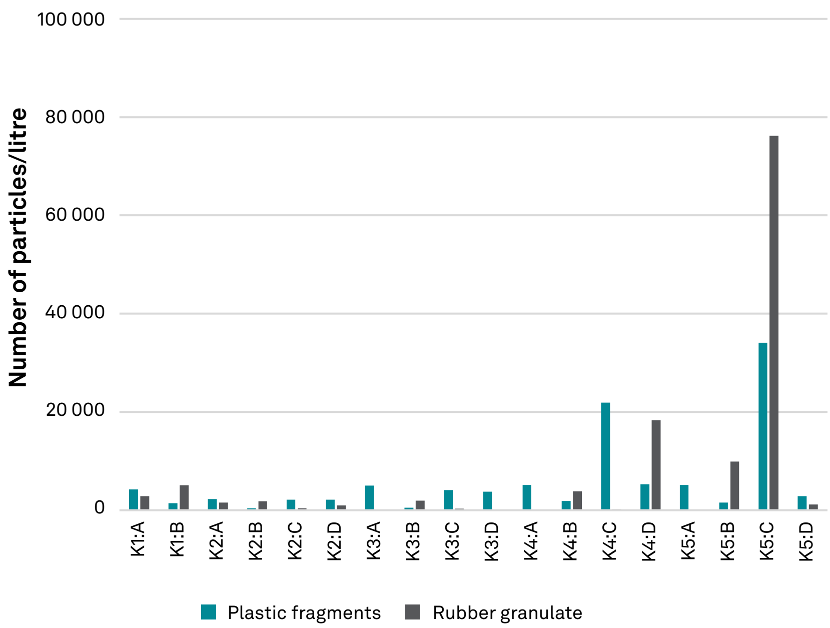


Figure 20. All artificial grass pitches, 50 µm.

Figure 21 shows the dispersion of green artificial grass fibres 300 and 50 µm, which are included in the category of plastic fragments.

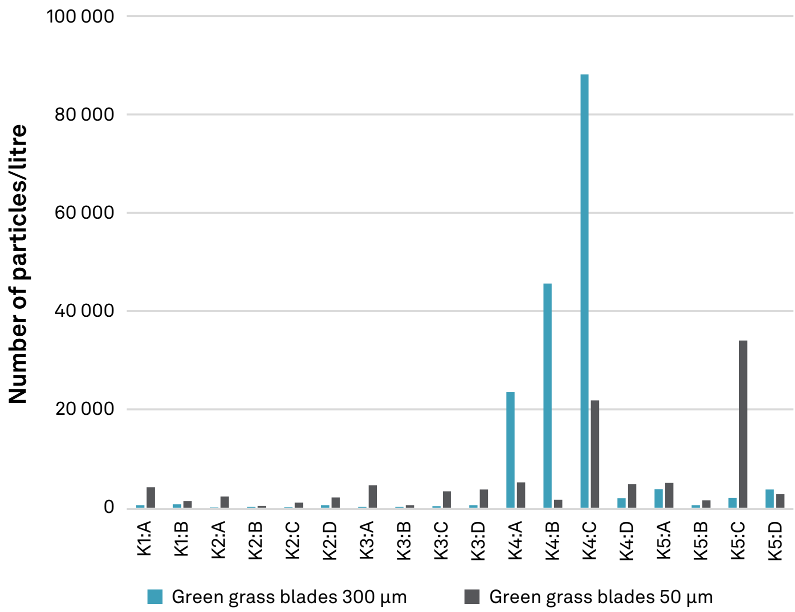


Figure 21. Dispersion of green artificial grass fibres 300 and 50 µm.

The washing water from the granulate-free artificial grass surfaces also contained rubber granulate of different colours, as shown in Figure 22 and Figure 23. These are mainly red rubber granulate and black, including SBR particles. K5:C had the highest content with 76,182 rubber granulates/L of washing water (see Figure 20).

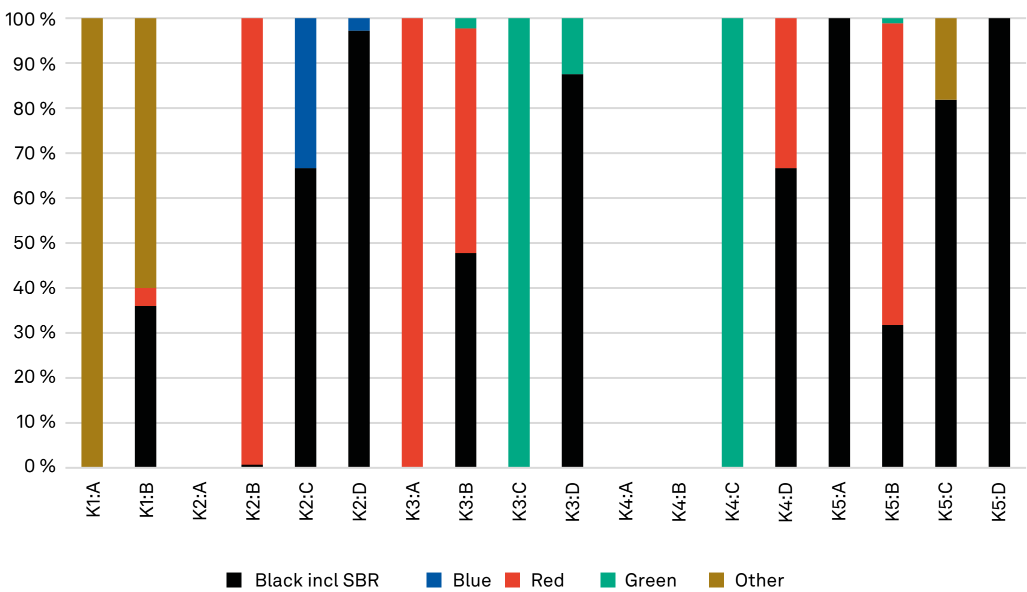


Figure 22. Colour distribution of granulate particles from artificial grass surfaces, 300 µm.

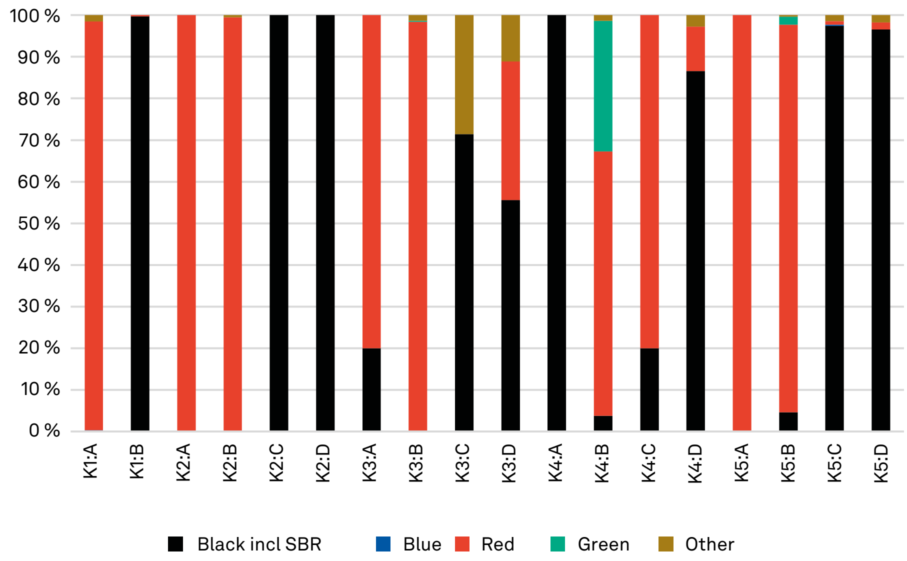


Figure 23. Colour distribution of granulate particles from artificial grass surfaces, 50 µm.

The largest proportion of plastic fragments and artificial grass fibres found in the washing water are, for obvious reasons, green, but there were also other colours, see Figure 24 and Figure 25.

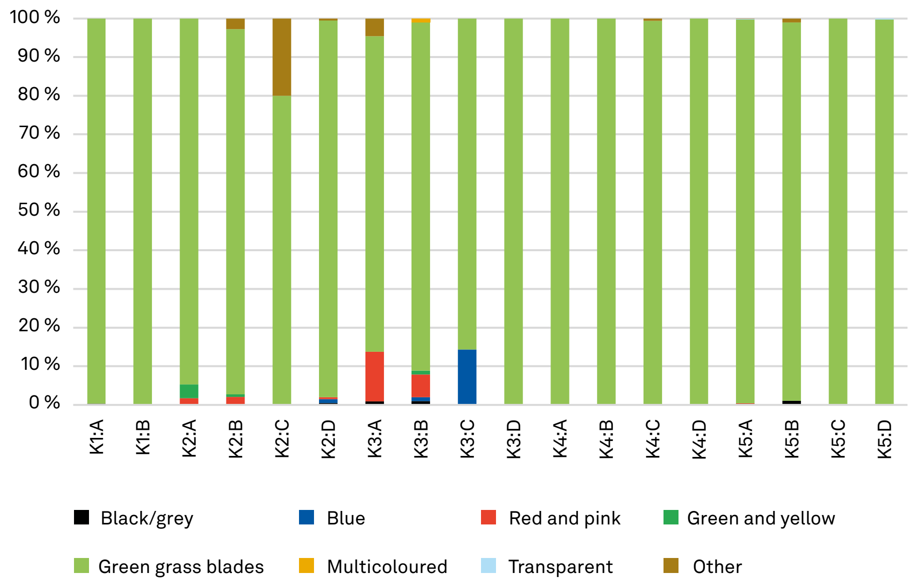


Figure 24. Colour distribution of plastic fragments from artificial grass surfaces 300 µm.

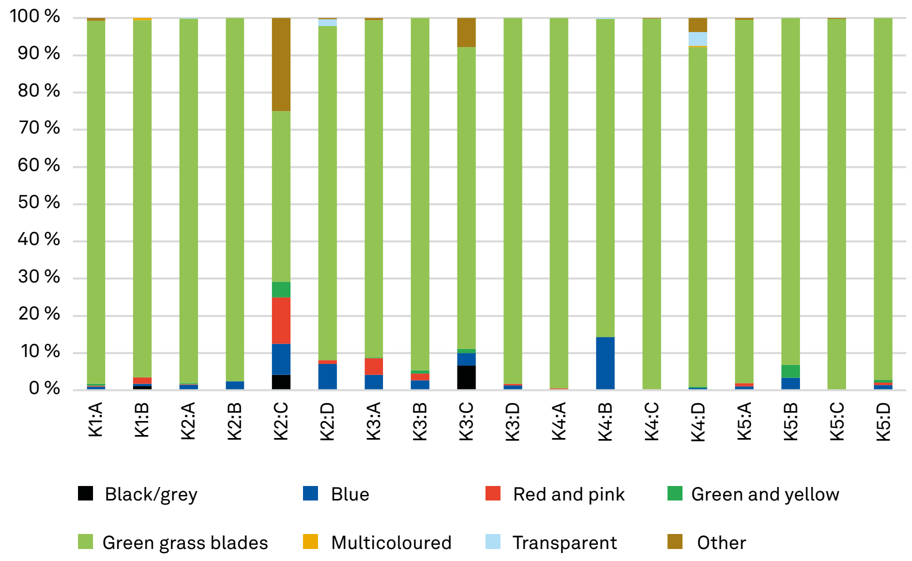


Figure 25. Colour distribution of plastic fragments from artificial grass surfaces 50 µm.

Transport of microplastic via stormwater

Between cleaning occasions, granulate traps were placed at four sampling points in adjacent stormwater drains to investigate possible transport of microplastics to the stormwater system, see Table 2. Each granulate trap had two nylon filters: an outer filter with a 200 µm mesh and an inner one with a 50 µm mesh. One of the granulate traps was placed inside the play area of a preschool. As the children obviously spilled granulate-mixed sand into the drain, this sample was considered contaminated and was not analysed. Even so, it should be noted that it is probably good to place granulate traps adjacent to these types of sites and that they should be inspected regularly.

Figure 26 shows the number of microplastic particles/gram of sediment from the sites Vingåker (GFV), Tyresö (GFT) and Ängelholm (GFÄ).

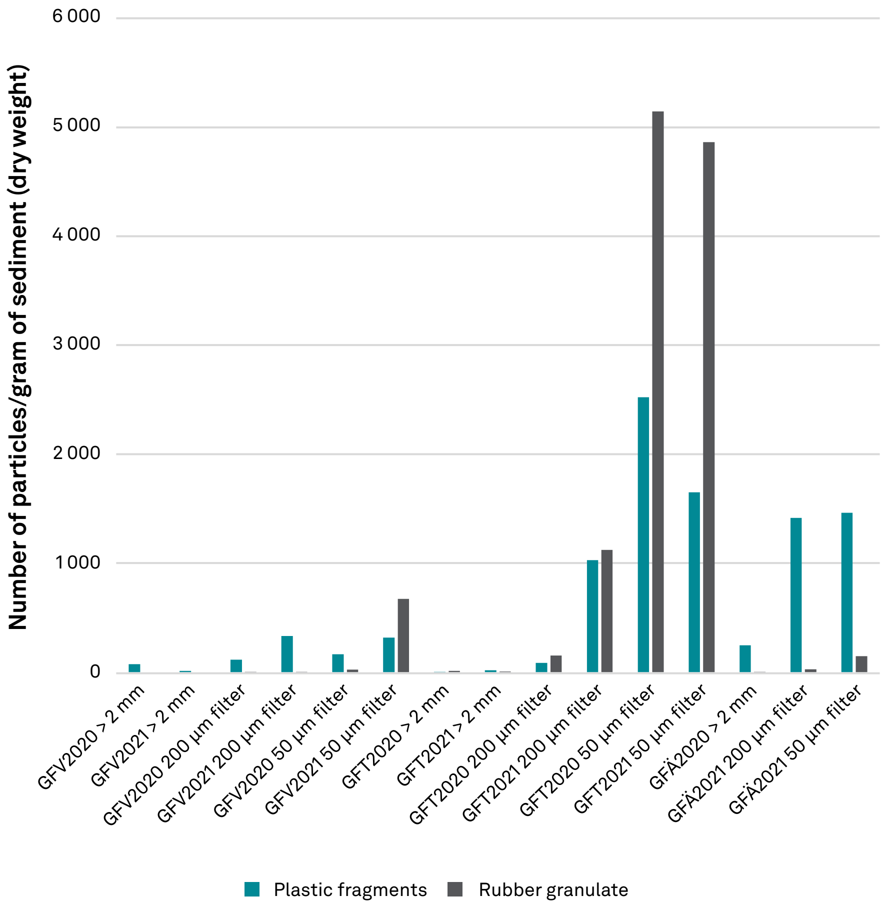


Figure 26. Granulate traps Vingåker (GFV), Tyresö (GFT) and Ängelholm (GFÄ).

The granulate trap in Tyresö municipality was located on a schoolyard. As shown in Figure 26, the 50 µm filter from this drain contained the most microplastic of all the drain filters examined. The number of rubber granulate here at the autumn 2020 sampling was 5,147 particles/gram of sediment (dry weight) and the number of plastic fragments was 2,521 particles/gram of sediment (dry weight). The spring sample from the same site also showed very high concentrations, which indicates a continuously high load on the drain.

Figure 27 below shows the distribution of plastic fragments in the granulate traps at the sites Vingåker (GFV), Tyresö (GFT) and Ängelholm (GFÄ).

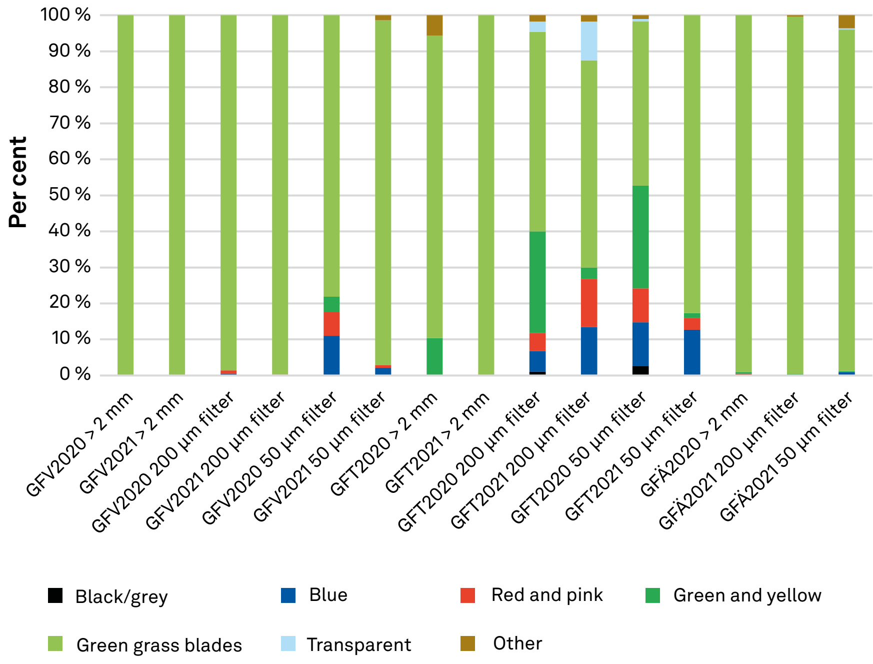


Figure 27. Plastic fragments in the granulate traps Vingåker (GFV), Tyresö (GFT) and Ängelholm (GFÄ)

Figure 28 shows the distribution of rubber granulate in granulate traps at the sites Vingåker (GFV), Tyresö (GFT) and Ängelholm (GFÄ).

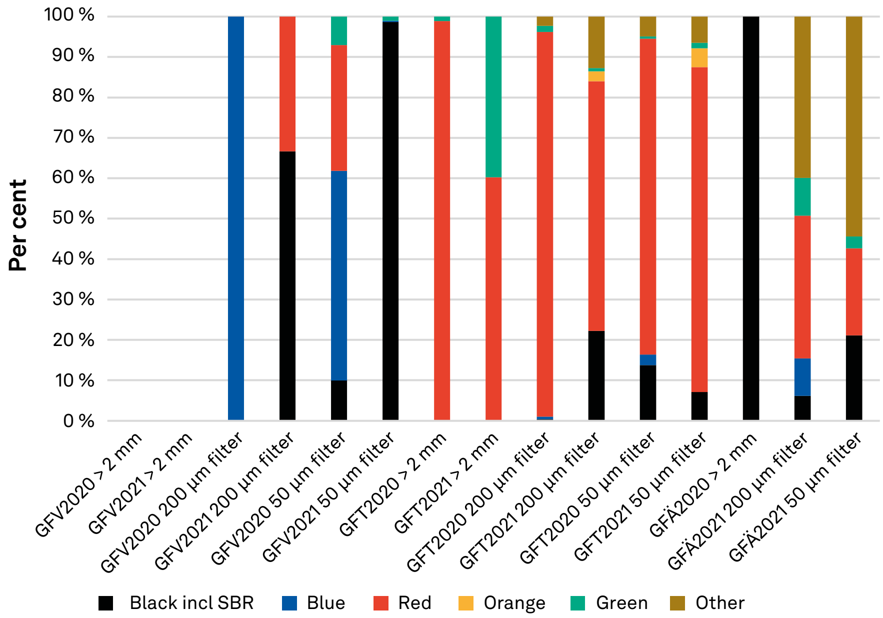


Figure 28. Rubber granulate in the granulate traps Vingåker (GFV), Tyresö (GFT) and Ängelholm (GFÄ)

Dispersion of microplastic from surfaces with cast rubber granulate and artificial grass without granulate

Sampling of washing water from studied surfaces gives a concentration of microplastic in the analysed samples per litre of washing water. To estimate the dispersal of microplastics per area unit and time unit from these surfaces, we recalculated the water concentrations according to the estimation assumptions about the sampling area and particle weight described in the method chapter. In this calculation, we include plastic particles that may originate from the sampled surface, where black SBR granulate can form part of the artificial grass construction, while different coloured granulate particles can be assumed to be external contamination. All rubber granulates are included for the granulate surfaces, while plastic fragments are assumed to be external contamination. Results are shown in Table 7 for the artificial grass areas and Table 8 for the granulate areas. The results show the dispersal in average value per sampling site, which consists of one or two shorter intervals between both autumn and spring samplings and a longer interval over the winter. As can be seen, there are large variations, and these figures must be interpreted with caution, as the statistical basis is small. The average dispersal of microplastic particles was 5.3 g/m^2/year for the granulate-free artificial grass surfaces and 13.4 g/m^2/year for the rubber granulate surfaces, see Table 7 and Table 8.

Table 7. Annual dispersion of plastic particles from granulate-free artificial grass surfaces.

	Artificial grass fibres 50 µm g/m^2 × year	Black SBR granulate 50 µm g/m^2 × year	Artificial grass fibres 300 µm g/m^2 × year	Black SBR granulate 300 µm g/m^2 × year	Total dispersion artificial grass surfaces g/m^2 × year
K1	0.13	1.54	0.64	0.05	2.35
K2	0.08	0.10	0.20	0.05	0.42
K3	0.14	0.01	0.22	0.05	0.42
K4	0.30	1.22	18.70	0.01	20.22
K5	0.32	1.56	1.08	0.13	3.09
Average	**0.19**	**0.89**	**4.17**	**0.06**	**5.30**

Table 8. Annual dispersion of granulate particles from granulate surfaces.

	Rubber granulate 50 µm g/m^2 × year	Rubber granulate 300 µm g/m^2 × year	Total dispersion granulate surfaces g/m^2 × year
G1	12.13	0.20	12.33
G6	5.40	0.14	5.55
G7	46.18	1.40	47.59
G8	0.52	0.04	0.56
G9	1.33	0.01	1.34
G10	11.15	2.00	13.15
Average	**12.79**	**0.63**	**13.42**

A corresponding calculation was performed for sediment in the five analysed drain filters, which assumed that all surface run-off from investigated areas led to these drains. The results are as shown in Table 9.

Table 9. Annual dispersion from artificial grass and granulate surfaces to drain filters.

	Artificial grass fibres 50 µm g/m² ×year	**Rubber granulate 50 µm** g/m² ×year	**Artificial grass fibres 200 µm** g/m² ×year	**Rubber granulate 200 µm** g/m² ×year	**Total dispersion to drain filters** g/m² ×year
GFV2020	0.00078	0.00006	0.02882	0.00003	0.03
GFV2021	0.00037	0.00033	0.04820	0.00003	0.05
GFT2020	0.07583	0.13645	0.61034	0.40190	1.22
GFT2021	0.04414	0.06330	0.55620	0.20762	0.87
GFÄ2021	0.01183	0.00050	0.10152	0.00033	0.11
Average	**0.03**	**0.04**	**0.27**	**SEK 0.12**	**0.46**

Uncertainties

All measurements include uncertainties. In this project, we investigated microplastic dispersion from several types of surfaces in different places in the country and over a limited time. We chose a measurement method that involved separating microplastics that were washed away from these surfaces and collected for analysis. Thus, the particles had not yet left the surface itself but only detached from it, and they could be transported further via several different dispersal pathways, such as water, snow, air and via users of these surfaces. The transport time also varies significantly. Naturally, microplastics that have come loose from a mound of cast rubber disperse faster to the environment than a fibre that has come loose in an artificial grass pitch. The cleaning machines' rinsing pressure and brushes are designed to not contribute to wear on the surfaces, but it cannot be ruled out that the washing itself can contribute to additional microplastics coming loose. The argument for washing the surfaces is, however, that this cleans out the pores, removes algae, etc. so that the surfaces have a longer life and function better, which leads to lower emissions of microplastics, less material use and reduced costs. For the samples to be as representative as possible, the tanks were cleaned before each washing cycle and the water in the tank was stirred vigorously before a 5-litre water sample was extracted and sent for analysis. However, rubber particles are relatively heavy, and a sludge often forms in the tank, making cleaning and homogenisation more difficult and, as such, contributing to uncertainty in the results.

Several aspects of the filtration and analyses of the samples in the lab also create uncertainties in the results. Some samples, which contained a lot of sediment or large amounts of green artificial grass fibres, were difficult to homogenise, making it more difficult to obtain a representative subsample for analysis. Several times, multiple subsamples were taken to reduce this uncertainty. Similarly, multiple subsamples were taken when the sample volume was considered low, usually at a sample volume of 11 ml or less. While small analysis volumes (down to 1 ml/water sample and 0.05 g/sediment sample) in relation to the original volumes in the cleaning tank and the granulate traps contribute to uncertainties in the results, larger volumes could not be passed through the filters. If the water suction is increased while filtering in a lab, the risk increases of capturing particles actually larger than the mesh size, as they are elastic. Several of the water samples from the cleaned rubber granulate surfaces contained large amounts of sediment. The sediment settles at the bottom of the tank together with the rubber granulate. When homogenising the samples, the tanks must first be shaken before the contents are poured into a 5-litre beaker placed on a magnetic stirrer. The rubber granulates are relatively fragile, and it cannot be ruled out that some fragmentation occurs during the homogenisation.

The analysis was performed by two individuals using two different stereomicroscopes. As the assessment is subjective, there is a certain individual variation in the analysis. To address this, careful comparisons and internal calibration were done, but obviously some variation may still occur. Particle colour can also cause some distortions in the results since brightly coloured particles (e.g., blue, red and yellow) are easier to detect than particles with a colour corresponding to natural minerals and organic particles (e.g., black, brown, green and transparent). This uncertainty is negatively correlated with size fraction and means that the number of particles with duller colour tones could be somewhat underestimated, especially in the smaller sizes.

The high magnification of the stereomicroscope (up to 135 times magnification) and advanced light settings still made it possible for analyses of particles down to 50 µm with sufficient certainty. The particles could be analysed with several different light settings and zooming in. In combination with the visual assessment, tactile assessment was also often performed using tweezers to get an idea of the particle's firmness. The rubber characteristic of the granulate particles was usually easy to identify in this way. In case of further uncertainty, melt tests were performed to determine the origin of the particle. Of course, the smaller particles on the 50 µm filters were more difficult to assess than the larger ones on the 300 µm filters, which is why there is greater uncertainty for these.

Some samples from rubber granulate surfaces had clusters of very small red particles. These were the same colour as the red rubber granulate and were therefore confusingly similar, but the particles were smaller than 50 µm and analyses indicated that they were of organic origin. They could possibly be algae. For samples with these clusters, both an overestimation of the number of red rubber granulate may occur, if the presumed organic particles were mistaken for rubber granulate, and an underestimation may occur if red rubber granulate ended up with the clusters of organic particles of the same colour and thus could not be discerned.

Small, black SBR particles can be visually very similar to black mineral grains but can be easily distinguished by tactile assessment, where mineral grains are hard to the touch and SBR particles are relatively soft. In samples with a lot of mineral particles and organic material on the 50 µm filters, however, there is a small risk that the number of SBR particles were underestimated, as there was not enough time to check all particles on a filter during the analysis.

The 50 µm filters from the rubber granulate surfaces occasionally had particles which, due to their shape and colour, were judged to be rubber granulate, but which were not as firm as a "classic" rubber granulate. The colour of these particles was often white/grey, white/pink or light turquoise, and their firmness can be compared to chewing gum and lacked the classic bounce-back effect. Fire tests showed that they were not of organic origin. In relation to the amount of "certain" rubber granulate, there were few of these particles. For this reason, they were included with other rubber granulate particles in the sample instead of placing them in a separate category.

Several transparent particles of unknown origin were identified in the early sample analyses from both rubber granulate surfaces and artificial grass pitches without rubber granulate. Fire tests showed that they were not of organic origin. Six fragments were selected and sent to ALS for analysis with FTIR. This analysis confirmed the conclusion of our own analyses. Two particles consisted of polyethylene (PE), one of polystyrene (PS), one of cellulose and two more could not be identified using the above method. Because the transparent particles were so numerous, were difficult to analyse and were not included in the original assignment, we decided to exclude them from analyses of other samples. It was also not possible to connect them to the investigated surfaces.

Discussion and conclusions

Microplastics, particularly nanoplastics, in sufficient concentrations can be hazardous to the health of living organisms. The degree of health hazard depends on the particle size, particle material, particle concentration, exposure time, pathway of exposure (e.g., inhalation, ingestion or exposure through the skin) and the recipient's (organism or person) age, sex and health status. Levels of micro- and nanoplastics in Sweden's drinking water are very low, but the precautionary principle should still prevail when installing surfaces that can potentially generate microplastics that can be leaked to nature. When ordering fall protection surfaces and sports facilities, there are often conflicting interests between parameters, such as price, availability, service life, play properties, fall protection properties, maintenance needs, recyclability, climate properties, emission of microplastics and chemical content. For example, recycled materials tend to have good climate properties, while newly manufactured materials usually have a more well-controlled chemical content. A good balance between all these goals should be sought.

The most common granulate materials used in rubber fall protection in existing playgrounds are styrene-butadiene rubber (SBR), which usually comes from recycled vehicle tyres, and ethylene-propylene-diene rubber (EPDM), which is usually newly manufactured. Other materials are also used, such as cork, expanded polyethylene and expanded thermoplastic polyurethane. The rubber granulates are bound together with polyurethane-based adhesive. Recycled SBR has a low climate impact but often contains higher levels of PAHs (polyaromatic hydrocarbons) than is permitted under the EU Toy Safety Directive. For this reason, recycled rubber should be avoided, if possible, as a surface layer on playgrounds. Running tracks and similar sports facilities usually use granulate of EPDM or polyurethane (PUR). In granulate-free artificial grass, the grass fibre usually consists of polyethylene (PE), polypropylene (PP), Nylon (PA6) or Polyester (e.g., PET), while the backing onto which the grass fibre is attached usually consists of PUR, natural rubber (latex), PP, PE or PA6.

All synthetic materials currently found in fall protection surfaces, artificial grass and sports tracks can break down into microplastics over time and risk dispersion in nature. The most effective way to minimise emissions of microplastics from playgrounds and similar places is to use natural materials, such as sand, gravel, bark or wood chips, instead of artificial materials whenever possible from an accessibility perspective. Natural materials are also often, but not always, better from a climate perspective compared with newly manufactured artificial materials. A suggestion when using sand is that it is better from a climate perspective to occasionally wash the sand than to regularly dispose of it and buy new sand.

Synthetic materials, however, also have their advantages, including durability, able to be manufactured in imaginative shapes and colours, being quite cheap, being good from an accessibility perspective, having a long service life and sometimes requiring less maintenance than certain natural materials. Using smart approaches to installing facilities and regular maintenance, microplastic emissions from rubber and artificial grass surfaces can be reduced significantly. When installing these surfaces, especially those with cast rubber granulate, it is important to ensure a stable and well-drained surface, that the edges of the surface are firmly attached with a solid divider, that the installation temperature is sufficiently high, that the amount of binder is appropriate, and that there is not a risk of unnecessary amounts of sand, gravel, leaves and other debris coming into contact with the surface. During maintenance, surfaces should be regularly cleaned/swept/blown and occasionally also washed and repaired. After a thorough washing, the amount of loose microplastics on the granulate surfaces decreases significantly. However, the washing water contains high levels of microplastics that should be disposed of appropriately, which rarely happens today. Technology to do this still needs to be developed. Also note that some granulate-free artificial grass surfaces release about 50 times more microplastics than others, which is why it is important to be able to identify these surfaces. Standardised methodology needs to be developed, e.g., by using measuring instruments which in their simplest form consist of a dynamometer that is attached to a grass fibre. A grass fibre is then pulled on until it comes off or detaches from the backing, providing a measurement of how durable the carpet is for mechanical wear. The artificial grass fibres probably come off from the carpet due to failing glue, but this should be examined. To gain a good description of the status of the carpet, this should be done on several grass fibres in a grid over the entire surface.

The three analysis methods show that, in 2020, the total area of outdoor rubber granulate in Sweden in playgrounds was approximately 550,000 m^2 and approximately 650,000 m^2 in sports facilities. For playgrounds, the values were produced through a combination of map analysis and analysis of data from municipalities and playground facilities. The three methods gave surprisingly consistent results (560,000, 540,000 and 520,000 m^2) despite many sources of error. For sports facilities, the area estimate primarily used map analysis. As a comparison, it can be mentioned that, according to the Swedish Football Association, there are 1,084 football pitches with rubber granulate infill in Sweden, with a total area of 6.9 km^2. This project did not estimate the total area of artificial grass pitches without granulate, and since this information is lacking, we can also not estimate total dispersion from these areas.

Sampling and analysis of microplastic dispersal from cast rubber surfaces and artificial grass surfaces without granulate are methodologically very difficult to do cost-effectively in several places in a short time, which were the criteria for this project. We think, however, that the chosen method with cleaning machines worked relatively well and the sampling went according to plan. On the other hand, the analyses have been very challenging and time-consuming as, unlike the previous project (Krång, et al. 2019), we also analysed fibres found in balls that had to be pulled apart carefully so that the analysis did not affect the number of particles. The water analyses show that microplastic dispersion varies greatly from surface to surface and results from surfaces not previously cleaned are difficult to interpret. We cannot draw conclusions from our data regarding how dispersal is affected by material type, facility, use, etc. However, we find the most artificial grass fibre in larger fractions compared with the smaller ones, while the opposite is true for the granulate surfaces, which have a significantly higher concentration of microplastic in the 50 µm filter compared with the 300 µm filter. For rubber surfaces, we see a general decreasing concentration of microplastic from repeated washing, which indicates that this can be a good method for reducing the leakage of microplastic from these surfaces if the washing water is treated in a sustainable manner. However, we see no such correlation for artificial grass surfaces.

Microplastic emissions (per m^2 and year) for surfaces with rubber granulate and granulate-free artificial grass were almost on par with those from motorways, but lower than those from artificial grass with infill (Järlskog, et al. 2020), (Krång, et al. 2019). Dispersion from artificial grass with infill, however, varies greatly depending on care, protective measures, use, assumptions, etc. (Krång, et al. 2019), (Regnell, 2019). Note, however, that some artificial grass surfaces even without granulate can leak more microplastic than the proposed limit of 7 g/m^2 × year that the European Chemicals Agency (ECHA) is now discussing for artificial grass with granulate (ECHA, 2020).

Table 10. Comparison of potential microplastic dispersion from different surfaces.

Surface	g/m^2 × year	tonnes/year	Source
Artificial grass with granulate	98	6.9 km^2 × 98 g/m^2/year = 676 tonnes/year	(Krång, et al. 2019)
Artificial grass surfaces without granulate	0.4–20	0.45[2] km^2 × 5.3 g/m^2/year = 2.4 tonnes/year	(Krång, et al. 2019) , this study
Rubber surfaces	0.6–48	1.2 km^2 × 13.4 g/m^2/year = 16 tonnes/year	This study
Roads (5,500–13,000 vehicles/day)	56	8,190	(Järlskog, et al. 2020), (Magnusson, et al. 2016)

Unfortunately, we had difficulty finding good stormwater drains to measure close to the studied artificial grass and rubber surfaces. However, from a dispersal perspective, it is positive that stormwater drains are not located close to these surfaces. Instead, dome drains should be used at low points on a nearby grass surface to minimise dispersal of microplastic to aquatic environments. It is preferable to avoid open drains near this type of surface completely. The measurements shown in Table 9 indicate that a smaller proportion of microplastics from these surfaces is dispersed via stormwater. However, the data is not sufficient to make general statements. The measurement drain excluded from the study because it was obviously intentionally filled with sand and granulate still shows the benefit of having granulate traps in highly exposed settings, but it is important that these are maintained and emptied regularly to avoid adverse effects to the drains and filters.

Other dispersal pathways, such as air and users of these surfaces, have not been investigated in this project. We did, however, consider it clear that most of the microplastics that came loose from surfaces remained on these or in the local environment, such as in grass areas. We do not know if the microplastics will eventually break down into more mobile nanoplastics, though this is likely, even if the process is slow as the rubber and plastic materials are durable.

[2] (Krång, et al. 2019) report surface artificial grass without granulate for 15 municipalities with 33 % of Sweden's population. To estimate the national total dispersion of microplastics, we assume the same surface of artificial grass without granulate per capita throughout the country.

Recommendations

The potential microplastic emissions from rubber granulate surfaces and surfaces with granulate-free artificial grass are relatively small compared with emissions from road traffic and from artificial grass with infill, but they are still far from negligible and are relatively easy to remedy since the surfaces are well defined. Based on the project's results and accumulated experience, we provide the following overall advice for reducing the leakage of microplastics from cast rubber surfaces and artificial grass pitches without granulate:

- The design and construction of rubber surfaces should be based on site-specific conditions and the recommendations of this project for granulate materials, adhesives, substrates, surroundings and design.
- If possible, use reliable stormwater management by avoiding open street drains near these surfaces. Using infiltration surfaces or dome drains in green areas can reduce dispersal to aquatic environments.
- Protective measures like drain filters can be reasonable in exposed areas but require regular inspection and maintenance. If several street drains around an artificial grass pitch are connected to a collection drain, it is normally better to put a filter in the outlet from the collection drain than granulate traps in each drain, since the collection drain has a sedimentation well and this solution will be more reliable and requires less maintenance.
- Well-designed and well-maintained granulate-free artificial grass pitches have good potential to meet the proposed EU threshold value for dispersion of granules of 7 g/m^2.
- Inspection of function and maintenance are very important so that surfaces are checked, cleaned and repaired as soon as possible when they are damaged. When there is a hole in the EPDM layer of a fall protection surface, underlying granules begin to rapidly spread. In the same way, deteriorating artificial grass pitches, where grass fibres begin to fall off from the carpet, need to be quickly identified. An SIS standard should be developed for this purpose.
- "Vacuuming" these surfaces is recommended instead of using leaf blowers to avoid the dispersal of microplastics. Wet cleaning can be an effective measure both in removing microplastics and in extending the life of the surfaces, primarily for rubber surfaces, if the washing water is treated in a sustainable way. Collected microplastic should be sent for incineration.
- Always consider natural materials or other more sustainable solutions.

Areas needing further investigation

There are still several knowledge gaps in this field of research that future studies should investigate in more detail. Here are the main ones:

- Some granulate-free artificial grass pitches shed significantly more artificial grass fibres than others (approx. 50 times more). It is crucial to identify why these pitches are so much worse and address the issue. The adhesive binding the grass fibres to the carpet (the backing) is probably failing in certain types of artificial grass pitches, but this needs to be established. Bad adhesives should be phased out, unless they have significant advantages over other solutions.
- Methodology should be developed to identify artificial grass with insufficient adhesion. A simple measuring instrument could be constructed by attaching the end of a dynamometer to a grass fibre and pulling until it comes loose or breaks off. This will provide a measure of the force required to pull off the grass fibre. By doing this for several fibres in a grid over the entire surface, an average value can be compared with a suitable threshold value.
- It is difficult to design granulate-free artificial grass surfaces that provide a high quality play experience. Many kinds of alternative bio-based granulate infills exist, but there is still no systematic compilation of the advantages and disadvantages of these from all sustainability aspects and functions.
- When washing surfaces with rubber granulate, most loose microplastic particles accumulate in the washing water. At present, however, there are no effective ways of treating this washing water. An appropriate method for doing this is needed.

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Annex 1 – Sampling sites for rubber surfaces

Sandbäck School, Sjöbo

Site name	Sandbäck School, Sjöbo		
Site designation	G1		
Surface type	Running track cast rubber		
	North	**East**	
Coordinates (lat./long. WGS 84)	55.3759	13.4141	
Surface area [m^2]	73×3 = 222		
Age of surface [years]	?		
Most recent cleaning [date]	Probably never		
Wear level	Major damage at the end of the track		
Demonstrated dispersal of microplastic	Nothing visible, but since there is a lot of rubber missing due to the damage, it should have dispersed a lot		
Utilisation	Frequently used by children during school hours and during after school activities		
Closest stormwater drain	0.5 m. Only hard surface in between		
Type of stormwater drain	Pipe diameter 395 with grate cover		
Sampling date	13 August 2020		
Sample taken by	Mats Svensson, Sandmaster Skandinavien AB		
Sampling conditions	Dry and sunshine		
The cleaned surface area [m^2]	222		
Cleaning pressure	200		
Sample volume [l]	10		
Total water volume when sampling volume [l]	250		
Sample label	Sjöbo 1		

Figure 29. Photos taken before and after cleaning.

Lagman Lekares väg 14–34, Norsborg

Site name	Spinning swing, Norsborg	
Site designation	G2	
Surface type	Spinning swing cast rubber	
	North	**East**
Coordinates (lat./long. WGS 84)	59.141	17.5025
Surface area [m²]	39	
Age of surface [years]	?	
Most recent cleaning [date]	Probably never	
Wear level	No damage	
Demonstrated dispersal of microplastic	None visible	
Utilisation	Frequently used by children during after school activities	
Closest stormwater drain	No drain in the area	
Type of stormwater drain		
Sampling date	27 August 2020	
Sample taken by	Mats Svensson, Sandmaster Skandinavien AB	
Sampling conditions	Dry and sunshine	
The cleaned surface area [m²]	39	
Cleaning pressure	200	
Sample volume [l]	5	
Total water volume when sampling volume [l]	250	
Sample label	Spinning swing Lagman Lekares väg 14–34	

Figure 30. Photo taken after cleaning.

Lagman Lekares väg 17–25, Norsborg

Site name	Basket al. court, Norsborg	
Site designation	G3	
Surface type	Basket al. court, Norsborg	
	North	**East**
Coordinates (lat./long. WGS 84)	59.1415	17.5025
Surface area [m²]	73×14.3 = 143	
Age of surface [years]	?	
Most recent cleaning [date]	Probably never	
Wear level	No direct visible damage	
Demonstrated dispersal of microplastic	None visible	
Utilisation	Frequently used by children during after school activities	
Closest stormwater drain	none nearby	
Type of stormwater drain		
Sampling date	28 August 2020	
Sample taken by	Mats Svensson, Sandmaster Skandinavien AB	
Sampling conditions	Dry and sunshine	
The cleaned surface area [m²]	143	
Cleaning pressure	200	
Sample volume [l]	5	
Total water volume when sampling volume [l]	250	
Sample label	Basket al. court Lagman Lekares väg 17–25	

Figure 31. Photos taken before and after cleaning.

Lagfartsvägen 12, Norsborg

Site name	Norsborg	
Site designation	G4	
Surface type	Slide cast rubber	
	North	**East**
Coordinates (lat./long. WGS 84)	59.144	17.5039
Surface area [m²]	8×9 = 72	
Age of surface [years]	?	
Most recent cleaning [date]	Probably never	
Wear level	Normal wear	
Demonstrated dispersal of microplastic	None visible	
Utilisation	Frequently used by children during after school activities	
Closest stormwater drain	None nearby	
Type of stormwater drain		
Sampling date	28 August 2020	
Sample taken by	Mats Svensson, Sandmaster Skandinavien AB	
Sampling conditions	Dry and sunshine	
The cleaned surface area [m²]	72	
Cleaning pressure	200	
Sample volume [l]	5	
Total water volume when sampling volume [l]	250	
Sample label	Slide Lagfartsvägen 12	

Figure 32. Photo taken before cleaning.

Lagman Lekares väg 14–34, Norsborg

Site name	Spinning swing, Norsborg		
Site designation	G2		
Surface type	Spinning swing cast rubber		
	North	**East**	
Coordinates (lat./long. WGS 84)	59.141	17.5025	
Surface area [m²]	39		
Age of surface [years]	?		
Most recent cleaning [date]	Probably never		
Wear level	No damage		
Demonstrated dispersal of microplastic	None visible		
Utilisation	Frequently used by children during after school activities		
Closest stormwater drain	No drain in the area		
Type of stormwater drain			
Sampling date	27 August 2020		
Sample taken by	Mats Svensson, Sandmaster Skandinavien AB		
Sampling conditions	Dry and sunshine		
The cleaned surface area [m²]	39		
Cleaning pressure	200		
Sample volume [l]	5		
Total water volume when sampling volume [l]	250		
Sample label	Spinning swing Lagman Lekares väg 14–34		

Figure 33. Photos taken before and after cleaning.

Brevik Preschool, Tyresö

Site name	Nytorpsvägen 32, Brevik School	
Site designation	G6	
Surface type	Swing set/Slide cast rubber	
	North	**East**
Coordinates (lat./long. WGS 84)	59.1346	18.1959
Surface area [m²]	112	
Age of surface [years]	?	
Most recent cleaning [date]	8 September 2020	
Wear level	normal wear, no damage	
Demonstrated dispersal of microplastic		
Utilisation	Frequently used by children during school hours	
Closest stormwater drain	1.5 m. Only hard surface in between	
Type of stormwater drain		
Sampling date	12 October 2020	
Sample taken by	Mats Svensson, Sandmaster Skandinavien AB	
Sampling conditions	11 degrees, some clouds	
The cleaned surface area [m²]	50	
Cleaning pressure	200	
Sample volume [l]	5	
Total water volume when sampling volume [l]	250	
Sample label	Brevikskolan Swing/slide	

Figure 34. Photo taken before and during cleaning. Filter installed in drain.

Brevik School, Tyresö

Site name	Nytorpsvägen 32, Brevik School	
Site designation	G7	
Surface type	Buddy swing cast rubber	
	North	**East**
Coordinates (lat./long. WGS 84)	59.1346	18.201
Surface area [m²]	37.5	
Age of surface [years]	?	
Most recent cleaning [date]	Probably never	
Wear level	normal wear, no damage, lots of loose granulate on the surface and around the entire play area	
Demonstrated dispersal of microplastic		
Utilisation	Frequently used by children during school hours	
Closest stormwater drain	1.7 m. Only hard surface in between	
Type of stormwater drain		
Sampling date	8 September 2020	
Sample taken by	Mats Svensson, Sandmaster Skandinavien AB	
Sampling conditions	Dry and sunshine	
The cleaned surface area [m²]	37.5	
Cleaning pressure	200	
Sample volume [l]	5	
Total water volume when sampling volume [l]	250	
Sample label	Brevik School buddy swing	

Figure 35. Photo taken before cleaning. Granulate filter placed in nearby drain.

Dalavägen 5–7, Slättåkra, Halmstad

Site name	Spring swing, Dalavägen 5–7	
Site designation	G8	
Surface type		
	North	**East**
Coordinates (lat./long. WGS 84)	56.8257	12.8833
Surface area [m^2]	20	
Age of surface [years]	?	
Most recent cleaning [date]	Probably never	
Wear level	normal wear, slightly damaged	
Demonstrated dispersal of microplastic		
Utilisation	Normally used play area in the courtyard	
Closest stormwater drain		
Type of stormwater drain		
Sampling date	21 September 2020	
Sample taken by	Mats Svensson, Sandmaster Skandinavien AB	
Sampling conditions	Dry	
The cleaned surface area [m^2]	20	
Cleaning pressure	200	
Sample volume [l]	5	
Total water volume when sampling volume [l]	175	
Sample label	Dalavägen 5–7	

Figure 36. Photo taken before cleaning.

Klockarevägen 63, Getinge, Halmstad

Site name	Jungle gym, Klockarevägen 63		
Site designation	G9		
Surface type			
	North	**East**	
Coordinates (lat./long. WGS 84)	56.8184	12.7428	
Surface area [m²]	40		
Age of surface [years]	?		
Most recent cleaning [date]	Probably never		
Wear level	Worn but no direct damage		
Demonstrated dispersal of microplastic			
Utilisation	Playground in inner courtyard		
Closest stormwater drain			
Type of stormwater drain			
Sampling date	21 September 2020		
Sample taken by	Mats Svensson, Sandmaster Skandinavien AB		
Sampling conditions	14 degrees, cloudy		
The cleaned surface area [m²]	40		
Cleaning pressure	200		
Sample volume [l]	5		
Total water volume when sampling volume [l]	250		
Sample label	Klockarevägen 53		

Figure 37. Photos taken before and after cleaning.

Getakärr playground, Varberg

Site name	Playhouse, Getakärr's playground	
Site designation	G10	
Surface type		
	North	**East**
Coordinates (lat./long. WGS 84)	57.112529	12.254260
Surface area [m²]	57	
Age of surface [years]	Only information available: built before 2015	
Most recent cleaning [date]	Probably never	
Wear level	Normal wear. Located on top of a gravel surface, a lot of gravel has been pulled into the rubber. Wide joints between the rubber	
Demonstrated dispersal of microplastic		
Utilisation	Frequently used by children during school hours and during after school activities	
Closest stormwater drain		
Type of stormwater drain		
Sampling date	23 October 2020	
Sample taken by	Mats Svensson, Sandmaster Skandinavien AB	
Sampling conditions	Slightly cloudy, 11 degrees	
The cleaned surface area [m²]	57	
Cleaning pressure	200	
Sample volume [l]	5	
Total water volume when sampling volume [l]	250	
Sample label	Getakärr's playground	

Figure 38. Photos taken before and after cleaning.

Ymergatan 32–38, Märsta

Site name	Ymergatan 32–38	
Site designation	G11	
Surface type		
	North	**East**
Coordinates (lat./long. WGS 84)	59.620141	17.822444
Surface area [m²]	18	
Age of surface [years]		
Most recent cleaning [date]	Probably never	
Wear level	normal wear	
Demonstrated dispersal of microplastic		
Utilisation	Normally used play area in courtyard	
Closest stormwater drain		
Type of stormwater drain		
Sampling date	13 October 2020	
Sample taken by	Mats Svensson, Sandmaster Skandinavien AB	
Sampling conditions	6 degrees, some clouds	
The cleaned surface area [m²]	18	
Cleaning pressure	200	
Sample volume [l]	5	
Total water volume when sampling volume [l]	175	
Sample label	Ymergatan 32–38	
IVL project number	713999	

Figure 39. Photos taken after cleaning.

Magnegatan 8–12, Märsta

Site name	Swing set, Magnegatan 8–12		
Site designation	G12		
Surface type			
	North	**East**	
Coordinates (lat./long. WGS 84)	59.620441	17.819251	
Surface area [m²]	152.2		
Age of surface [years]			
Most recent cleaning [date]	probably never		
Wear level	normal wear		
Demonstrated dispersal of microplastic			
Utilisation	Normally used play area in the courtyard		
Closest stormwater drain			
Type of stormwater drain			
Sampling date	13 October 2020		
Sample taken by	Mats Svensson, Sandmaster Skandinavien AB		
Sampling conditions	6 degrees, some clouds		
The cleaned surface area [m²]	152.2		
Cleaning pressure	200		
Sample volume [l]	5		
Total water volume when sampling volume [l]	250		
Sample label	Magnegatan 8–12		

Grevhag School, Eksjö

Site name	Swings and jungle gym, Lustigkullegatan 1		
Site designation	G13		
Surface type			
	North	**East**	
Coordinates (lat./long. WGS 84)	57.659325	14.972040	
Surface area [m²]	106		
Age of surface [years]			
Most recent cleaning [date]	probably never		
Wear level	normal wear		
Demonstrated dispersal of microplastic			
Utilisation	Used daily, located at a school.		
Closest stormwater drain			
Type of stormwater drain			
Sampling date	14 October 2020		
Sample taken by	Mats Svensson, Sandmaster Skandinavien AB		
Sampling conditions	7 degrees, cloudy		
The cleaned surface area [m²]	106		
Cleaning pressure	200		
Sample volume [l]	5		
Total water volume when sampling volume [l]	250		
Sample label	Lustigkullegatan 1		

Annex 2 – Sampling sites for granulate-free artificial grass pitches

Sunnansjö School, Ludvika

Site name	Sunnansjö School	
Site designation	K1	
Surface type	Multisport pitch (artificial grass with sand)	
	North	**East**
Coordinates (lat./long. WGS 84)	14.5737	14.5737
Surface area [m²]	18×36 = 648	
Age of surface [years]	3	
Most recent cleaning [date]	probably never	
Wear level	Two decimetre-large holes in the artificial grass pitch	
Demonstrated dispersal of microplastic		
Utilisation	Frequently used by children during school hours and during after school activities for football and play	
Closest stormwater drain		
Type of stormwater drain		
Sampling date	18 August 2020	
Sample taken by	Mats Svensson, Sandmaster Skandinavien AB	
Sampling conditions	Sunshine and dry	
The cleaned surface area [m²]	648	
Cleaning pressure	45 bar	
Sample volume [l]	10	
Total water volume when sampling volume [l]	350	
Sample label	Sunnansjö School 1	

Facility also sampled 22 September 2020.

Figure 40. Photo taken before cleaning.

Lagman Lekares väg 14–34, Norsborg

Site name	Lagman Lekares väg 14–34, Norsborg	
Site designation	K2	
Surface type	Multisport pitch (artificial grass with sand)	
	North	**East**
Coordinates (lat./long. WGS 84)	59.141	17.5036
Surface area [m²]	20×13.4 = 268	
Age of surface [years]		
Most recent cleaning [date]	probably never	
Wear level	Larger piece of artificial grass loose about 4 m × 60 cm	
Demonstrated dispersal of microplastic		
Utilisation	Frequently used by children during after school activities for football and play	
Closest stormwater drain	No drain nearby	
Type of stormwater drain		
Sampling date	25 August 2020	
Sample taken by	Mats Svensson, Sandmaster Skandinavien AB	
Sampling conditions	Dry and sunshine	
The cleaned surface area [m²]	268	
Cleaning pressure	45 bar	
Sample volume [l]	5	
Total water volume when sampling volume [l]	350	
Sample label	Small Multiarena Lagman Lekares väg 14–34	

The facility also sampled 30 September 2020.

Figure 41. Photo taken before and during sampling.

Lagman Lekares väg 17–25, Norsborg

Site name	Lagman Lekares väg 17–25, Norsborg	
Site designation	K3	
Surface type	Multisport pitch (artificial grass with sand)	
	North	**East**
Coordinates (lat./long. WGS 84)	59.1416	17.5027
Surface area [m²]	21.1×32.8 = 692.1	
Age of surface [years]		
Most recent cleaning [date]	26 August 2020	
Wear level	Normal wear	
Demonstrated dispersal of microplastic		
Utilisation	Frequently used by children during after school activities for football and play	
Closest stormwater drain	No drain nearby	
Type of stormwater drain		
Sampling date	30 September 2020	
Sample taken by	Mats Svensson, Sandmaster Skandinavien AB	
Sampling conditions	17 degrees, light cloud cover	
The cleaned surface area [m²]	692.1	
Cleaning pressure	45 bar	
Sample volume [l]	5	
Total water volume when sampling volume [l]	350	
Sample label	Multiarena Lagman Lekares väg 17–25	

Figure 42. Photo taken before sampling.

Kungsgård School, Ängelholm

Site name	Kungsgårdshallen, Ängelholm		
Site designation	K4		
Surface type	Multisport pitch (artificial grass with sand)		
	North	**East**	
Coordinates (lat./long. WGS 84)			
Surface area [m²]	40×20 = 800 m²		
Age of surface [years]			
Most recent cleaning [date]	1 May 2018		
Wear level	High wear, lots of loose fibres		
Demonstrated dispersal of microplastic			
Utilisation	Frequently used by children during after school activities and school hours for football and play		
Closest stormwater drain	About 4 m to the nearest drain with an asphalt substrate		
Type of stormwater drain			
Sampling date	2 September 2020		
Sample taken by	Mats Svensson, Sandmaster Skandinavien AB		
Sampling conditions	Sunshine and dry		
The cleaned surface area [m²]	800		
Cleaning pressure	35 bar		
Sample volume [l]	5		
Total water volume when sampling volume [l]	400		
Sample label	Kungsgårdshallen		

Facility also sampled on 13 October 2021.

Figure 43. Photos taken before and after cleaning the pitch.

Vingåker

Site name	Västergatan 3, Vingåker	
Site designation	K5	
Surface type	Multisport pitch (artificial grass with sand)	
	North	**East**
Coordinates (lat./long. WGS 84)	59.0352	15.8668
Surface area [m^2]	19×11 = 209 m^2	
Age of surface [years]		
Most recent cleaning [date]	Probably never	
Wear level	Worn but no damage	
Demonstrated dispersal of microplastic		
Utilisation	Frequently used by children during after school activities for football and play	
Closest stormwater drain	About 4 m to the nearest drain with an asphalt substrate	
Type of stormwater drain		
Sampling date	3 September 2020	
Sample taken by	Mats Svensson, Sandmaster Skandinavien AB	
Sampling conditions	Sunshine and dry	
The cleaned surface area [m^2]	209	
Cleaning pressure	35 bar	
Sample volume [l]	5	
Total water volume when sampling volume [l]	400	
Sample label	Vingåker	

Figure 44. Sampling drain at multisport pitch.

Annex 3 – Closer examination of polymeric materials

Overview

Polymers are macromolecular materials where simple chemical structures, so-called repeating units, are joined together into long chains (Gedde & Hedenqvist, 2019). Most polymers consist mainly of hydrocarbons. All synthetic plastics, rubbers and textile fibres are polymers, but natural materials like cellulose, DNA and proteins are also (bio) polymers. Many plastics, such as polyethylene, can be made either from petroleum products or from renewable raw materials, such as ethanol (Gedde et al. 2021). In both cases, basically the same kind of plastic is formed, with all its pros and cons. Most plastics are durable and degrade very slowly in nature, but some polymers are degradable, in the sense that they decompose relatively quickly under the right external conditions. Degradation can occur thermally, mechanically, biologically, chemically or physically (SAPEA, 2020). It has not yet been fully determined which degradable polymers degrade completely and which form long-lasting nanoplastics. Macroplastics that degrade usually form microplastics, but their lifespan and toxicity vary widely depending on the material and degradation mechanism. Intensive research is underway in this area (Magalhaes et al. 2020), (Haider et al. 2019), (Straub, Hirsch, & Burkhardt-Holm, 2017), (Pico, Alfarhan, & Barcelo, 2019), (Tiwari, Santhiya, & Gopal Sharma, 2020), (Wang, et al. 2021).

All polymers that occur in fall protection contexts are either plastics, elastomers (rubbers) or textile fibres. The plastics can be further divided into thermoplastics and thermoset plastics, the elastomers into natural rubber, synthetic rubber and thermoplastic elastomers, and the textile fibres into synthetic fibres and natural fibres (Figure 45).

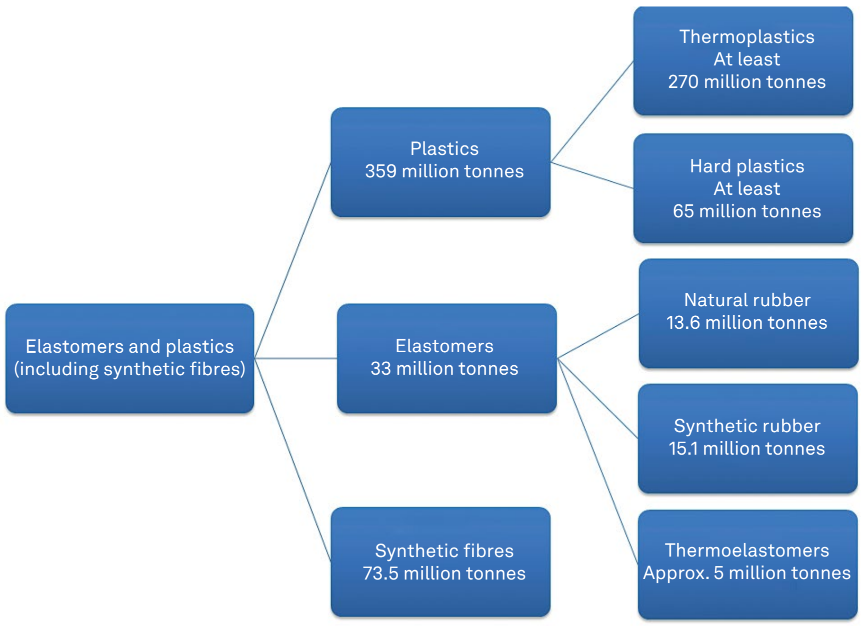

Figure 45. Global production of elastomers (Levin N, 2018) and plastics in 2018 (Statista, 2020d).

World production of plastic has increased sharply in recent decades (1.5 million tonnes in 1950 to 359 million tonnes in 2018) (Statista, 2020a) (Figure 46). Rubber (18 million tonnes in 2000 to 29 million tonnes 2019) ((Statista, 2020b) and synthetic fibre production (11 million tonnes in 1975 to 80 million tonnes 2019) (Statista, 2020c) have also increased. For historical reasons, synthetic fibres are usually reported separately from other plastics, despite being chemically the same material. Of global production of textile fibres in 2019, synthetic fibres made up about 76 % (mainly polyester/PET and some nylon, polypropylene and acrylic) and natural fibres 24 % (mainly cotton and some wool and cellulose-based fibres) (Statista, 2020c). The difference between plastic and rubber (and other elastomers) is that elastomers can be stretched several times their original length and still regain their original shape when the tension is removed, while plastics are permanently deformed (= plasticised) if they are stretched more than a few per cent (Gedde & Hedenqvist, Fundamental Polymer Science, 2nd ed., 2019).

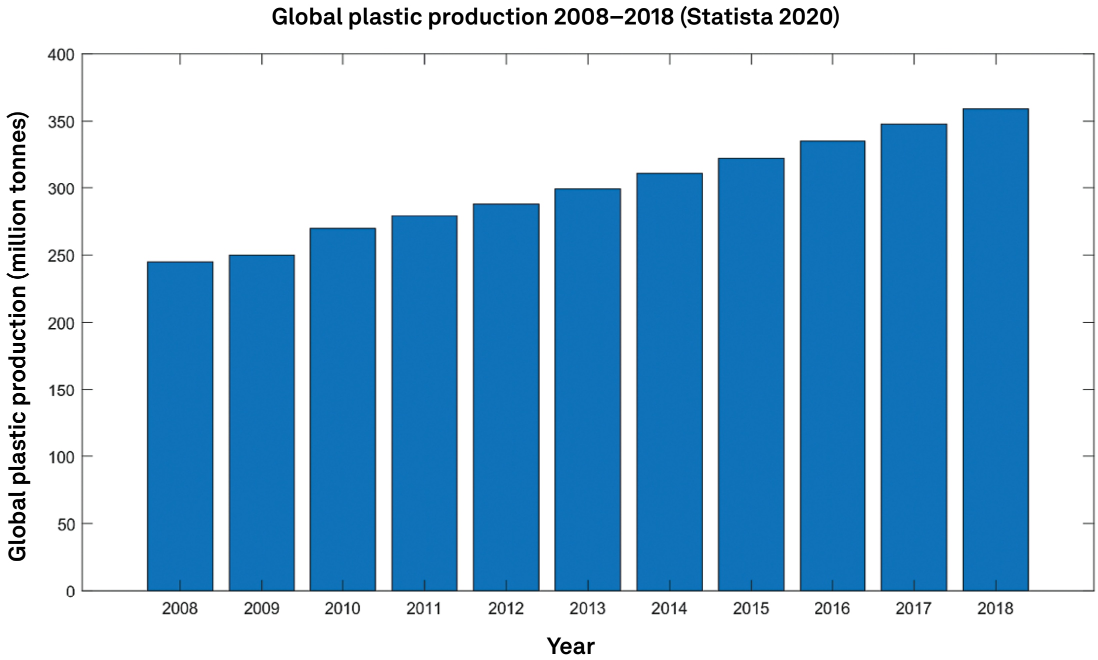

Figure 46. Global production of plastic 1950–2018 (Statista, 2020a).

The material group plastics (335 million tonnes 2016) can be divided into thermoplastics (270 million tonnes 2016) and thermoset plastics (65 million tonnes 2016) (Levin & Mårtensson, 2018). Thermoplastics melt when heated and can then be transformed into new geometric shapes. Once they are then cooled and harden, they regain in principle their previous material characteristics. This makes many thermoplastics easy to recycle. Thermoset plastics, on the other hand, do not melt when heated, which makes them more thermally stable but more difficult to recycle. The two most common thermoplastics, the semi-crystalline polyolefins polyethylene (PE, LDPE, HDPE) and polypropylene (PP), make up just over half of total global plastic production (Statista, 2020d). Polyvinyl chloride (PVC), polystyrene (PS), and polyethylene terephthalate (PET) make up about a quarter and other plastics the remaining quarter, see Figure 47.

Global plastic production 2018 (total 359 million tonnes) (Statista 2020d)

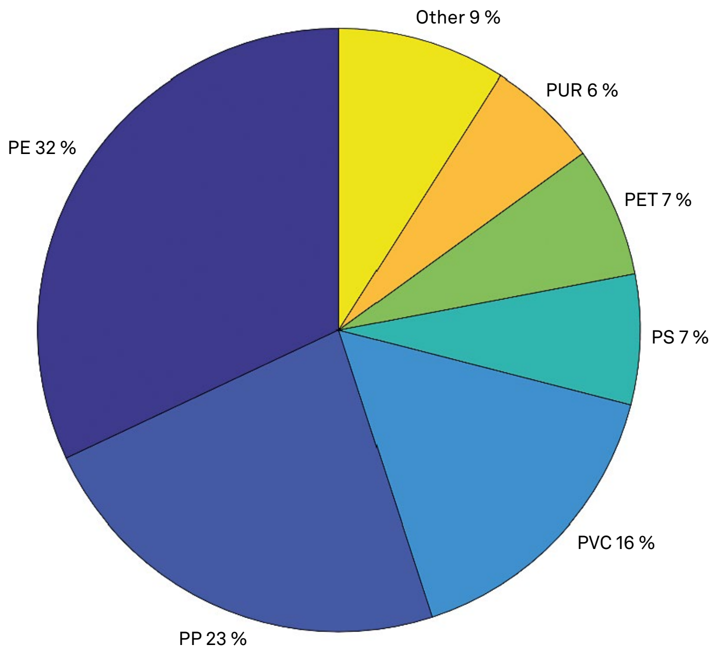

Figure 47. Global plastic production 2018 (total 359 million tonnes) by plastic type (Statista, 2020d).

The material group elastomers (33 million tonnes 2017) can be divided into rubbers (28 million tonnes 2017) and thermoplastic elastomers (5 million tonnes 2017) (Levin & Mårtensson, 2018). Rubber consists of long, tangled polymer chains that are crosslinked through vulcanisation, often with sulphur. It can often be stretched 6–8 times its original length without permanent deformation. When rubber is heated, it can not be easily melted and reshaped into a new shape due to its crosslinks, making it often difficult to recycle, provided that the existing material cannot be given a new use. For example, old car tyres can be granulated and used as shock absorption in granulate-filled artificial grass pitches and in fall protection surfaces with cast rubber granulate. Almost half (13.3 million tonnes 2016) of all rubber annually produced globally consists of natural rubber (NR), which is tapped in the form of latex from the rubber tree *Hevea Brasiliensis* and about a quarter (6.5 million tonnes 2016) consists of styrene-butadiene rubber (SBR), which is manufactured synthetically from petroleum (Levin & Mårtensson, 2018). Other important rubbers are butadiene rubber (BR), butyl rubber (IIR), isoprene rubber (IR) (a synthetic natural rubber), ethylene propylene diene monomer rubber (EPDM), chloroprene rubber (CR) and nitrile butadiene rubber (NBR) (SGF, 1996). More than half of all newly produced rubber is used for vehicle tyres. Thermoplastic elastomers (TPE) are mixtures of plastic and unvulcanised rubber or block polymers with both soft and hard segments. Thermoplastic elastomers have rubber-like mechanical properties and can be stretched 1–2 times their own length without permanent deformation. At the same time, they can be melted and reshaped like thermoplastics, which facilitates recycling. In thermoplastic elastomers, the unvulcanised rubber usually contributes to flexibility, while the stiffer plastic, which melts at high temperatures, acts as a crosslinker.

Global rubber production 2018 (total 28 million tonnes) (Levin 2018)

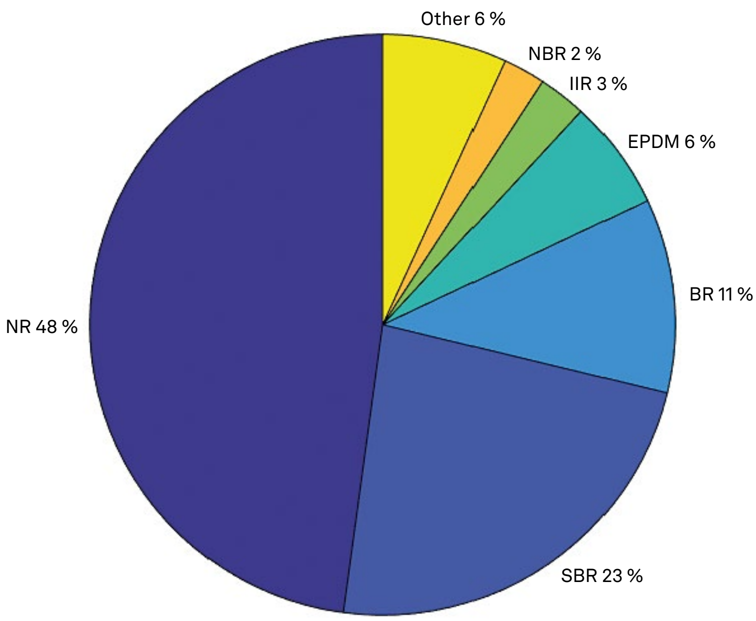

Figure 48. Global rubber production 2017 (total 28 million tonnes) by rubber type (Levin & Mårtensson, 2018).

Materials in recycled tyres

Both the lower layer in surfaces with cast granulate and filling granulate in artificial grass pitches are traditionally made of rubber granulate from recycled tyres. Recycled tyre rubber is commonly referred to as SBR or R-SBR (to clarify that it is recycled). However, there are many types of tyres, and most categories have a mixture of several types of rubber. Tyres also contain other components, including metals (e.g., steel and heavy metals like zinc), fibres, antioxidants, plasticisers (e.g., phthalates), additives, crosslinking chemicals (mainly sulphur), polymers, polyaromatic PAH oils and fillers (e.g., carbon black (CB)). An example of the chemical content of rubber granulate from recycled car tyres (excluding steel) is 30 % SBR, 20 % NR, 29 % carbon black, 6 % silicon, 1.6 % sulphur, 1.9 % zinc oxide and 11.5 % additives (Goodpoint, 2016) (Figure 49).

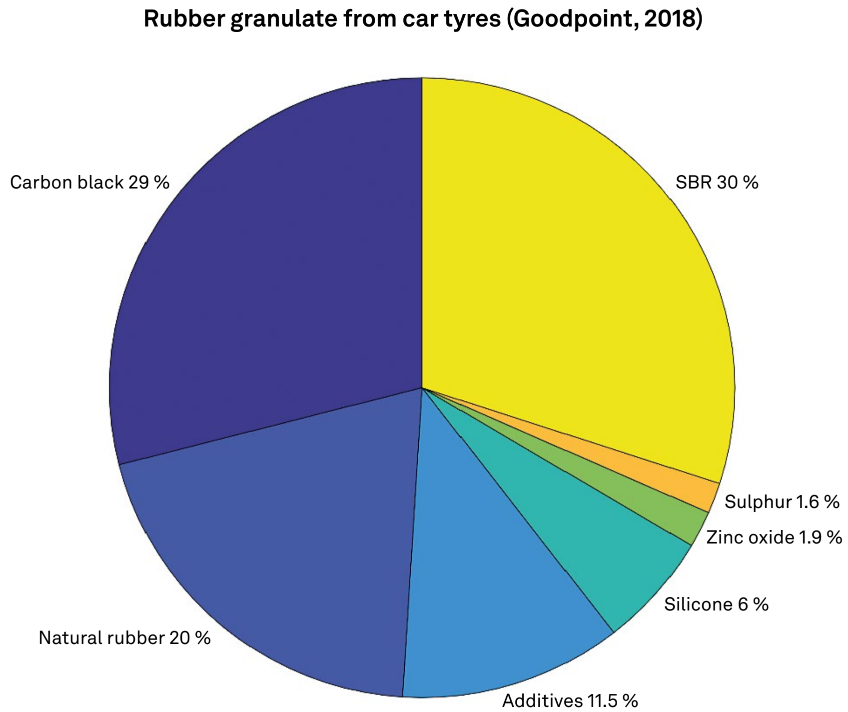

Figure 49. Material in a car tyre (Goodpoint, 2016) (the composition can vary greatly).

Tyres often contain at least five different rubber materials, especially SBR, NR and BR. Passenger car tyres contain higher levels of SBR and BR in summer tyres and NR and BR winter tyres (Mårtensson, 2013). Lorry tyres (treads) often have a high content of NR and potentially SBR. Forestry machines and tractors use NR and SBR. Implement tyres and industrial tyres are based mainly on SBR, while tubeless tyres have sealing layers of halogenated butyl rubber (BIIR or CIIR). Swedish suppliers of fall protection rubber use R-SBR from car, lorry and bus tyres. At the European level, R-SBR from car tyres is most common (approx. 70 %), followed by bus/truck tyres (approx. 20 %) and other tyres (approx. 10 %) (ECHA, 2017). Most types of rubber have good cold properties and retain their shock-absorbing ability even at moderate minus temperatures. Compared with 25 °C, the elastic modulus often only doubles at about −10 °C. Natural rubber, which is included with SBR in lorry tyres and winter tyres for passenger cars, retains its good elasticity at even lower temperatures, approx. −25 °C.

Around 2010, the EU decided to start phasing out carcinogenic, polyaromatic PAH oils from tyres (EU, 2011), which means that current levels of these chemicals are significantly lower than before, even though they are sometimes still higher than the Toy Safety Directive allows. Examples of PAH chemicals are benzopyrene, benzoanthracene, chrysene, benzofluoranthene, , and dibenzoanthracene. When using R-SBR, it is therefore important to ensure that the rubber comes from European tyres that are at least newer than 2010, but preferably significantly newer than that. There have been several studies on the health and environmental effects of microplastics from tyre rubber, and the overall picture is that it is slightly less dangerous than first feared, but still not completely harmless (US EPA, 2019), (ECHA, 2017), (Baensch-Baltruschat et al. 2020), (Halsband et al. 2020), (Pronk et al. 2020), (Wang et al. 2020), (Kole et. al., 2017), (Hüffer et al. 2019), (Amato, 2018).

NR (natural rubber)

Natural rubber (Figure 50) is the world's most common elastomer and accounts for about half of today's rubber production (Mårtensson, 2013). The vast majority of all natural rubber is tapped in the form of liquid latex from the rubber tree (*Hevea Brasiliensis*), which is mainly grown on rubber plantations in East Asia (Kohjiya & Ikeda, 2014). Smaller amounts of natural rubber from the North American tree gauyule (Eranki, 2019) and synthesised, petroleum-based natural rubber (isoprene, IR) are also produced. *Hevea Brasiliensis* rubber trees start producing latex after 6–8 years and can then be regularly tapped of latex until they are about 30 years old. Natural rubber is common in vehicle tyres, especially in bus tyres, truck tyres and winter tyres, and remains pliable and elastic at lower temperatures than SBR. Vulcanised natural rubber has high elasticity and impact resiliency, high tensile yield strength (750–850 %), low cushioning, high wear resistance, good strength, high resistance to water and non-oxidising acids, good cooling properties and low settling after deformation. However, it is sensitive to high temperatures, aging/oxidation, fuels, oils and ozone. Many of the material properties of natural rubber coincide with the properties of SBR, but natural rubber is mechanically more stable than SBR, and therefore does not need as much reinforcing filler (e.g., carbon black). It is also more cold-resistant, has better adhesive characteristics and is easier to process. Pure natural rubber (latex) is not toxic.

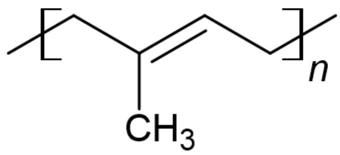

Figure 50. Chemical structural formula for natural rubber (latex).

SBR (Styrene-butadiene rubber)

Styrene butadiene rubber (SBR) (Figure 51) is a synthetic, petroleum-based rubber developed during World War II as a replacement for natural rubber in vehicle tyres (Mårtensson, 2013). Even today, SBR is mainly used for tyres and now accounts for about a quarter of all newly manufactured rubber. Recycled SBR, in the form of granulated tyres, is a common fall protection material used for such things as a lower shock-absorbing layer in surfaces of rubber granulate and as infill granulate in artificial grass pitches. SBR is a copolymer combining styrene (often about 23.5 %) and butadiene (about 76.5 %), and in vulcanised (crosslinked) form and with the right additives it can be given approximately the same mechanical properties as natural rubber. A higher proportion of butadiene leads to better elasticity, cushioning, and friction and cold resistance, but poorer processability and durability. Butadiene occurs in at least three different stereo structures, and the properties of the SBR will vary depending on the balance between these. Typically, SBRs are made by cold polymerisation at about 5 °C, either by emulsion polymerisation (E-SBR) or solution polymerisation (S-SBR). In addition to styrene and butadiene, SBR has many additives, including a high inclusion of reinforcing fillers, like carbon black, to give the SBR the desired mechanical rigidity and durability. Antioxidants, organic acids, vulcanising agents (e.g., sulphur) and others are also added. Unvulcanised rubber can be melted and formed into the desired shape and then vulcanisation can be initiated by raising the temperature sharply, causing the sulphur to react with the butadiene to form crosslinks. These result in the rubber forming an elastic, stretchable, dimensionally stable network that retains its properties even when heated. Vulcanised SBR has good wear resistance, good heat resistance, low water absorption, good damping, high friction, relatively good cooling properties with a glass transition temperature around −50 °C, can be stretched 500–600 % before fracture, and is moisture resistant but is sensitive to ozone and oil. Pure SBR without additives is not directly toxic. However, SBR tyres should not be burned, since SBR contains styrene, which in gaseous form can cause cancer and neurological damage in humans (Banton, 2019).

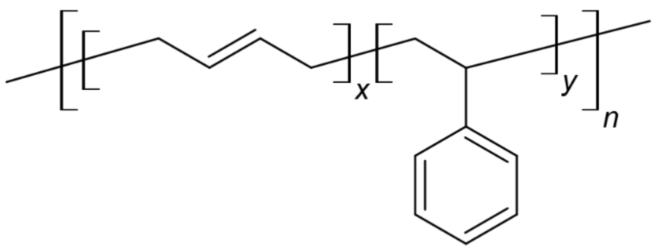

Figure 51. Chemical structural formula for styrene-butadiene rubber.

BR (Butadiene rubber)

Butadiene rubber (BR) (Figure 52) is a homopolymer of the butadiene also present in the copolymer SBR (Mårtensson, 2013). Annual global production is about 3.0 million tonnes. BR has good strength, high elasticity and, above all, very good cold resistance and flexibility at low temperatures, which means that it is often included in rubber compounds intended for tyres to complement other rubber materials. Mixing BR in SBR or NR can also improve cushioning, lower heat generation during dynamic work, increase elasticity and impact resiliency, increase abrasion resistance, lower rolling resistance and increase fatigue resistance. Pure BR's stretch at break is around 500 %. Pure BR is difficult to process and is mainly used in mixtures with natural rubber and SBR.

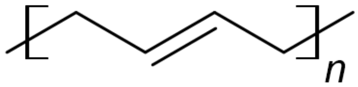

Figure 52. Chemical structural formula for butadiene rubber

EPDM (ethylene propylene diene monomer rubber)

Ethylene propylene diene monomer rubber (EPDM) (Figure 53) is a copolymer with the monomers ethylene and propylene together with a small amount of diene (Mårtensson, 2013). If no diene is included, the material is called ethylene propylene rubber (EPM). The annual global production of EPDM (including EPM) is about 1.7 million tonnes. EPDM is the dominant surface material for fall protection surfaces of cast rubber granulate and is also used as a granulate filler in artificial grass pitches, just like recycled R-SBR from used tyres. Unlike R-SBR, however, newly produced EPDM rarely contains significant amounts of heavy metals or harmful PAH chemicals. EPDM has good resistance to heat aging, ozone, oxidation, hot water, polar liquids, acids and alkalis (bases), making it a good surface material. On the other hand, it swells sharply in contact with liquid hydrocarbons (e.g., petrol) and is difficult to attach to metals and textiles. EPMD can be vulcanised (vulcanised, crosslinked) with sulphur, peroxides or resins. Because the carbon bonds occurring during peroxide vulcanisation are stronger than the sulphide bonds occurring during sulphur vulcanisation, peroxide-vulcanised EPDM is more stable against heat and settling. Vulcanised EPMD has quite good elasticity, high cushioning, excellent fatigue properties, high elasticity at low temperatures and good settling properties. Tear strength is good at low temperatures but drops sharply at elevated temperatures.

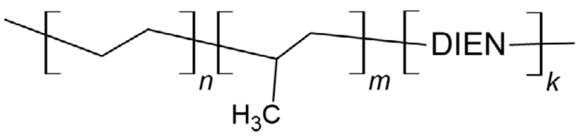

Figure 53. Chemical structural formula for ethylene propylene rubber.

PUR (Polyurethane plastic)

Polyurethanes (PU, PUR) (Figure 54) are a group of materials manufactured by combining isocyanates with polymeric polyols, i.e., alcohol-like polymers with at least two hydroxyl groups (-OH) (Brydson, 2016), (da Silva, 2018). Depending on the manufacturing process and the chemicals involved, the properties of the polyurethanes can be varied greatly. For this reason, polyurethanes are used as rigid heat-insulating polyurethane foams, as hard thermosets, as solid rubber-like elastomers, as expanded, cross-linked cellular materials, and as adhesives/binders. Examples of applications are mattresses, insulation materials, artificial leather, adhesives, shoe soles, elastic man-made fibres (spandex), sponges and water-based adhesives. PUR-based binders are used to bond the rubber granulate together in fall protection materials made from cast rubber granulate and cork granulate. Expanded thermoplastic polyurethane (E-TPU) is a closed-cell foam material that sometimes is used as an alternative to SBR in the lower shock-absorbing layer of moulded fall protection surfaces. E-TPU is a thermoplastic elastomer (TPE). Isocyanates in PUR have at least two isocyanate groups (-N=C=O) that can react with the groups of polyols (-OH). Aromatic isocyanates toluene diisocyanate (TDI) and polymethylene diphenyl isocyanate (MDI) are mainly used in PUR. The most common polyols in PUR are polyether and polyester polyols. Short polyol chains with many -OH groups create tightly cross-linked, rigid materials, while long polyol chains create more flexible materials with rubber-like properties. Pre-polymerised polyurethane is not dangerous to use, but the included isocyanates pose a work environment hazard during the manufacturing process and can also be released during combustion. PUR degrades more rapidly at elevated temperatures and in contact with water (Le Gac, Choqueuse, & Melot, 2013).

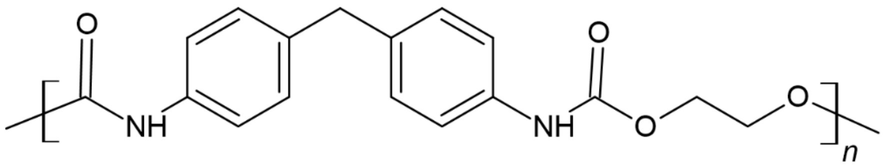

Figure 54. Chemical structural formula for polyurethane.

TPE (thermoplastic elastomers)

Thermoplastic elastomers are characterised by having rubber-like mechanical properties despite being able to be melted and reshaped like thermoplastics (Mårtensson, 2013). Rubber differs from TPE in that it has chemical crosslinks that do not break easily at elevated temperatures while the crosslinking points in TPE materials melt at high temperatures. The mechanical properties of TPE are generally slightly worse than those of rubber. There are several subgroups of TPE materials, including urethane-based (TPU), styrene-based (TPS), olefin-based (TPO), polyether-based (TPC), and polyamide-based (TPA). Abbreviations and definitions for different thermoelastic elastomers are specified in the standard "SS-ISO 18064: 2014 Thermoplastic elastomers – Nomenclature and abbreviated terms" (Swedish Institute of Standards, 2014). TPE materials can be a mixture of plastic and rubber materials or be block polymers with alternating soft and hard segments. If vulcanised rubber (e.g., EPDM) is mixed as a filler in a plastic matrix (e.g., PP), the finished material becomes a dynamic thermoplastic vulcanisate (TPV). Expanded thermoelastic polyurethane (E-TPU) has recently come on the market as an alternative to R-SBR in moulded rubber granulate fall protection, and it is probably only a matter of time before other TPE materials begin being used for the same purpose. TPE materials are sometimes also used as infill in artificial grass pitches. The thermoelastic properties of TPE materials make them easier to recycle, which is used as an environmental argument for TPE over rubber.

PE (polyethylene plastic)

The polyolefin polyethylene (PE) (Figure 55) is the world's most common plastic and makes up about 32 % of global plastic production (Brydson, 2016). PE is used in artificial grass and (sporadically) in other fall protection material as well as in plastic bags, food packaging, insulation material and hip prostheses. Most PE is made from petroleum, but it is also possible to produce PE from renewable raw materials, such as sugar cane, sugar beet and other raw materials from which ethanol can be obtained. Bio-PE has essentially the same properties as traditional PE and is not biodegradable. Depending on the density and degree of branching, PE is called low-density polyethylene (LDPE), linear low-density polyethylene (LLDPE), medium-density polyethylene (MDPE), high-density polyethylene (HDPE), or ultra-high-density polyethylene (UHMWPE). LDPE (and LLDPE) is soft and is used for plastic bags, films and other soft plastics. HDPE (and MDPE) is stiffer and is used in shampoo bottles, dish brush handles, water pipes and toys. UHMWPE is used in special applications, such as medical prostheses. All PE is semicrystalline at room temperature, i.e., has both crystalline and amorphous regions. Crystallinity generally increases with density. The polymer chains in PE are long linear hydrocarbon chains (about 10,000 carbon atoms) that can have short side branches (2–10 carbon atoms), especially in LDPE. Ordinary PE is a thermoplastic that melts at around 110 °C, allowing it to be recycled with small energy losses, which is good from a climate perspective. For special applications where the material must be thermally stable, e.g., insulation material for high-voltage cables, crosslinking is required to maintain stable mechanical properties even at elevated temperature. Crosslinked PE (XLPE) cannot be easily melted and recycled. Crosslinking is usually done with peroxides that generate crosslinking chemicals requiring gasification before application. Macroscopically, PE has a simple chemical structure (C2H4) and is normally inert and harmless. However, there may be hazardous additives (e.g., flame retardants) in the plastic that are released (faster) when heated. Therefore, heating or storing hot food in plastic containers should be avoided. Micro-/nanoplastics from PE can impair the growth of microorganisms and have other negative impacts.

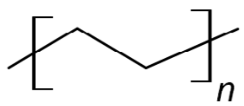

Figure 55. Chemical structural formula for polyethylene.

PP (polypropylene plastic)

Like polyethylene, polypropylene (PP) (Figure 56) is a semi-crystalline, transparent, thermoplastic polyolefin that can be easily recycled and is often used in artificial grass (Brydson, 2016). PP is the world's second most common plastic (23 % 2018). Examples of PP products are packaging materials, plastic film, medical implants, DVD cases, plastic corks, water pipes, toys, and food packaging. The structural formula for PP is similar to PE, the difference being that one hydrogen per repeating unit is replaced by a carbonyl (-CH3). PP is stiffer than PE, is light, has good mechanical strength and becomes brittle at low temperatures. Like PE, pure PP is not toxic but can contain harmful additives that migrate faster out of the plastic at high temperatures. For this reason, hot food should not be combined with PP and other plastics.

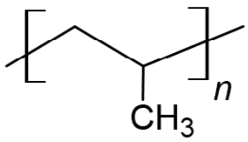

Figure 56. Chemical structural formula for polypropylene.

PS (polystyrene plastic)

Polystyrene plastic (PS) (Figure 57) is an aromatic polymer made from the suspected carcinogenic, endocrine disrupting and nerve-affecting monomer styrene (Brydson, 2016). PS accounts for about 7 % of global plastic production, but other plastics and rubbers also contain styrene, including acrylonitrile-butadiene-styrene (ABS) plastic, styrene-acrylonitrile (SAN) plastic and styrene-butadiene (SBR) rubber. Depending on how the styrene is polymerised, PS can be made hard and transparent as high-impact (HI) glass or formed into an expanded, soft, white, Styrofoam-type insulating foam (EPS). Examples of areas of use of HI-PS are hard, transparent CD packaging, bottles, disposable mugs, transparent packaging materials for toys and other consumer products, and disposable razors. Expanded PS (EPS), commonly referred to as Styrofoam, is often used as insulation material and packaging material. None of the major Swedish manufacturers of fall protection materials use EPS or other PS in their products. The reason for PS being noted here is that many microplastic studies examine PS and that styrene is a central component in SBR. Monomer styrene in gaseous form has several hazardous properties, including suspected of being endocrine disruptive, neurotoxic and carcinogenic (Banton, 2019). Polymerised macroscopic PS, on the other hand, is in principle non-hazardous, except that small amounts of unpolymerised styrene, flame retardants and other chemicals can be released upon heating. Polystyrene should therefore be avoided in food-grade applications. There are also indications that nanoplastics from PS have a negative impact on microbes, plants and animals (Sökmen, et al. 2020).

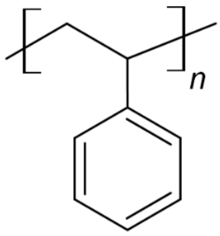

Figure 57. Chemical structural formula for polystyrene.

PA6, PA6.6 (Nylon)

Nylon (PA6, PA66, PA6G and others) (Figure 58) is the collective name for a group of thermoplastic polyamides that occur in artificial grass fibres (together with PE and PP) but not in surfaces made from cast rubber granulate (Brydson, 2016). Common applications include kitchen utensils, fishing line, food packaging and, in particular, synthetic fibres in textiles for the clothing industry. Nylon is made by reacting amines with acids, such as hexamethylenediamine and adinpinic acid. Pure polyamides are harmless but may contain additives that are released upon heating.

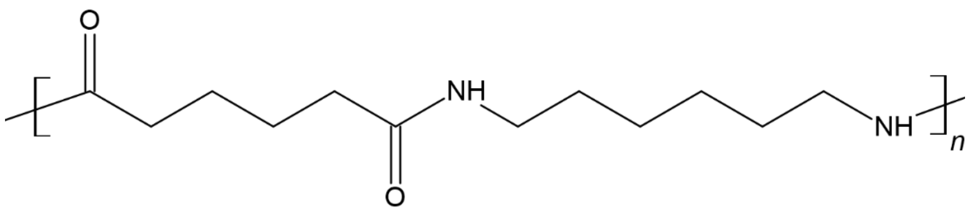

Figure 58. Chemical structural formula for nylon.

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Microplastic from cast rubber granulate and granulate-free artificial grass surfaces

This assignment focused on expanding knowledge about the dispersion of microplastics from cast rubber and granulate-free artificial grass surfaces by supplementing previous studies with new measurements and calculations. The goal was to improve estimates of how much these sources contribute to microplastics nationally and to identify strategies to better prevent leakage into the environment.

Based on the estimated rubber area on playgrounds and sports pitches nationally, combined with the measured microplastic emissions per year and square metre, total emissions from Sweden's rubber surfaces are estimated to be about 16 tonnes/year. The equivalent estimate for artificial grass surfaces without granulates is about 2 tonnes/year. These are considerably smaller sources of emissions than sources such as; road traffic or artificial grass with infill, and in line with estimated microplastic emissions from fishing nets and other fishing implements. The relatively low values are attributable to the total area of these surfaces being significantly smaller compared with the total area of roads in Sweden. Microplastic emissions per $m^2 \times$ year for surfaces with rubber granulate and granulate-free artificial grass were however almost on par with those from motorways, but lower than those from artificial grass with infill.

The project also developed technical specifications to limit the leakage of microplastics from surfaces with cast rubber granules. These include making good material choices, as well as considering the use of natural materials, which do not generate microplastics. Construction (environment, substrate and design) is another important aspect for reducing the leakage of microplastics from rubber surfaces and artificial grass surfaces, as is maintenance, which is crucial for a long lifespan and reduced leakage of microplastics from rubber materials. Always consider the use of natural materials, which do not generate microplastics, such as grass, wood chips or sand. Available cork products on the market have the same function and appearance as rubber materials. Construction (environment, substrate and design) is another important aspect for reducing the leakage of microplastics from rubber surfaces and artificial grass surfaces, as is maintenance, which is crucial for a long lifespan and reduced leakage of microplastics from rubber materials.

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