Life cycle assessment of two end-of-life tyre applications: artificial turfs and asphalt rubber

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Summary

The current use of the Earth's resources is not sustainable. Globally, we live as if we have 1,7 globes and in Sweden alone we consume 4,2 globes worth of resources each year. At this rate, the resource consumption and the environmental impacts caused by the use of resources will lead to problems for the future generations. One solution to decrease the extraction rates of the Earth's resources is to recycle and reuse some of the materials that has already been extracted. This study focuses on recycled tyres compared to a variety of materials.

The use of end-of-life tyres is studied in two different applications in this life cycle assessment: as an infill layer on artificial football fields and as a binder additive in asphalt rubber pavements. In the artificial turf scenario, granulated tyres are compared with three alternative infill materials: expanded cork, ethylene propylene diene monomer (EPDM) and thermoplastic elastomers (TPE). In the asphalt rubber scenario, three different road constructions containing rubberized asphalt in different layers are compared with one reference pavement containing no rubber. The asphalt constructions are based on a real project located at Ragn-Sells' granulate factory in Vänersborg, Sweden.

In both LCAs six impact categories are included, which are listed below. Two extra categories are included in the artificial turf scenario that are not included in the asphalt rubber scenario: agricultural land use and water depletion.

- Global warming potential (kg CO_2-eq.)
- Fossil fuel depletion (kg oil-eq.)
- Acidification (kg SO_2-eq.)
- Eutrophication (kg P-eq. and N-eq.)
- Photochemical oxidant formation potential (kg NMVOC)
- Land use (m^2*year)
- Water depletion (m^3)

The applications have been compared in a product's perspective, meaning that the functional unit is expressed in terms of the final application. The functional units are defined as:

- 1 football field (defined as 7881 m^2 with an expected life span of 10 years)
- 1 stretch of road (defined as 240 m^2*year)

The intended audience for this LCA is principally suppliers and purchasers of either artificial turf systems or asphalt pavements. Also tyre recycling companies should get use from the results of this LCA to map the environmental benefits of using recycled tyres.

Some of the conclusions which could be made in this LCA are:

- Granulated tyres used as an infill in artificial turfs have the lowest environmental impact compared to expanded cork, EPDM and TPE
- Cork infill have the highest land use footprint: approximately 35 hectares of cork forests are needed to produce infill for one football field
- EPDM and TPE have the highest carbon footprints, releasing almost 15 and 28 times as much greenhouse gases as granulated tyres

- Pavements containing asphalt rubber have lower environmental impact than pavements constructed entirely from conventional asphalt
- It is of great importance to construct either thinner pavements when using asphalt rubber, or to construct pavements which have a longer life than conventional asphalt pavements, to be able to lower the environmental footprint of asphalt rubber

Artificial turfs

An artificial turf system usually consists of a shock pad, artificial grass, sand and a granulated infill material. In this comparison the only part of the football field assumed to vary is the layer of infill material, all other parts of the turf have therefore been excluded. Due to disparities in material properties, different amounts of infill materials are needed to fill one football field, which is presented in Table 1 below.

Table 1: List of included infill materials, the amount needed to fill one football field (15 mm infill layer) and the estimated life span of the respective infill material.

Infill material	Amount of infill needed per football field	Life span
SBR	52 tons	10 years
Cork	8,3 tons	4 years
EPDM	77 tons	10 years
TPE	65 tons	10 years

The results from the LCA show that infill produced from recycled tyres (SBR) have the lowest environmental impact when compared to the other infill materials. This is the case for all studied impact categories. The result for the climate change category is presented in Figure 1 below. Due to its relatively short life span, expanded cork have a higher carbon footprint than SBR. EPDM and TPE have the largest carbon footprints of all studied infill materials.

When comparing the land use, cork infill have by far the largest footprint. 35 hectares of cork forests are needed to produce infill for one football field.

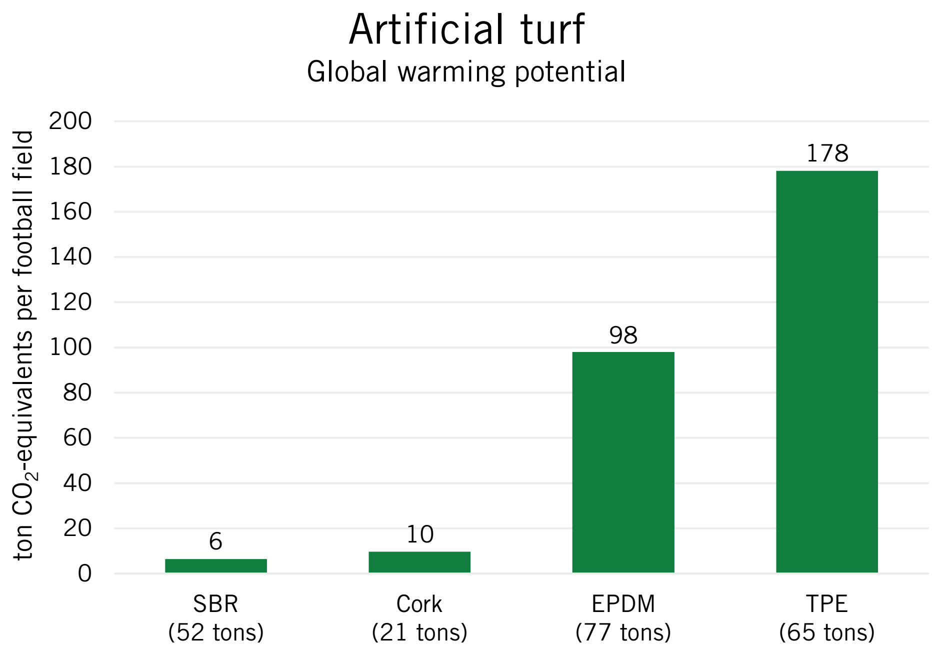


Figure 1: Results for the artificial turf comparison in the impact category global warming potential. The results are expressed as ton CO_2-equivalents per football field.

When comparing the prices of the infill materials, which is illustrated in Figure 2 below, it is clear that SBR and cork have the lowest prices as well as the lowest carbon footprints. The cost for EPDM and TPE for one football field are similar and are approximately 11 or 12 times higher than SBR and cork.

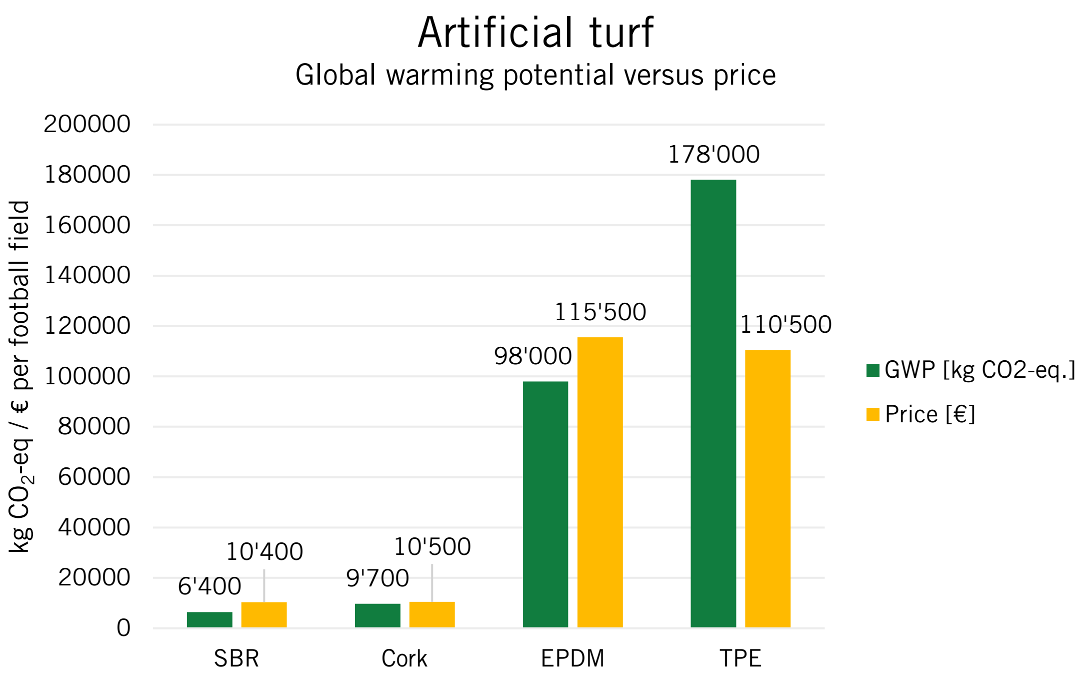


Figure 2: Comparison of carbon footprints and prices of different infill materials. The results are expressed in Euro and kg CO_2-equivalents.

Three sensitivity analyses were made to test the rigidity of the results. Alternative bulk densities of EPDM and TPE infill were assumed, both higher and lower than the base case illustrated above. The ranking of the infill materials did not change depending on the chosen bulk densities.

In the second analysis reuse of the EPDM and TPE infills were assumed. If the quality of the infill materials is good both can be reused. This assumption does not affect the ranking of the infill materials: EPDM and TPE still have the highest environmental footprints.

In the third sensitivity analysis refilling of the infill materials was included. SBR, EPDM and TPE were assumed to be refilled 6% each year, and cork was assumed to be refilled 10% per year due to it being a lighter material. This did not affect the overall comparison of the infill materials.

Asphalt rubber

Three asphalt pavements containing asphalt rubber in different layers and with varying thicknesses, are compared to one reference pavement containing no rubber modification. In the studied object, there were indications of longer life spans for the pavements containing layers of asphalt rubber compared to the reference surface. Strain measurements performed during the first year after construction concluded that the asphalt rubber could have a positive effect on the fatigue cracking of the pavements. However it is likely that constructions containing asphalt rubber will give rise to larger surface deformations since asphalt rubber has lower stiffness than conventional pavements. With regards to the strain measurements and the amount of traffic on the test surfaces, the technical life spans of the surfaces have been calculated and are presented in Table 2 below.

Table 2: The calculated life spans of three asphalt rubber pavements (named AR 1, AR 2 and AR 3) compared to the life span of the reference pavement without rubber modification (named REF 4).

Test surface	Life span
AR 1	5,8 years
AR 2	8,3 years
AR 3	8,3 years
REF 4	4,6 years

From the result in Figure 3 below it is possible to draw the conclusion that production of pavements containing asphalt rubber contribute less to climate change than conventional asphalt pavements. The main reasons for this are the extended life spans of pavements containing asphalt rubber and the possibility to reduce the thickness of the pavement, which is the case for the pavement AR 2.

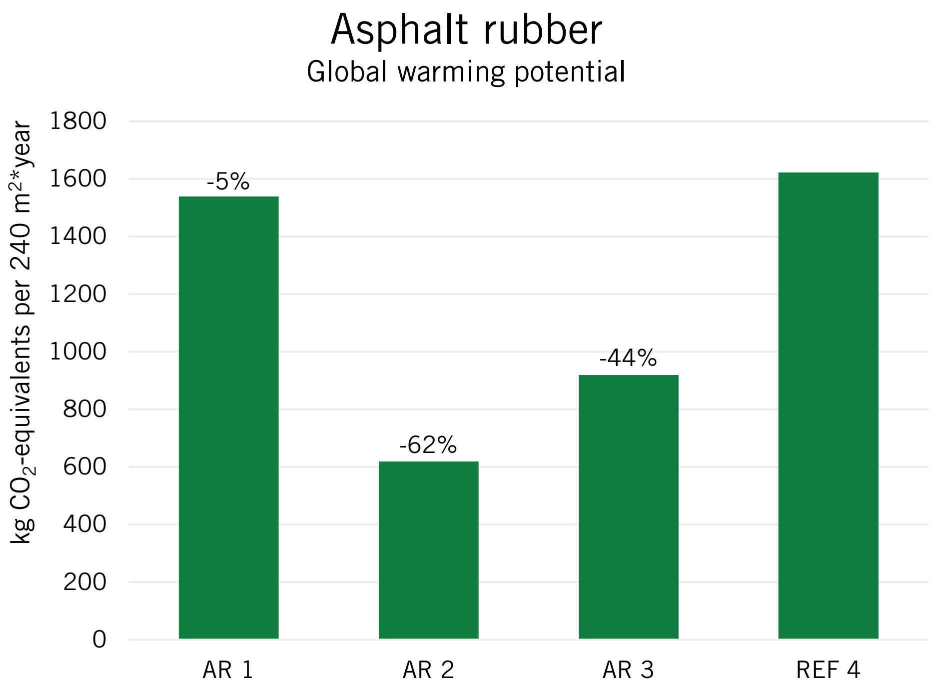


Figure 3: Comparison of three asphalt rubber pavements and one conventional in the global warming potential category. The results are expressed as kg CO_2-equivalents per functional unit.

Two sensitivity analyses were made. Due to a production fault, the asphalt rubber masses had a higher binder content than planned. In the first sensitivity analysis the binder content was decreased by 1,5% for all AR masses to test the influence this has on the results. If assuming similar life spans as in the base case the surfaces containing AR have an even lower environmental footprint than before.

In the second analysis the life spans of the surfaces were excluded, presented in Figure 4 below. This resulted in a less clear ranking between pavements containing AR and the reference pavement. The reason for this is the differences in constructions. AR 3 and REF 4 have the most similar constructions but due to a higher resource consumption for asphalt rubber production AR 3 have a higher carbon footprint than the reference pavement.

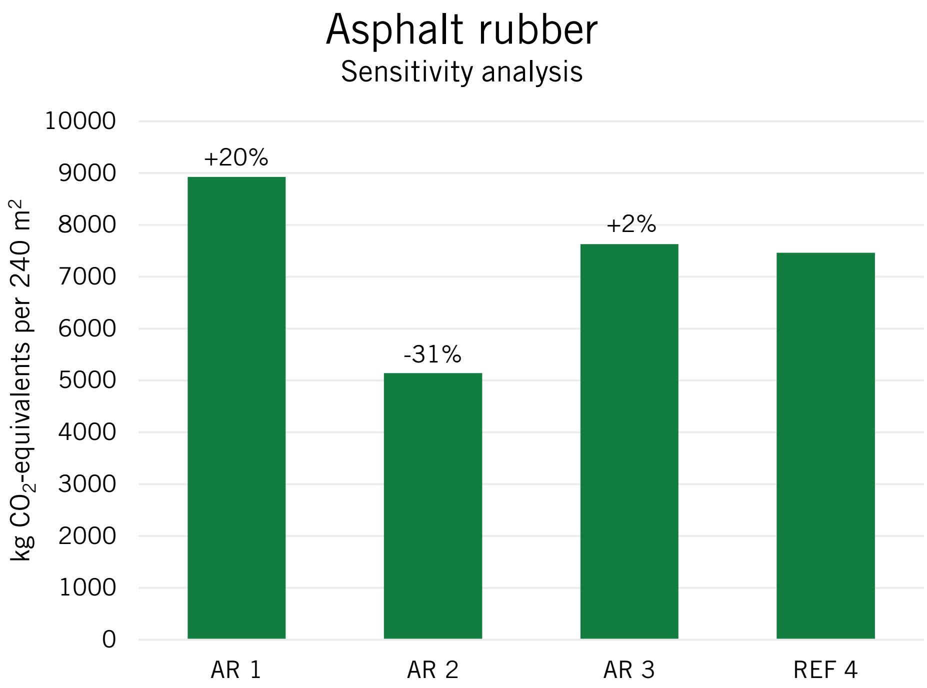


Figure 4: Results from the sensitivity analysis where the life spans have been excluded from the functional unit. The results are expressed in kg CO_2-equivalents per 240 m^2 road.

Sammanfattning

Dagens användningstakt av Jordens resurser är inte hållbar. Globalt sett lever vi som om vi hade 1,7 jordklot, medan vi i Sverige förbrukar resurser motsvarande 4,2 jordklot per år. I denna takt kommer resursförbrukningen och miljöpåverkan relaterad till denna att leda till problem för nästkommande generationer. En lösning för att minska uttömningstakten av resurserna är att återvinna och återanvända redan utvunna material. Den här studien fokuserar på återvinning av däck jämfört med några alternativa material.

I denna livscykelanalys studeras återvunna, granulerade däck i två olika applikationer: som fyllnadslager i konstgräsplaner och som ett additiv till bindemedel i gummiasfalt. I konstgrässcenariot jämföra granulerade däck med tre alternativa fyllnadsmaterial: expanderad kork, EPDM och TPE. I gummiasfaltscenariot jämförs tre olika teststräckor med gummiasfalt i olika lager med en referenssträcka av konventionell asfalt utan gummiinblandning. Vägkonstruktionerna är baserat på ett verkligt projekt lokaliserat utanför Ragn-Sells granulatfabrik i Vänersborg.

Sex miljöpåverkanskategorier har studerats i båda livscykelanalyserna, vilka är listade nedan. Två extra kategorier har studerats i konstgrässcenariot: markanvändning och vattenförbrukning.

- Klimatpåverkan (kg CO_2-ekv.)
- Fossil energianvändning (kg olje-ekv.)
- Försurning (kg SO_2-ekv.)
- Övergödning (kg P-ekv. och kg N-ekv.)
- Marknära ozon (kg NMVOC)
- Markanvändning (m^2*år)
- Vattenförbrukning (m^3)

De två användningsområdena har jämförts i ett produktperspektiv och de funktionella enheterna har definierats som:

- 1 fotbollsplan (definierad till 7881 m^2, med en uppskattad livslängd på 10 år)
- 1 vägsträcka (definierad till 240 m^2*år)

Den tänkta läsekretsen till denna LCA är främst försäljare och inköpare av antingen konstgräsplanssystem eller asfalt. Däckåtervinningsföretag torde också ha nytta av resultatet från denna LCA för att kartlägga de miljömässiga fördelarna med att återvinna däck.

Några av slutsatserna som kan dras från denna LCA är:

- Granulerade däck som används som fyllnadslager i konstgräsplaner har den lägsta miljöpåverkan jämfört med expanderad kork, EPDM och TPE
- Fyllnadsmaterialet kork har den högsta markanvändningen: cirka 35 hektar skogsmark krävs för att producera fyllnadsmaterial för en fotbollsplan
- EPDM och TPE har de allra högsta koldioxidavtrycken: tillverkning av dessa orsakar ca 15 och 28 gånger högre växthusgasutsläpp än granulerade däck
- Teststräckor som innehåller gummiasfalt i olika lager har lägre miljöpåverkan än referenssträckan utan gummiinblandning
- I gummiasfaltscenariot är det viktigt att antingen konstruera tunnare lager av asfalt eller att tillverka vägar av gummiasfalt med längre livslängd än konventionell asfalt för att minska miljöpåverkan för gummiasfalt

Konstgräsplaner

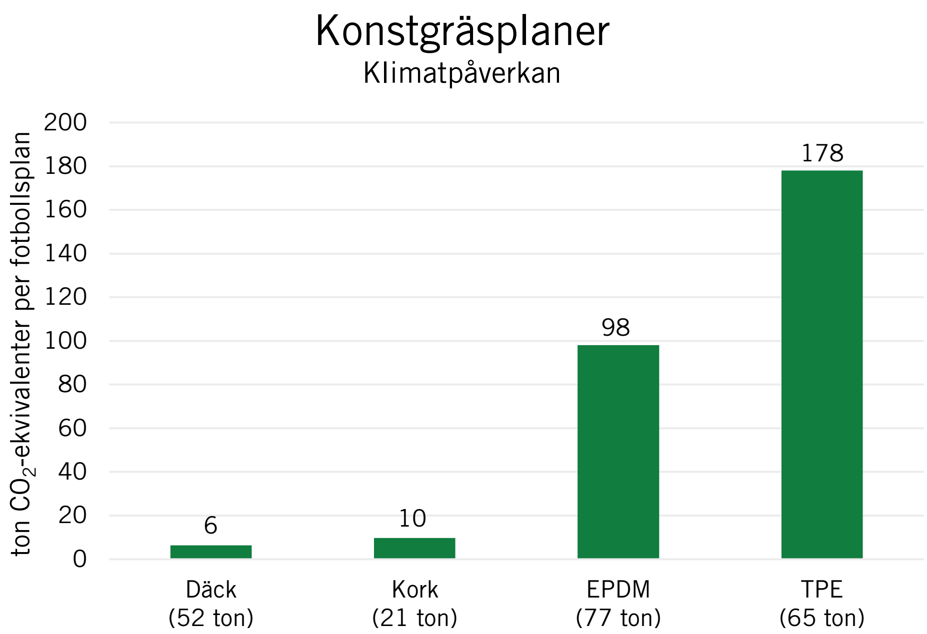
Ett konstgrässystem består vanligtvis av en sviktpad, konstgräs, sand och granulerat fyllnadsmaterial. I denna jämförelse har endast fyllnadslagret inkluderats eftersom det är det enda lagret som antas variera. På grund av inneboende egenskaper i de olika fyllnadsmaterialen krävs olika mängder av materialen för att fylla en fotbollsplan med granulerat material. Dessa mängder är presenterade i Tabell 1 nedan.

Tabell 1: Lista med inkluderade fyllnadsmaterial, mängden material som krävs per fotbollsplan (15 mm lager) samt de uppskattade livslängderna för respektive material.

Fyllnadsmaterial	Mängd som krävs per fotbollsplan	Livslängd
Däck	52 ton	10 år
Kork	8,3 ton	4 år
EPDM	77 ton	10 år
TPE	65 ton	10 år

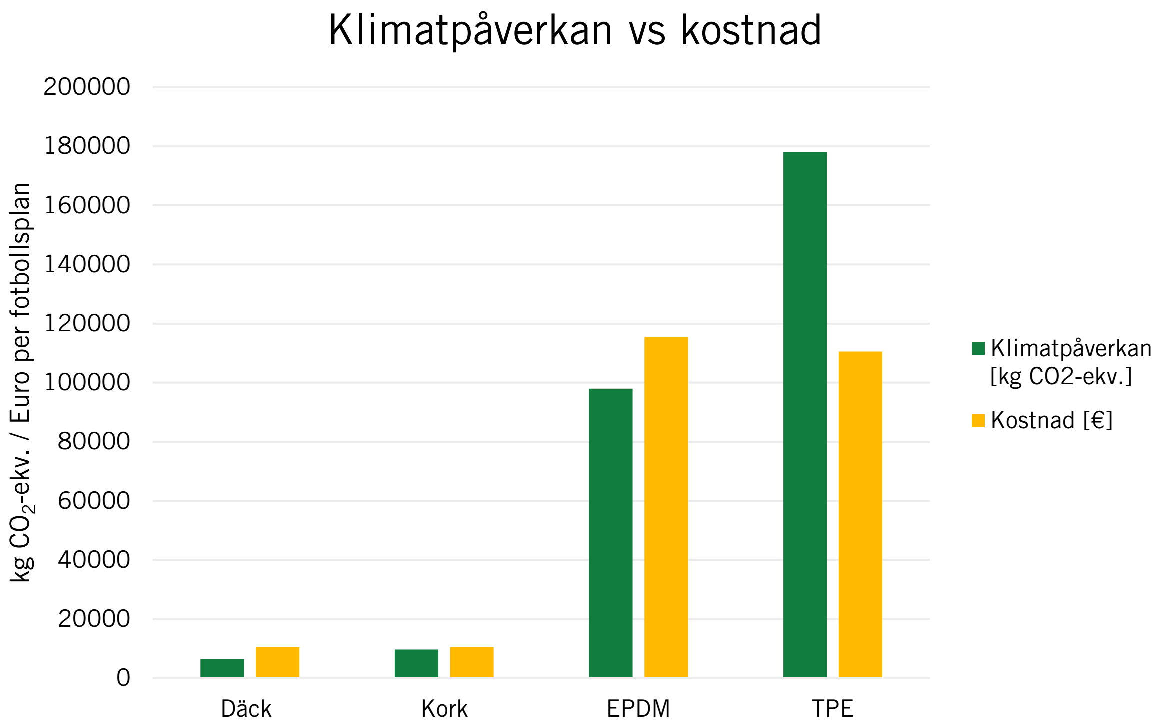
Resultaten från livscykelanalysen visar att granulerade däck har den lägsta miljöpåverkan jämfört med de andra fyllnadsmaterialen. Det här gäller för all studerade miljöpåverkanskategorier. Resultatet för kategorin klimatpåverkan presenteras i Figur 1 nedan. På grund av korkens relativt korta livslängd har den ett något större klimatavtryck än granulerade däck. EPDM och TPE har de största klimatavtrycken av de studerade fyllnadsmaterialen.

I jämförelsen av markanvändning har kork den största påverkan. Cirka 35 hektar skogsmark krävs för att producera fyllnadsmaterial av kork till en fotbollsplan.



Figur 1: Resultat för jämförelsen av fyllnadsmaterial till konstgräsplaner för kategorin klimatpåverkan. Resultatet uttrycks i ton CO_2-ekvivalenter per fotbollsplan.

Jämför man prisskillnaderna mellan fyllnadsmaterialen, vilka presenteras i Figur 2 nedan, ser man klart och tydligt att granulerade däck och expanderad kork både har de lägsta kostnaderna och de lägsta klimatavtrycken. Kostnaderna för EPDM och TPE är ca 11 eller 12 gånger högre än kostnaden för granulerade däck.



Figur 2: Jämförelse av koldioxidavtryck och kostnad för de fyra olika fyllnadsmaterialen. Resultaten är uttryckta i kg CO_2-ekvivalenter och Euro.

Tre känslighetsanalyser gjorde för att testa några av antagandena i analysen. Alternativa bulkdensiteter för EPDM och TPE testades, både högre och lägre än i basfallet. Rankingen av materialen förändrades inte.

I den andra känslighetsanalysen gjordes antagandet att EPDM och TPE kunde återanvändas till nästa fotbollsplan, dvs livslängden utökades till 20 år istället för 10 som i basfallet. Även detta antagande påverkade inte rankingen mellan de olika materialen.

I den tredje och sista känslighetsanalysen inkluderades återfyllnad av materialen. En 6% återfyllnadsgrad per år antogs för däck, EPDM och TPE medan en återfyllnadsgrad på 10% antogs för kork. Detta beror på att kork är ett lättare material än de övriga. Detta antagande påverkade inte resultaten i stort.

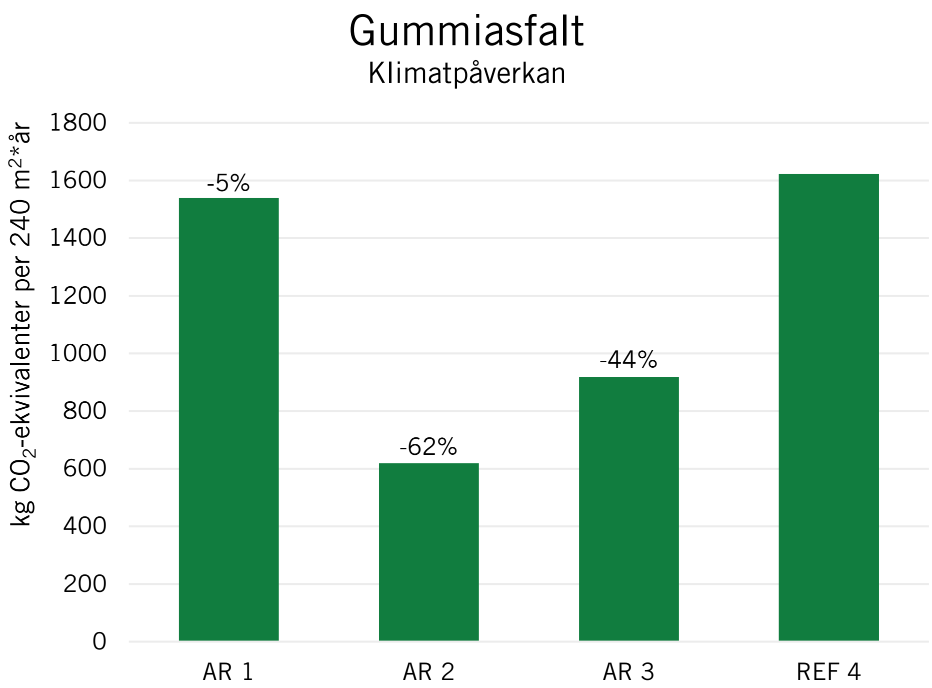
Gummiasfalt

Tre teststräckor med gummiasfalt i olika lager och med olika tjocklekar jämförs med en referenssträcka av konventionell asfalt utan gummiinblandning. Inom det studerade projektet fanns indikationer på en längre teknisk livslängd för gummiasfaltsträckorna. Belastningsmätningar genomfördes under det första året efter utläggning och det bevisades att gummiasfalt kan ha en positiv effekt på spridningen av utmattningssprickor på beläggningarna. Det är dock troligt att vägar med gummiasfalt kan ge upphov till större deformationer på ytan eftersom gummiasfalt har lägre styvhet än konventionell asfalt. Med avseende på belastningsmätningarna och den aktuella trafikmängden på teststräckorna har den tekniska livslängden beräknats. Detta presenteras i Tabell 2 nedan.

Tabell 2: Uppskattningar av teststräckornas olika livslängder.

Teststräcka	Livslängd
AR 1	5,8 år
AR 2	8,3 år
AR 3	8,3 år
REF 4	4,6 år

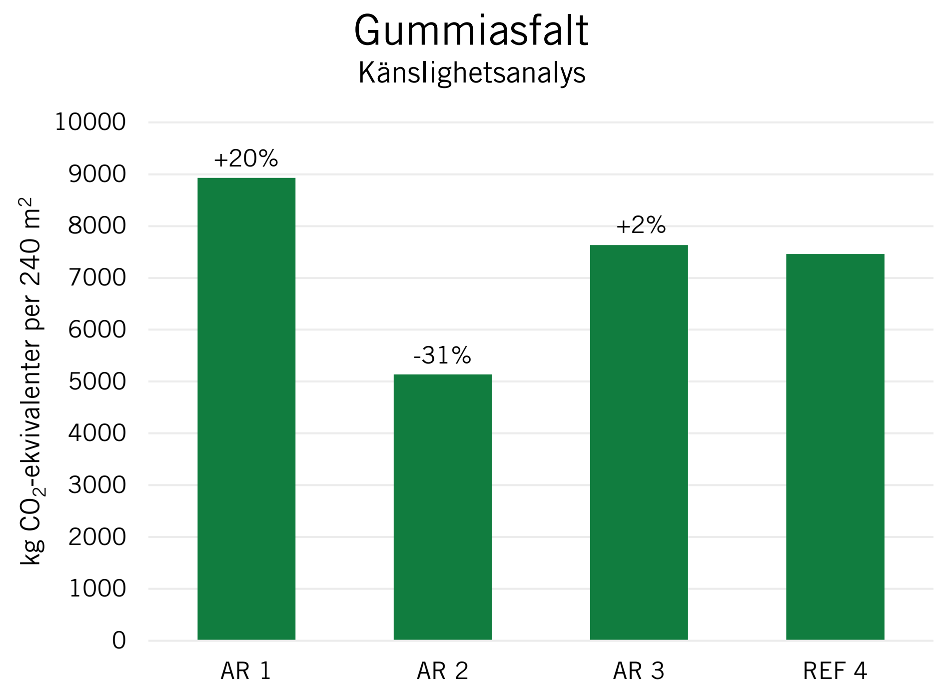
Från resultatet i Figur 3 nedan kan man dra slutsatsen att sträckorna med gummiasfalt har ett lägre klimatavtryck än referenssträckan. De främsta anledningarna till detta är att vägarna med gummiasfalt har längre livslängd och att det är möjligt att tillverka tunnare lager med gummiasfalt, vilket illustreras i teststräckan AR 2.



Figur 3: Resultatet för jämförelsen av koldioxidavtryck mellan de olika teststräckorna med gummiasfalt och konventionell asfalt. Resultatet uttrycks i kg CO_2-ekvivalenter per funktionell enhet. Siffrorna ovanför staplarna med gummiasfalt (AR) anger den relativa skillnaden jämtemot referenssträckan.

Två känslighetsanalyser gjordes. På grund av ett produktionsfel fick gummiasfaltsmassorna 1,5% högre bindemedelshalt än planerat. I den första känslighetsanalysen testades därför att sänka bindemedelshalten för alla gummiasfaltsmassor för att se hur detta påverkade resultatet. Det antogs att livslängderna för vägarna var detsamma och resultatet visade att sträckorna som innehöll gummiasfalt fick ett ännu lägre fotavtryck än i basfallet.

I den andra känslighetsanalysen exkluderades livslängderna för vägarna, där resultatet presenteras i Figur 4 nedan. Resultatet visade en mer otydlig ranking mellan gummiasfaltsträckorna och referenssträckan. Orsaken för detta är främst skillnader i tjocklekar för de olika lagren. AR 3 och REF 4 har de mest lika konstruktionerna men eftersom tillverkningen av gummiasfalt är mer resurskrävande har AR 3 ett något högre koldioxidavtryck än referenssträckan.



Figur 4: Resultatet för känslighetsanalysen där skillnaderna i livslängd är exkluderat. Resultatet uttrycks i kg CO_2-ekvivalenter per 240 m^2 väg. Procentsatserna ovanför staplarna med gummiasfalt (AR) anger den relativa skillnaden jämtemot referenssträckan.

List of abbreviations

ABb – "Asfaltbetong, bindlager" (A type of binder course)

ABS – "Asfaltbetong, Stenrik" (A type of wearing course, equal to Stone Mastic Asphalt)

AG – "Asfaltgrus" (A type of base course)

ALO – Agricultural Land Occupation

AR – Asphalt Rubber

ELTs – End of Life Tyres

EPDM – Ethylene Propylene Diene Monomer

FDP – Fossil Depletion Potential

FEP – Freshwater Eutrophication Potential

FU – Functional Unit

GAP – "Gummimodifierad Asfaltmassa med Partikelsprång" (A type of wearing course)

GWP – Global Warming Potential

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

LCIA – Life Cycle Impact Assessment

MEP – Marine Eutrophication Potential

NDR – Norsk Dekkretur AS

NMVOC – Non-Methane Volatile Organic Carbon

POFP – Photochemical Oxidant Formation Potential

RM – Rubber Modified

RMB – Rubber Modified Bitumen

SBR – Styrene-Butadiene Rubber

SDAB – Svensk Däckåtervinning AB

TAP – Terrestrial Acidification Potential

TPE – Thermoplastic Elastomers

WDP – Water Depletion Potential

Table of contents

1 Introduction

Ragn-Sells Tyre Recycling AB, a subsidiary to Ragn-Sells AB, collects and recycles all tyres in Sweden and Norway. End-of-life tyres (ELTs) are covered by producer's responsibility in both of the countries, meaning that tyre producers are responsible for the treatment and recycling when the tyres are worn out. This is solved by applying a recycling fee on each tyre. Landfilling of tyres have been banned in the EU since the year 1999.

Production of tyres is a resource demanding process and the technical life span of a passenger car tyre is between four and five years. Lorry tyres in turn have a life span of approximately 1,5 years. It is therefore important to recycle the tyres in a sustainable and efficient way. Through recycling the need for new materials decrease and depletion of the earth's resources can be reduced.

Ragn-Sells wants to compare the environmental impact of new and important applications of used tyres to conventional materials. The purpose of this project is to compare two applications of used tyres: asphalt rubber and artificial turf infills and compare it to conventional or alternative materials. The environmental impact has been assessed using life cycle assessment (LCA). LCA is a holistic method and a systematic approach for assessing environmental impacts throughout a product's life cycle, from extraction of raw materials to the final end-of-life treatment.

Asphalt rubber is a technique where rubber granulate is blended into bitumen and used as a binder in asphalt production. It has been tested in several projects in Sweden since 2007. Asphalt rubber under Swedish conditions has not been evaluated using LCA before. One of the asphalt rubber projects, located in Vänersborg, Sweden, in the vicinity of Ragn-Sells' granulate factory, has been chosen as a study object in this LCA. Only a few percent of the rubber granulate are dedicated today for asphalt rubber. However Ragn-Sells is evaluating the potential of asphalt rubber in Sweden in a series of studies: including evaluation of technical preconditions, suitable business models and environmental aspects through an LCA.

Rubber granulate used as infill material on artificial turfs is a large market for ELTs. A comparative LCA was made by IVL in 2012 (Alongi Skenhall et al. 2012) where the environmental impact from using different infill materials was compared. The aim of the present work is to make an update of the existing LCA to better suit the turf constructions and infill alternatives of today.

The two applications have been separated in the report: chapter 3 is dedicated to artificial turfs and chapter 4 is dedicated to asphalt rubber. The chapters are outlined in the same fashion and a few details may be repeated due to this, for instance the life cycle inventory (LCI) for rubber granulate production from used tyres which are the same for both applications. The choice of separating asphalt rubber and artificial turfs has been made since the two applications differ significantly from each other and to simplify if readers are only interested in one of the two applications.

1.1 Tyre recycling in Sweden and Norway

Ragn-Sells Tyre Recycling AB, as a subcontractor to Svensk Däckåtervinning AB (SDAB), collected and recycled approximately 90 000 tons of used tyres in Sweden in 2017. Ragn-Sells is also a subcontractor to Norsk Dekkretur AB (NDR) and collects roughly 60 000 tons of tyres per year in Norway (SDAB, 2018; NDR, 2018).

SDAB and NDR have been appointed by the tyre industry and are responsible for the collection and recycling of used tyres in Sweden and Norway which are covered by producer's responsibility. Companies that produce or import tyres pay a fee which covers the costs for collection and recycling.

The producer responsibility of tyres in Sweden is regulated by ordinance 1994:1236. The ordinance specifies in 4 § how the tyres should be recycled: by reuse, material recycling, energy recycling or any other environmentally preferable way. The ordinance also specifies in 5 § that SDAB will report the results of the final applications of used tyres to Naturvårdsverket (Swedish EPA). Collection and recycling of tyres in Norway have been regulated since 1994 as well and can be found in chapter 5 in "avfallsforskriften". The ordinance specifies the banning of landfilling of used tyres and, equal to the Swedish ordinance, it specifies that the tyres should either be reused, recycled or be used for energy recovery. The contractor, NDR, reports to Miljødirektoratet (Norwegian EPA) regarding the collection and recycling of tyres.

In the EU there are three different systems for managing used tyres: producer responsibility, tax system and free market system. Most countries in the EU have adopted the producer responsibility system, like Sweden and Norway, where one or several collectors recycle all tyres. Denmark and Croatia have adopted a tax system where the producers pay a tax to the government which is responsible for the organisation of ELTs. Countries such as Germany, Switzerland, Austria and Great Britain have adopted a free market system for ELT organisation. Legislation sets the objectives for the collection and recycling of tyres to be met but does not specify those who are responsible. This implies that all companies operating in the recovery chain are obliged to recycle the tyres (ETRMA, n.d.).

1.2 Applications of used tyres in Sweden

The main focus in this report is the recycling and applications of used tyres in Sweden. Nearly half of all collected ELTs in Sweden are recycled for energy purposes in cement kilns and coal-fired plants. Around 30% of all tyres are incinerated in cement kilns and 20% in coal-fired plants. To improve handling, tyres are usually shredded before incineration but whole tyres are used directly as well.

Ragn-Sells owns the only rubber granulate factory in Sweden, Norway and Finland combined and it is located in Vänersborg, Sweden. Nearly 30 000 tons of ELTs in Sweden and Norway are granulated in Vänersborg and around 90% of all granulate are used as infill material on artificial turfs. In the granulation process metal studs, metal wires and textile are separated. The metal fractions are being recycled back to the steel industry, whereas the textile is used for energy recovery in cement kilns. Rubber granulates are also used in rubberized asphalt production and as bullet traps at shooting-ranges.

Whole tyres can be used for production of blasting mats, representing 9% of all collected ELTs in Sweden. 6% of tyres (shreds and whole tyres) are being reused as paddocks, construction materials and as insight protection devices. A small percentage of used tyres are being exported or re-treaded.

1.3 Existing LCAs covering tyre recycling

1.3.1 IVL (2006 and 2012)

Two LCAs have been carried out by the Swedish Environmental Institute (IVL) in 2006 and 2012. The first LCA by Hallberg et al. (2006) compared six different scenarios for the utilisation of used tyres: incineration in cement kilns and district heating plants, recycling in artificial turfs and in rubberized asphalt, and reuse of the tyres as drainage material in final covering of landfills and as filling material in noise banks. The functional unit was 1 ton of used tyres. The most favourable options regarding the global warming potential (GWP) were reuse in artificial turfs and incineration in cement kilns. The least favourable options were recycling of tyres in asphalt and incineration in district heating plants.

In the LCA by Alongi Skenhall et al. (2012) three different facilities were included: the use of granulated tyres in artificial turfs, tyre cuts used in drainage layers of the final covering of landfills and tyre cuts in equestrian floors. Unlike the LCA from 2006, this one compared the applications in a product's perspective. The functional units were 1 football field, 1 landfill and 1 paddock. Due to different functional units the applications were not comparable. However the use of used tyres as infill material fared well compared to the alternative infill materials EPDM and TPE.

1.3.2 Aliapur (2010)

In an LCA published by French Aliapur in 2010, nine recovery methods were compared to each other. The functional unit was 1 ton of used tyres. Both destructive methods (incineration in cement kilns, district heating plants and steelworks) and non-destructive methods (artificial turf, moulded objects, equestrian floor, retention- and infiltration basins) were included in the assessment. Looking at the GWP the most favourable recovery method is synthetic turfs. However Aliapur (2010) assumed a lifespan of the EPDM of four years whilst the ELTs had a lifetime of ten years. It is also important to remember that 1 ton of ELTs not necessarily replaces 1 ton of EPDM due to differences in densities. The main application is artificial turfs where the volume of the infill material is the limiting factor, not the weight of the material.

1.3.3 Genan (2009)

Two LCAs have been carried out by Genan in 2009. The main purpose was to compare material recycling of the tyres to either co-incineration in cement kilns (2009a) or civil engineering applications (2009b), i.e. as a drainage layer. In both studies material recycling is the favourable option.

1.3.4 Østfoldforskning (2010)

An LCA was performed by Norwegian Østfoldforskning in 2010 (Lyng & Brekke, 2010). The scenarios included were drainage layer on landfills, artificial turfs, rubberized asphalt, shock absorbing floors on playgrounds, water filtration mediums and noise banks. Also in this report the use of ELTs in artificial turfs is the most favourable option, looking at the GWP. The least favourable option is ELTs used in asphalt.

1.3.5 Ecotest (2015)

A Dutch LCA performed by Ecotest in 2015 compared different artificial turf infill materials: SBR (Styrene-Butadiene Rubber) (i.e. used tyres), PU-coated SBR, EPDM, TPE and the natural infill material cork. The study compared GWP and costs, and the conclusion was that cork had the lowest GWP of the five alternatives but the third highest cost (Ecotest, 2015). It is important to know when comparing the results that the functional unit was "per ton of infill", which in the end application (artificial turf) is not a comparable function as mentioned earlier.

2 Life cycle assessment methodology

An LCA identifies the potential environmental impacts of a product throughout its life cycle. The environmental aspects could include use of resources and energy, but also aspects related to emissions, such as global warming potential. Depending on the goal and scope, the study could include the product's whole life cycle (i.e. cradle-to-grave) or parts of the life cycle which are affected in the study (cradle-to-gate or gate-to-gate) (ISO, 2006a).

An LCA is an iterative process and consists of the four phases listed below, and the relationships are illustrated in Figure 5 below:

1. goal and scope definition
2. inventory analysis
3. impact assessment
4. interpretation

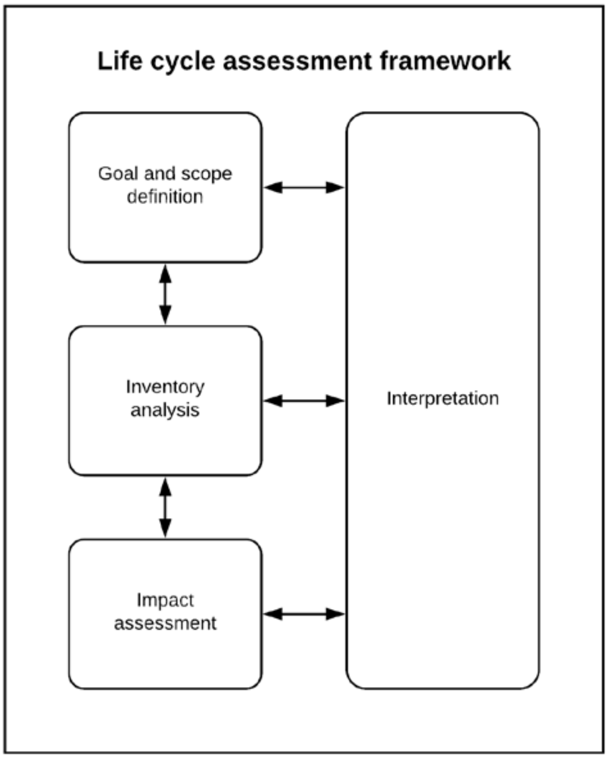


Figure 5: LCA framework and applications of LCA. Based on figure from ISO 14040 (2006a).

These phases are further described in the upcoming parts. A more detailed description of the LCA framework can be found in the ISO standards 14040 (2006a) and 14044 (2006b).

2.1 Goal and scope definition

The first phase of an LCA is the definition of a study's goal and scope. The goal should be clearly defined regarding the intended applications, audience and the reasons for carrying out the study (ISO, 2006b).

When defining the scope of the LCA some of the things that have to be outlined are: which product systems that are included, the functions and comparability of them, which functional unit should be used, relevant system boundaries and level of detail, how to solve the possible multi-functionality and which environmental impact categories are relevant for the study. Issues like data quality and lack of data have to be addressed as well (ISO, 2006b).

2.2 Inventory analysis

The second phase of an LCA is the life cycle inventory analysis. The main purpose of this stage is to make an inventory of the input and output data regarding the systems under study. An inventory analysis includes material inputs (both technical materials and resources from the natural environment), energy consumption, material outputs (products, by-products and wastes), transports and direct emissions to the environment (air, water or ground).

Depending on the level of detail and the goal of the study collection of data is an essential component of the LCA. If a life cycle inventory (LCI) study is performed the inventory analysis itself is the main result and no assessment of the potential environmental impacts is made.

2.3 Impact assessment

The third phase of an LCA is the life cycle impact assessment (LCIA) where the main purpose is to translate the results from the inventory analysis to potential environmental impacts. Depending on the impact categories chosen in the goal and scope definition, the environmental impacts are expressed in different units. Examples of impact categories include climate change, acidification, eutrophication, toxicity and resource depletion.

The result can either be expressed as midpoint-categories (e.g. climate change, acidification, toxicity) or endpoint-categories (human health, finite resources, ecosystem quality) depending on the goal and intended audience of the LCA. Optional elements of the LCA include normalisation, grouping and weighting (ISO, 2006b).

2.4 Interpretation

The final phase of an LCA is the life cycle interpretation. The main purpose is to summarise and discuss the LCI and LCIA results with regards to limitations of the study and the goal and scope definition. Conclusions and recommendations regarding the LCA results should be included.

In the interpretation phase it is of great importance to identify data gaps or other significant issues that were unresolved in the LCA and evaluate them with the purpose of making correct conclusions. A sensitivity analysis or other ways to evaluate inconsistencies or limitations should be performed (ISO, 2006b).

3 Artificial turf infill materials

3.1 Background

There are a number of different infill materials available on the market where the most popular materials are SBR (produced from used tyres), EPDM and TPE (which are produced from virgin resources, i.e. petroleum). Natural infill materials, such as granulated cork, coconut husk, walnut husk and silica sand have become more popular in the recent years, partly as a solution to the problem related to the dispersion of microplastics. Turfs that require no infill material such as natural grass and hybrid grass are also popular but have not been assessed in this LCA. The different infill materials may look similar, in some cases identical, and may share some characteristics when applied on artificial football fields. However, the production and raw materials needed to produce infills are diverse.

In an LCA published by IVL in the year 2012, authored by Alongi Skenhall, Hallberg and Rydberg, three different granulated infill materials were compared: granulated tyres, EPDM and TPE. The results showed that of all three materials granulated tyres had the lowest environmental impact with regards to all studied impact categories. Ragn-Sells Tyre Recycling are interested in updating the LCA and adjusting it to today's artificial turf constructions and material choices. A natural infill, cork, has been included as an infill alternative.

3.2 Goal and scope of the LCA

3.2.1 Goal definition

The goal of this LCA is to analyse and compare the differences in environmental impacts between granulated infill materials used in artificial football fields in Sweden. The infill materials included in the assessment are SBR, EPDM, TPE and expanded cork.

3.2.2 Function and functional unit

The main function of the studied systems is the production of granulated infill material used in artificial football fields. The purpose of the infill is to provide shock absorption, better rolling properties and to minimise injuries for football players. Due to inherent differences of the materials (such as density) different amounts of infill material are needed to fill one football field. The functional unit (FU) is therefore 1 football field defined as 7881 m^2 (71 m x 111 m) the same as in Alongi Skenhall et al. (2012). The lifespan of the field is estimated to 10 years[1]. After this time the artificial grass is usually changed.

3.2.3 System boundaries

The system boundaries of the LCA start with extraction of raw materials and ends with the transport of granulate to the location of the artificial turf, which is assumed to be Stockholm. In the case of SBR, the system boundaries start with the collection of used tyres and end with the transport of granulate to the assumed location of the football field.

Only the production of the infill material has been included within the system boundaries. All other parts of the football field (foundation, shock pad, sand and artificial grass) has been excluded since

[1] Ingvar Björkman, Field developer, Svenska Fotbollsförbundet, personal communication in June 2018

they are assumed to be equal in all scenarios and therefore do not contribute to the overall comparison.

The use phase of the football field, i.e. maintenance, plowing, harrowing and machinery needed for refilling of granulate etc, has not been included. The need for refilling of granulated material varies from field to field and is dependent on many parameters; compaction of the material over time, what type of turf system, how the field is maintained (where plowing is an important factor) and how often the field is used have an impact on how much refilling the field needs. The impact of refilling of granulate has been tested in a sensitivity analysis. The loss of granulate from the fields that end up in the aquatic environment has not been further assessed in this LCA due to lack of consistent data and lack of adequate characterisation factors. Ragn-Sells provide recommendations on turf management actions to prevent spreading of granulate to the environment.

Environmental risks in the form of metal leaching from the infill materials has not been included in the LCA. Alongi Skenhall et al. (2012) concluded that leaching of metals from SBR, EPDM and TPE does not constitute a substantial problem for artificial turfs. One possible exception was leaching of zinc, where SBR and EPDM presented higher leaching than TPE. Magnusson (2015) presents leaching tests of SBR, EPDM, R-EPDM and TPE. Leaching of all metals, except zinc, were below the detection limits. R-EPDM had the highest leaching of zinc. All detected concentrations were below the limits for drinking water standards and in parity with storm water. Supposedly leaching of metals from cork infill is lower or non-existent in comparison to the earlier mentioned infills.

Health risks related to the exposure of rubber granulate in artificial football fields have not been assessed in this LCA. The European Chemicals Agency (ECHA) (ECHA, 2017) has found no health risks related to playing on artificial football fields containing recycled, granulated tyres. Substances that are present in tyres are, for example, polycyclic aromatic hydrocarbons (PAHs). These are carefully controlled by REACH since 2010 and very few tyres manufactured before this year are still circulated within the system.

The life span of the artificial turf is estimated to be 10 years. According to Björkman[2] a normal football field with approximately 2000 playing hours per year and sufficient maintenance lasts 8-10 years. To be able to make a fair comparison the infills are assumed to be shipped or transported to the same final location: in this LCA it is assumed that Stockholm is the place of application.

The end-of-life treatment of the artificial turf system has not been included. Both incineration and reuse of the infill are possible today, depending on the quality and price of the infill. Wastes and by-products of sufficiently small amounts arising during the production of infills have been cut off in order to focus on the main material streams.

3.2.4 Impact assessment categories

The impact categories considered to be relevant in this study are climate change, fossil fuel depletion, agricultural land use, water depletion, terrestrial acidification, freshwater and marine eutrophication and photochemical oxidant formation. Characterisation factors for the ReCiPe 2008 method (hierarchist perspective) were used, apart from the category climate change, where the most recent characterisation factors from IPCC 2013 were used. Long-term effects are excluded.

[2] Ingvar Björkman, Field developer, Svenska Fotbollsförbundet, personal communication in June 2018

Table 3: List of included impact categories, indicators, impact assessment models, units and examples of relevant contributors to each impact category.

Impact category	Indicator	Impact assessment model	Unit	Contributors
Climate change	Global warming potential	IPCC 2013	kg CO_2-eq	Carbon dioxide, methane, nitrous oxide etc.
Fossil fuel depletion	Fossil depletion potential	ReCiPe 2008	kg oil-eq	Fossil fuels (crude oil, natural gas, coal)
Land use	Agricultural land occupation potential	ReCiPe 2008	m^2*yr	Occupation (annual and permanent crop, forest, shrub land)
Water depletion	Water depletion potential	ReCiPe 2008	m^3	Water (from rivers, lakes, wells)
Acidification	Terrestrial acidification potential	ReCiPe 2008	kg SO_2-eq	Sulphur dioxide, nitrogen oxides, ammonia
Eutrophication	Freshwater eutrophication potential	ReCiPe 2008	kg P-eq	Phosphorus and phosphate emissions to water
	Marine eutrophication potential	ReCiPe 2008	kg N-eq	Emissions of nitrogen compounds to air and water
Photochemical oxidant formation	Photochemical oxidant formation potential	ReCiPe 2008	kg NMVOC	Volatile organic compounds (alcohols, aldehydes etc.) and nitrogen oxides

3.2.5 Data quality

Data on production of rubber granulate from used tyres were provided by Ragn-Sells. Data on production of infill materials EPDM and TPE were mainly based on information from Alongi Skenhall et al. (2012) with respect to the material composition and assumptions regarding the contents of additives used in the production. Information regarding the origin of the products and bulk densities were based on information from the artificial turf system supplier Unisport[3]. Data on production of expanded cork granulate were taken from Demertzi et al. (2017). All background data were taken from the LCA database ecoinvent v. 3.4 (Wernet et al., 2016) and are listed in Appendix A.

[3] Andreas Jakobsson, Business unit manager, Unisport, personal communication in May 2018.

3.3 Life cycle inventory

A typical construction of an artificial turf system is presented in Figure 6 below. Not all artificial turf systems require a shock pad, although in this LCA a pad was assumed. The use of cork infill (or any natural infill) require a shock pad to achieve better shock absorbance. EPDM and TPE do not require a pad although it reduces the costs of infill material.

If a shock pad is used the height of the artificial grass is lower than for a turf system without one. According to Unisport's website it is recommended to not design an infill layer with a height of less than 15 mm when using a shock pad. The purpose of this is to make the field playable during winter and to increase the overall playability (Unisport, 2018a).

A layer of sand is used to provide stability of the grass, and rubber granulate is used to provide a layer of spring and better rolling properties. However the purpose of this LCA is to compare different infill materials and the rest of the artificial turf system (i.e. grass, sand and shock pad) are assumed to be equal for all scenarios and therefore do not contribute to the overall comparison. This means that the final results do not present the environmental impacts of the complete artificial turf system but only the differences related to the choice of infill material.

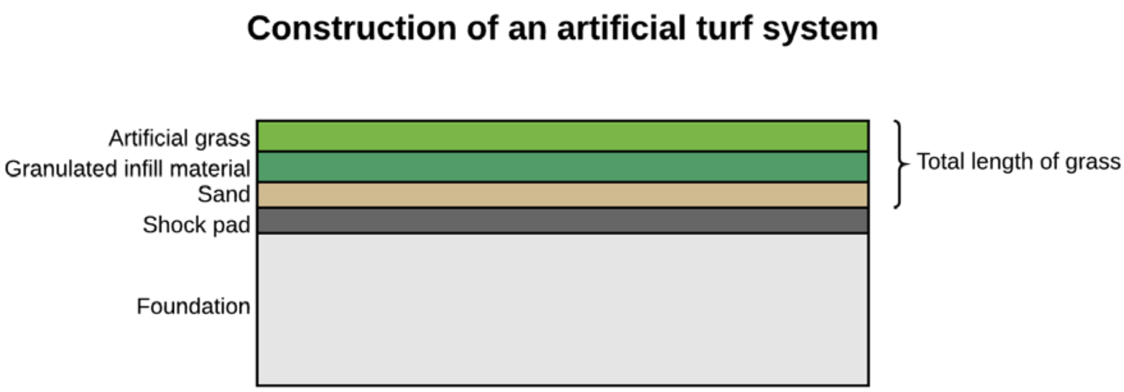


Figure 6: A simplified figure presenting the construction of an artificial football field including artificial grass, rubber granulate, sand, shock pad and foundation.

In Table 4 below the amounts of different infill materials are listed, expressed as per football field. Information regarding the bulk densities were obtained from reseller Unisport (cork), Ragn-Sells (SBR), SO.F.TER (TPE, product Holo) and Stargum and Unirubber (EPDM). Information regarding densities of TPE and EPDM were based on rough estimations made by Unisport (500-600 kg/m^3). Based on this estimation, more detailed data regarding densities were obtained by studying technical data sheets of different EPDM and TPE producers. There are however large variations in bulk densities of different TPE and EPDM infills: both low-density and high-density materials are available on the market. This affects both the price, playability and life span of the material. The purpose of this LCA is to give a general picture of the infill materials and it is therefore important to consider the many possible variations of artificial football field constructions when analysing the results.

Table 4: List of included infill materials, bulk densities and the amount of infill required to fill a football field.

Infill material	Bulk density	Amount of infill per football field (7881 m^2, 15 mm infill layer)	Life span
SBR	440 kg/m^3	52 tons	10 years
Cork	70 kg/m^3	8,3 tons	4 years
EPDM	650 kg/m^3	77 tons	10 years
TPE	550 kg/m^3	65 tons	10 years

In Figure 7 below, the system boundaries of the production of infill materials are illustrated. For all infill types the systems end with transport of the granulate to the location of the football field, which in this LCA has been assumed to be Stockholm. Since SBR is a recycled material the system boundaries start with the collection of tyres from local tyre workshops. Tyre manufacturing as well as raw material acquisition has been cut off since it belongs to the first production system.

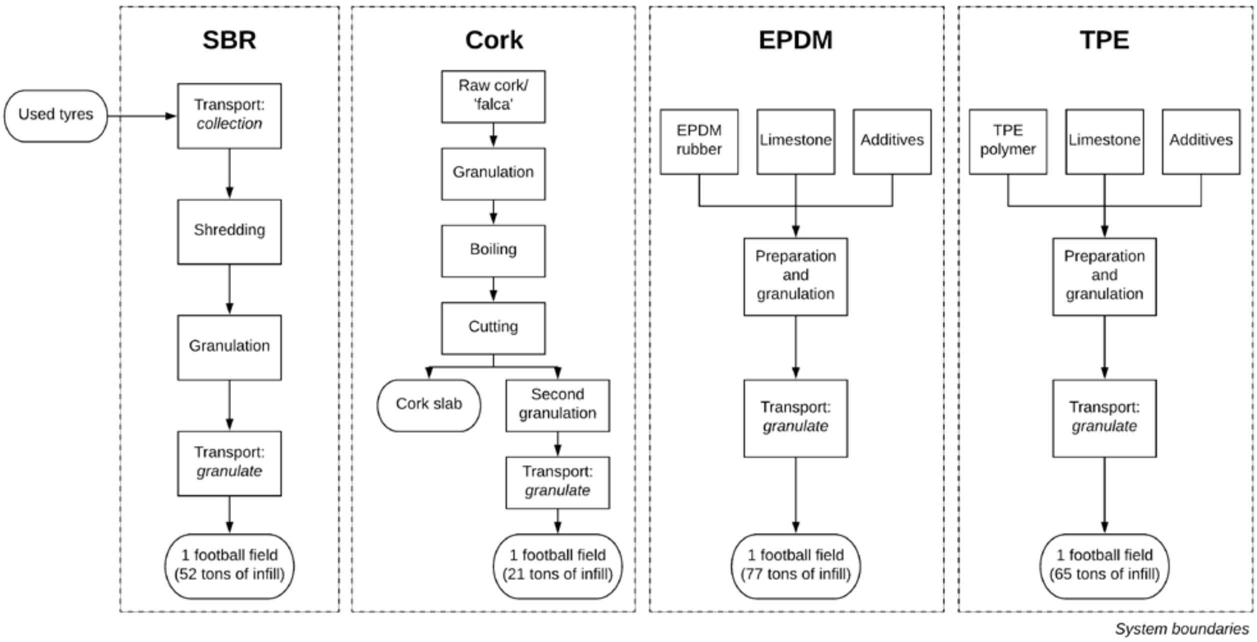


Figure 7: Flow schemes illustrating the included processes and system boundaries of artificial turf infill production.

3.3.1 SBR

SBR, or rubber granulate produced from used tyres, is used as an infill material in approximately 60% of all artificial turfs in Sweden. In total, there are approximately 630 artificial turfs in Sweden and 100 fields are being built every year (Wallberg et al., 2016).

Ragn-Sells is the sole producer of rubber granulate in Sweden and Norway and owns a granulate factory in Vänersborg, Sweden. Granulation of tyres is a purely mechanical process where the rubber is separated from the steel cords and the textile. No other additives or materials are used in the process.

The contents of rubber granulate are presented in Figure 8 below (excluding steel and textile). Zinc oxide and sulphur are used as vulcanisation agents and are present in both SBR and EPDM infill. Any environmental impacts originating from the first production system, i.e. production of tyres, are not allocated to the recycling system and has been cut off.

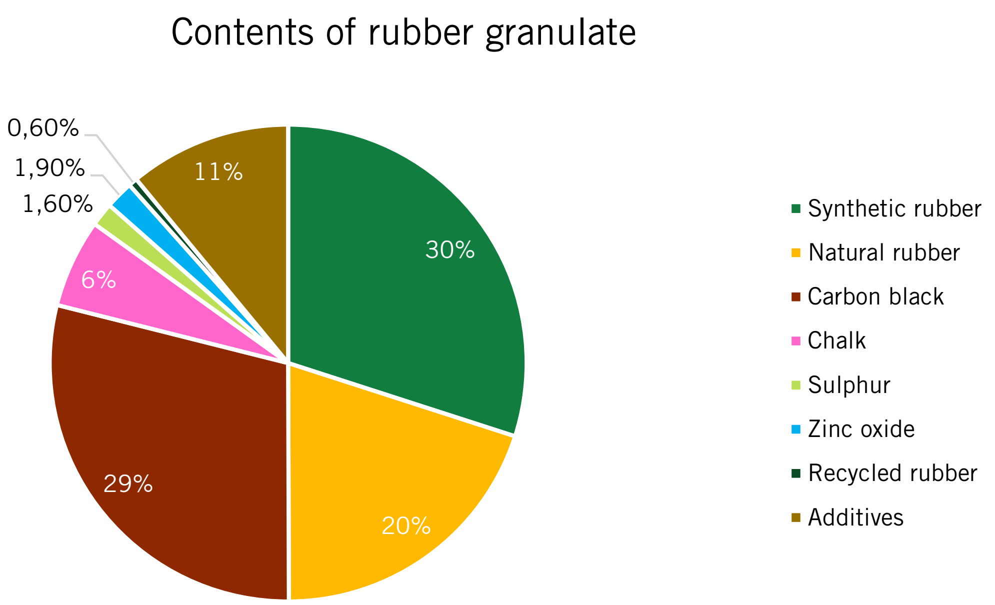


Figure 8: Contents of rubber granulate made from ELTs. From Alongi Skenhall et al. (2012).

A typical collection route is 150 km where used tyres are collected from local tyre workshops. The tyres are then shredded and granulated at the factory in Vänersborg. Apart from the rubber granulate, steel and textile are separated in the process (15-20% steel, 15-20% textile) resulting in a material exchange of approximately 60% for the rubber granulate. Steel and textile have not been treated as by-products, all impacts have been allocated to the rubber granulate. Three size fractions of rubber granulate are produced; fine, medium and coarse. The fine fraction represents 8% of the total rubber granulate output. Depending on the demand, coarse granulate can be shredded into medium size granulate, which is mainly used as an infill material on artificial turfs. The electricity consumption for shredding and granulation is 212 kWh/ton of incoming tyres[4]. The price of SBR granulate is approximately 200 € per ton[5].

The rubber granulate is transported by lorry from Vänersborg to Stockholm, where the granulate is assumed to be used in an artificial football field. The transport distance is 420 km. The inventory analysis of SBR granulate production at Ragn-Sells factory is presented in Table 5 below.

[4] Peter Svahn, Head of section tyres, Ragn-Sells Tyre recycling, personal communication in May 2018.
[5] Sara Stiernström, Business developer, Ragn-Sells Tyre recycling, personal communication in August 2018.

Table 5: Inventory analysis of SBR granulate production at Ragn-Sells granulate factory in Vänersborg, Sweden.

Unit process: production of SBR infill		
Reference products	**Quantity**	**Unit**
Rubber granulate	1000	kg
Steel	340	kg
Textile	340	kg
Inputs		
Used tyres	1730	kg
Electricity	368	kWh
Outputs		
Steel studs, gravel, dust	50	kg
Transports		
Collection of tyres (lorry 16-32 tons)	150	km
Granulate to Stockholm (lorry 16-32 tons)	420	km

The lifespan of rubber granulate produced from used tyres is usually the same as for the artificial grass, i.e. 8 to 12 years[6]. In this LCA a life span of 10 years has been assumed, matching the life span of the turf.

3.3.2 Cork

Cork is a natural infill made from the bark of cork oak trees. The main product produced from cork is wine stoppers, but this requires a bark of high quality which can only be obtained from the third harvest and forward. The cork from the first two harvests becomes raw material for insulation, flooring and more. Cork bark is regenerated and is harvested every nine years. A tree lasts on average for 200 years (Amorim cork composites, 2018).

Unisport, a reseller of artificial turf systems, sells a cork infill named eCork. The cork is expanded meaning that the granules are boiled. This results in a lighter product with a bulk density of 70-80 kg/m^3 while natural, untreated cork granulate has a density close to 200 kg/m^3 (Corklink, 2018; Cork-shop, 2018; Greenplay, 2018). However this varies depending on what part of the bark is used (inner or outer). The expanded cork is more freeze-resistant and does not absorb water as easily as untreated cork or other natural infill materials (Unisport, 2018b). The price of expanded cork granulate is around 500 € per ton.

Inventory data on production of expanded cork granules have been extracted from Demertzi et al. (2017). The article contains a life cycle inventory and life cycle assessment on expanded cork slab and the co-product expanded cork granules. Cork slab is the main product and is used as an isolation material. Cork granulate is produced from the rejected slabs and residues which does not meet the

[6] Sven Åke Hoel, Sales manager tyres/rubber granulate, Ragn-Sells Tyre recycling, personal communication in June 2018

correct criteria. A mass-based allocation principle has been implemented, resulting in allocation factors of 25% to cork granulate and 75% to cork slab.

To match the level of details of the other infill materials, some inventory results have been excluded in the impact assessment, for example small waste streams, some transports and production of packaging materials.

The raw cork, or ‘falca’, refers to the virgin bark (first bark) grown on cork trees. The virgin bark is of low quality and cannot be used in the production of cork stoppers. Both cork slab and cork granules are mainly used as insulation materials. The bark is transported to a separation location where the bark is separated from the wood and then transported to the manufacturing industry where the bark is dried for about 6 months. The dried cork is then granulated and impurities are separated. Cork dust, a by-product, is used as a fuel in the agglomeration stage. The granules are heated up in water vapour to about 360°C for approximately 20 minutes. The granules expand up to 30% of their initial size and their natural resins are extracted, resulting in a block form. After the blocks are stabilized they are cut into the desired shapes. The slabs that are rejected and the residues from the cutting stage are granulated again, producing the co-product cork granules (Demertzi et al., 2017). The cork granules are assumed to be shipped from Portugal to Gothenburg and later transported by lorry from Gothenburg to Stockholm.

The life span of cork granules used as an infill material is on average 3-4 years, depending on the quality of the cork[7]. Due to the relatively short life of the cork granules the infill layer needs to be exchanged approximately 2,5 times during the life of the artificial grass (if a span of 4 years is assumed). Per functional unit, which is defined as 1 football field with an expected life span of 10 years, approximately 21 tons of cork granules are required.

Natural infills generally require more maintenance than synthetic infills: irrigation, de-compaction twice a year and replacement of infill due to composition and wind throw. Organic materials harden which could lead to reduced performance of the turf and an increased risk or injuries for players (Bauer et al., 2017).

Cork granulate has not been on the Swedish market for long. The first football field using cork infill was built 7 years ago. According to Björkman[8] the infill still works well, although not during winters. The cork infill used was not expanded. In Table 6 below the inventory analysis for production of 1 ton of cork granules is presented.

[7] Ole Myhrvold, Field Manager, Norges Fotballforbund, personal communication in June 2018
[8] Ingvar Björkman, Field developer, Svenska Fotbollsförbundet, personal communication in June 2018.

Table 6: Inventory analysis of expanded cork granules.

Unit process: production of expanded cork granules (based on Demertzi et al. 2017)			
Reference products	**Quantity**	**Unit**	**Comment**
Cork slab	670	m^2	Main product
Cork granules	1000	kg	Co-product
Inputs from technosphere			
Raw cork, 'falca'	10700	kg	
Burnt cork dust	68400	MJ	
Sludge	3,68E-02	kg	
Diesel (for internal transports)	773	MJ	
Electricity	563	kWh	
Inputs from environment			
Water	28,2	m^3	
Outputs			
Ashes	48,3	kg	
Stones	403	kg	
Soil	403	kg	
Transports			
Pruned branches	50	km	
Raw cork from separation location to industrial unit	30	km	
Cork dust from another industry	30	km	
Granulate from Amorim Isolamentos SA to Stockholm	3600	km	Barge tanker and lorry
Emissions to air			**Sub-category**
CH_4	2,05	kg	Non-urban air or from high stacks
CO	39,0	kg	Non-urban air or from high stacks
N_2O	0,27	kg	Non-urban air or from high stacks
NH_3	2,53	kg	Non-urban air or from high stacks
NMVOC	1,63	kg	Non-urban air or from high stacks
NOx	21,5	kg	Non-urban air or from high stacks
PM	16,5	kg	Non-urban air or from high stacks
SO_2	0,75	kg	Non-urban air or from high stacks

3.3.3 EPDM

EPDM, or ethylene propylene diene monomer rubber, is a type of synthetic rubber. Like SBR it is vulcanised. EPDM can be produced from both virgin and recycled rubber (R-EPDM). In this LCA only virgin EPDM is included. There are a number of different qualities of EPDM available on the market, both high- and low density types. One EPDM producer, Stargum, produces infills where the bulk density varies between 450-670 kg/m^3 (Stargum, 2018). The price of EPDM is approximately 1300-1600 € per ton according to Bauer et al. (2017), and 700 € per ton for R-EPDM.

The composition of EPDM infill was obtained from Alongi Skenhall et al. (2012) which obtained information from EPDM producers Melos and Gezolan. The inventory analysis for EPDM infill production is presented in Table 7 below.

The EPDM infill is assumed to be produced in Central Europe and the transport distance between the factory and the football field in Stockholm is estimated to 1750 km. The infill is assumed to be transported by lorry. Depending on the quality of the EPDM infill, the lifespan varies. According to Myhrvold[9] it is common to reuse the infill if the quality is good, however if the quality is bad it only lasts for 5-6 years before it crumbles. Therefore it is estimated that an average lifespan for EPDM is 10 years. According to Bauer et al. (2017) high levels of chemical fillers cause premature aging and degradation.

Table 7: Inventory analysis of EPDM infill production.

Unit process: production of EPDM infill		
Reference product	**Quantity**	**Unit**
EPDM infill	1000	kg
Inputs		
EPDM rubber	220	kg
Limestone	680	kg
Mineral oil	80	kg
Phthalates	20	kg
Electricity	214	kWh
Transports		
Granulate to Stockholm (lorry)	1750	km

3.3.4 TPE

TPE, or thermoplastic elastomers, is a generic term for extruded plastics made from a rubber and plastic polymer. Unlike EPDM, TPE is not vulcanised. TPE is often composed of ethylene, butadiene and styrene compounds, and usually SEBS (Styrene Ethylene Butadiene Styrene) is used as raw material (Magnusson, 2015). No data on production of SEBS have been accessed for this LCA. To avoid data gaps, data on production of ABS (Acrylonitrile Butadiene Styrene), another kind of TPE,

[9] Ole Myhrvold, Field manager, Norges Fotballforbund, personal communication in June 2018

was used. The composition of TPE was also obtained from Alongi Skenhall et al. (2012) which obtained information from TPE producer Terra.

Like EPDM, there are a number of different types and marks of TPE infills available on the market today. Terra, for example, produces both a standard type infill and a hollow variant, called Holo, with a lower bulk density. The bulk densities are within the span on 550 to 850 kg/m^3. The price of TPE infill can be between 1600 and 1800 € per ton.

TPE, like EPDM, is assumed to be produced in Central Europe. It is common to reuse the TPE infill when the artificial turf is being exchanged. However, depending on the quality, different types of TPE infills can have shorter lifespans. Therefore a lifespan of 10 years has been assumed in this LCA. The inventory analysis of TPE infill is presented in Table 8 below.

Table 8: Inventory analysis of TPE infill production.

Unit process: production of TPE infill		
Reference product	**Quantity**	**Unit**
TPE infill	1000	kg
Inputs		
TPE polymer	400	kg
Limestone	400	kg
Mineral oil	160	kg
Phthalates	40	kg
Electricity	214	kWh
Transports		
Granulate to Stockholm (lorry)	1750	km

3.4 Life cycle impact assessment

In this chapter, the results of the LCA are presented. The chapter is divided into all impact categories, normalisation of the results and sensitivity analyses. Some of the environmental impact categories (photochemical oxidant formation, freshwater eutrophication, marine eutrophication and acidification) are presented in Appendix B instead of in the main report.

3.4.1 Global warming

The results from the global warming category, as presented in Figure 9 below, show a clear ranking of the infill materials with regards to their environmental footprint. TPE and EPDM have 30 and 16 times higher global warming potential than SBR. Expanded cork have roughly 1,7 times higher impact than SBR.

Although the cork is transported nearly 8 times further than SBR granulate the environmental impact of the transport is equal. It was assumed that the cork is transported from Portugal to Sweden by ship, which has a very low impact compared to transport by lorry, if expressed per ton of product.

The impact of the transport of EPDM and TPE infill are considerably higher since they are assumed to be transported by lorry. If another mode of transport were to be evaluated, e.g. train, the ranking of the materials would not differ. The raw materials of both EPDM and TPE infills are primarily based on fossil resources, i.e. petroleum, and therefore contribute to the global warming potential.

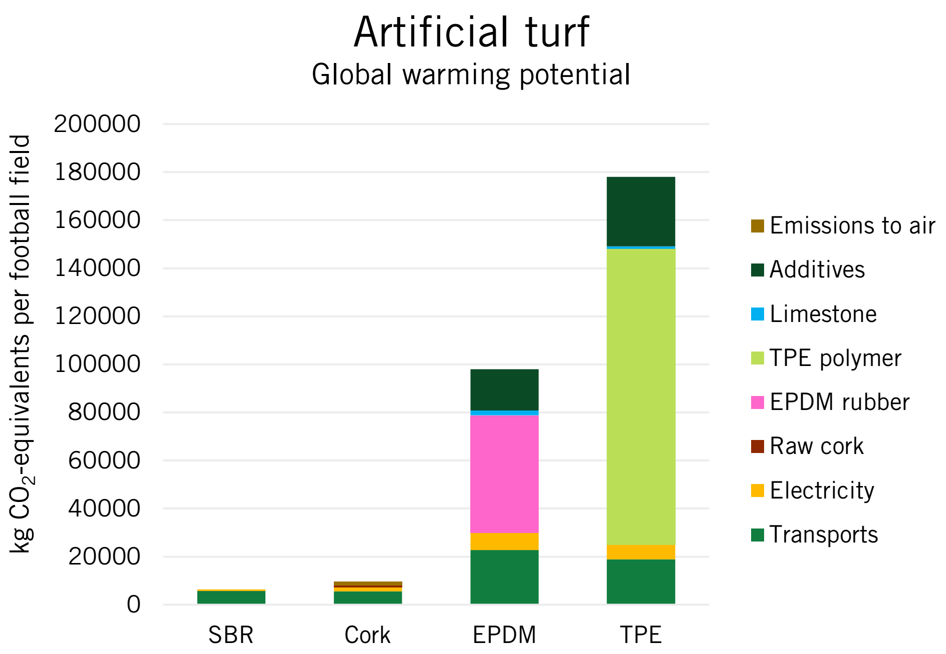


Figure 9: Comparison of global warming potential of infill materials. The results are expressed in kg CO_2-equivalents per functional unit.

3.4.2 Fossil fuel depletion

The results for the category fossil fuel depletion are similar to those in the climate change category. The reason for this is that global warming is mainly caused by combustion of fossil fuels. However this category does not describe the environmental impact caused by fossil fuels, it simply states the amount of fossil fuels needed to produce the infills.

One clear trait from the result in Figure 10 below is that EPDM and TPE infill have a higher depletion potential of fossil fuels than SBR and cork granulate. This is perhaps not a surprise since both EPDM and TPE infills are products based on petroleum (synthetic rubber and polymer). The contents of the additives (mineral oil and phthalates) are petroleum based as well.

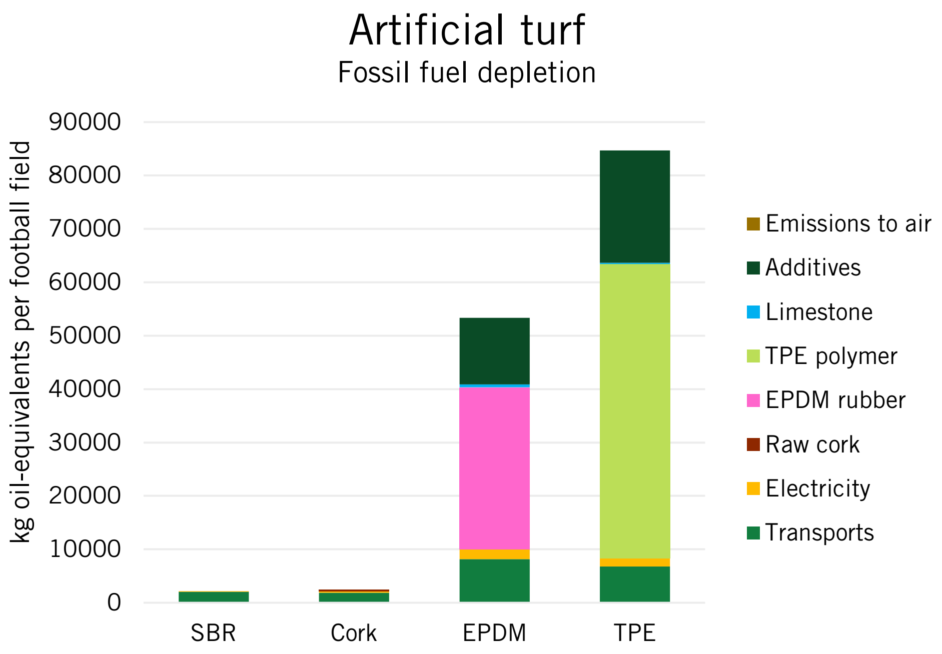


Figure 10: Fossil fuel depletion comparison of infill materials. Results expressed in kg oil-eq. per functional unit.

3.4.3 Land use

Since a natural infill is included in the comparison, agricultural land use as an impact category is of interest in the LCA. The results are presented in Figure 11 below.

Nearly 88 hectares of agricultural land are needed for the production of expanded cork infill required for one football field during 10 years. In other words, 110 football fields of cork oak plantation is needed to produce infill for one football field. If the life span of the field and infill is excluded, the area needed to fill one football field is 35 hectares.

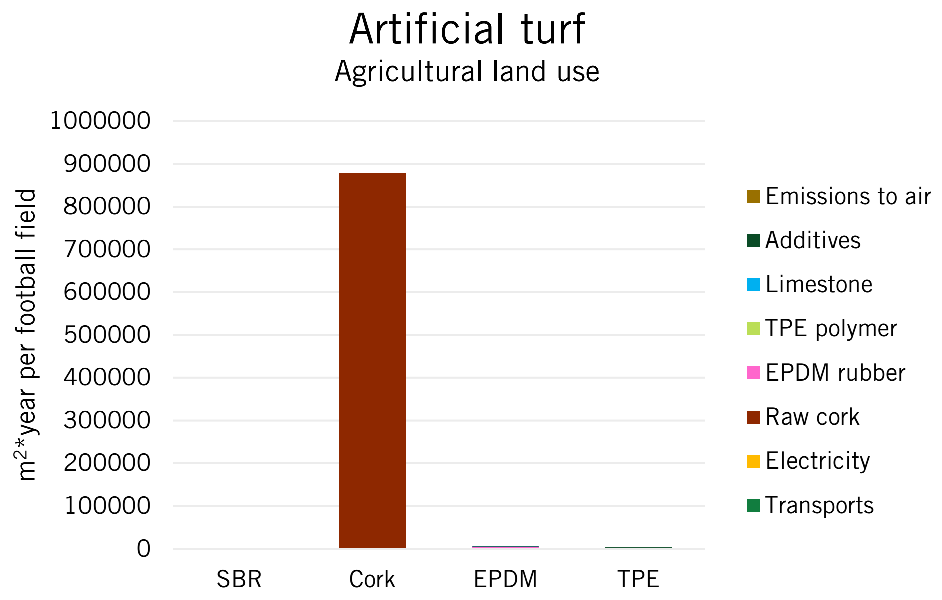


*Figure 11: Agricultural land use comparison of infill materials. The results are expressed in m^2*year per functional unit.*

3.4.4 Water depletion

The water depletion potential is a measurement of the water use related to the production of infill materials. The comparison is presented in Figure 12 below. Also in this category EPDM and TPE have the highest impact, or water consumption. The water needed for the extrusion of cork granules is almost 150 m^3 per football field. If an untreated cork infill were to be included in the comparison this post would not be included. However the natural cork would probably need to be irrigated as a part of the maintenance.

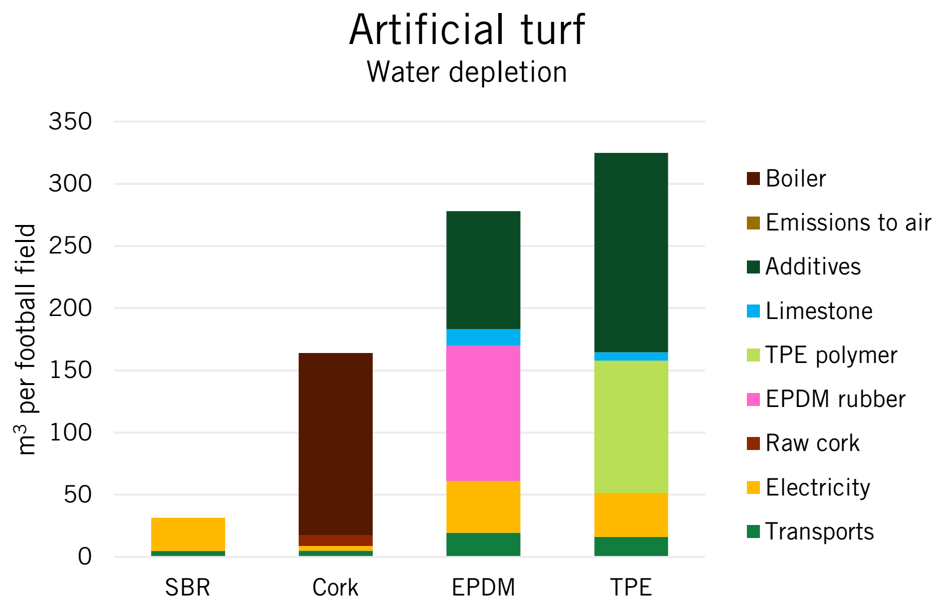


Figure 12: Water consumption comparison of infill materials. The results are expressed in m^3 per functional unit.

3.4.5 Normalisation

To put the results in a wider perspective and express them using a common reference unit, normalisation can be performed. The purpose is to identify which environmental effects are of importance and which are of minor relevance, with regards to one person's annual environmental impact.

Every year approximately 100 new artificial football fields are being built in Sweden (Wallberg et al., 2016). Per person and year, this corresponds to roughly $1 \cdot 10^{-5}$ football fields. Normalisation values, i.e. values of one average European person's annual environmental impact with regards to the studied impact categories, are presented in Table 9 below.

Table 9: Normalisation values and units for all included impact categories. No normalisation factor for water depletion is available.

Impact category	Normalisation value	Unit	Reference
Global warming	9220	kg CO_2-eq/person*year	Sala et al., 2015
Fossil fuel depletion	1556	kg oil-eq/person*year	ReCiPe, 2015
Agricultural land use	4518	m^2*year/person*year	ReCiPe, 2015
Water depletion	-	-	-
Acidification	34,4	kg SO_2-eq/person*year	ReCiPe, 2015
Freshwater eutrophication	0,42	kg P-eq/person*year	ReCiPe, 2015
Marine eutrophication	10,1	kg N-eq/person*year	ReCiPe, 2015
Photochemical oxidant formation	56,9	kg NMVOC/person*year	ReCiPe, 2015

The results in Figure 13 below demonstrates what environmental impact the production of infill material of artificial football fields has per person and year in Sweden. Clearly visible in the figure below is the impact of the land use caused by cork forestry. However, the land use needed for cork oak plantations only represents 0,2% of the total land use per person and year. The fossil fuel depletion potential related to the production of EPDM and TPE is also important to consider. It is assumed in this graph that all new artificial football fields use one type of infill material. In reality a mix of materials is used.

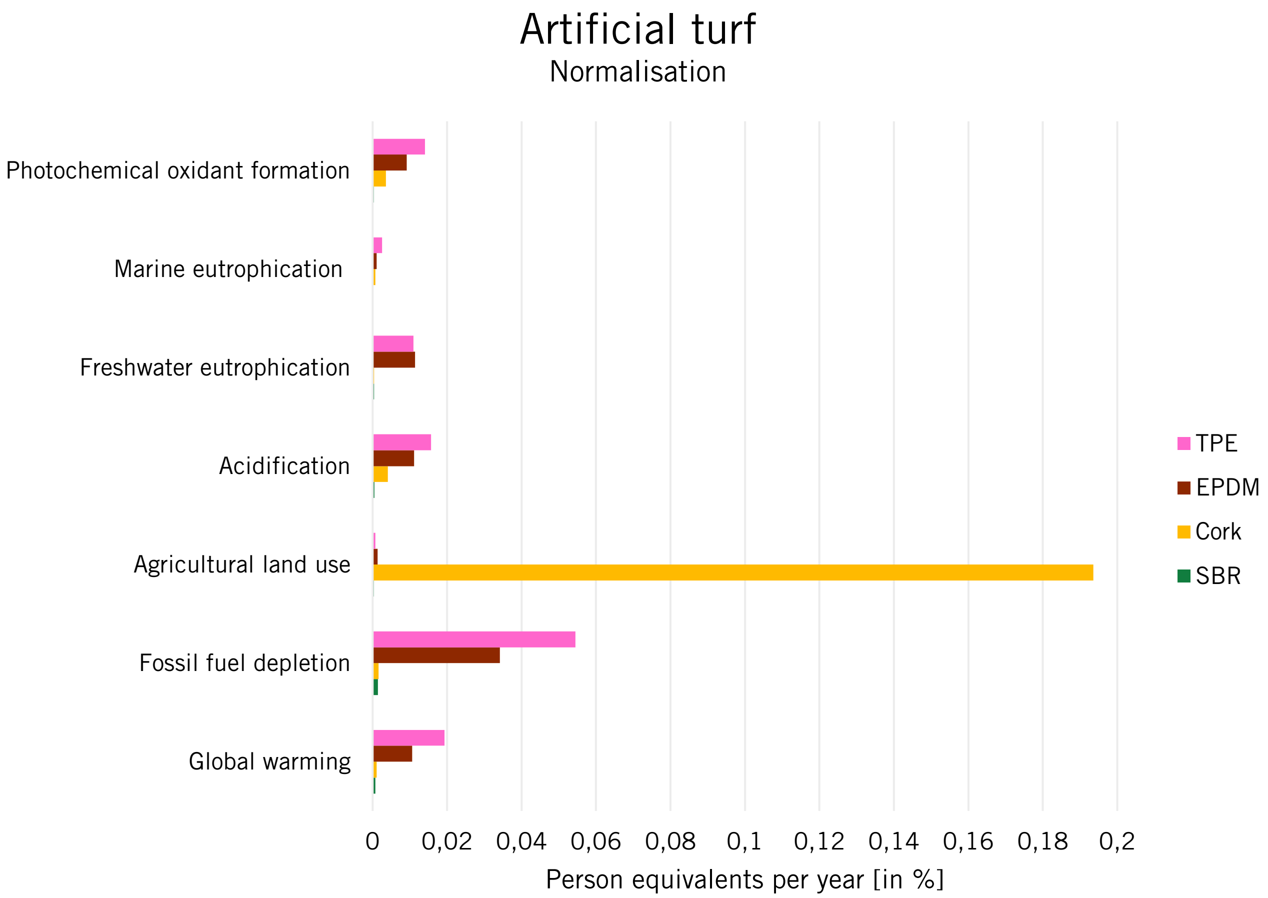


Figure 13: Normalisation of the LCA results comparing different artificial turf infill materials SBR, cork, EPDM and TPE on a common reference unit (person equivalents per year).

3.4.6 Sensitivity analysis

In this chapter some of the assumptions made in this LCA are tested in sensitivity analyses. The first part of the chapter is a compilation of sensitivity analyses, and their effect on the results, made by Alongi Skenhall et al. (2012). For this LCA other parameters were therefore tested.

Table 10: A list of sensitivity analyses made by Alongi Skenhall et al. (2012) and their effect on the results.

Sensitivity analysis made by Alongi Skenhall et al. (2012)	Effect on results
Allocating impact to steel and textile from granulation of tyres	Decreased the total GWP of tyre granulate with 12,5%. No difference in ranking: tyres still have the lowest GWP compared to EPDM and TPE.
Include production of artificial grass and shock pad	Addition of roughly 60 ton CO_2-eq to all scenarios. No difference in ranking. The shock pad was assumed to be manufactured from pressed tyre granulate.
Include end-of-life treatment of granulate	Emission of CO_2 from incineration included within the analysis. System expansion where granulate is assumed to be replaced by natural gas. No difference in ranking.
Include tyre manufacturing	1,5% of the impact from tyre manufacturing was allocated to the ELTs (based on the recycling fee). Addition of 35 kg CO_2-eq to tyre scenario. No difference in ranking.

Alternative bulk densities of EPDM and TPE infill

Both EPDM and TPE infills come in a number of different types and qualities from many manufacturers. To test the impact of the choices made in the LCA regarding the bulk densities, alternative variants of the infills were included. A low density type of EPDM infill were chosen from Stargum (2018) and a solid type TPE were tested from producer Terra (2018). The alternative bulk densities are presented in Table 11 below.

Table 11: Sensitivity analysis where alternative bulk densities of EPDM and TPE are tested.

Infill type	Bulk density (base case)	Amount per football field	Bulk density (alternative case)	New amount per football field
SBR	440 kg/m^3	52 tons	-	-
Cork	70 kg/m^3	21 tons	-	-
EPDM	650 kg/m^3	77 tons	450 kg/m^3	53 tons
TPE	550 kg/m^3	65 tons	850 kg/m^3	100 tons

The results of the analysis are presented in Figure 14 below. Clearly visible is the major impact the bulk density has on the total environmental impact of the infill choice. The GWP of TPE increased with 50% and EPDM decreased by 30%. However the ranking is still the same, i.e. SBR has the lowest GWP and TPE and EPDM have the highest GWP. The density might have an impact on the quality and life span of the infill but this has not been further assessed.

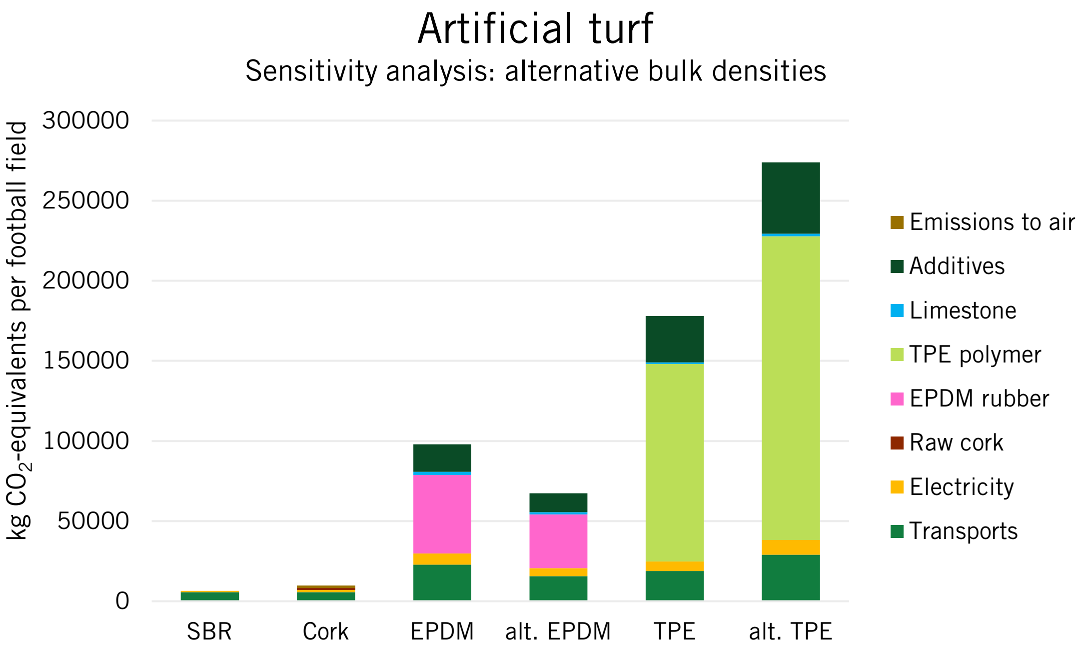


Figure 14: Sensitivity analysis testing the impact of alternative bulk densities of EPDM and TPE. The results are expressed as kg CO_2-equivalents per functional unit.

Assuming reuse of EPDM and TPE infill

According to Björkman[10] it is common to reuse EPDM and TPE infill after the life of the artificial turf is over, depending on the quality of the infills. It is therefore assumed that a new life span of EPDM and TPE is 20 years, i.e. the span of two artificial turfs. This results in a new functional unit:

- 1 football field (7881 m^2, 15 mm infill) during 20 years

The amounts of infills needed for the new functional unit is listed in Table 12 below.

Table 12: Amounts of infill needed with regards to the new functional unit.

Infill type	Adjusted life span	Amount of infill needed per new functional unit
SBR	10 years	104 tons
Cork	4 years	41 tons
EPDM	20 years	77 tons
TPE	20 years	65 tons

[10] Ingvar Björkman, Field developer, Svenska Fotbollsförbundet, personal communication in June 2018.

The end-of-life treatment of the infill which is discarded after 4 or 10 years is not included, which is similar to earlier choices of system boundaries. The machinery and resources needed for the actual turf exchange is not included (similar in all scenarios). The results are presented in Figure 15 below. The assumption of doubled life span did not have an effect on the ranking between the infill types: SBR still have the lowest GWP even though the EPDM or TPE is recycled.

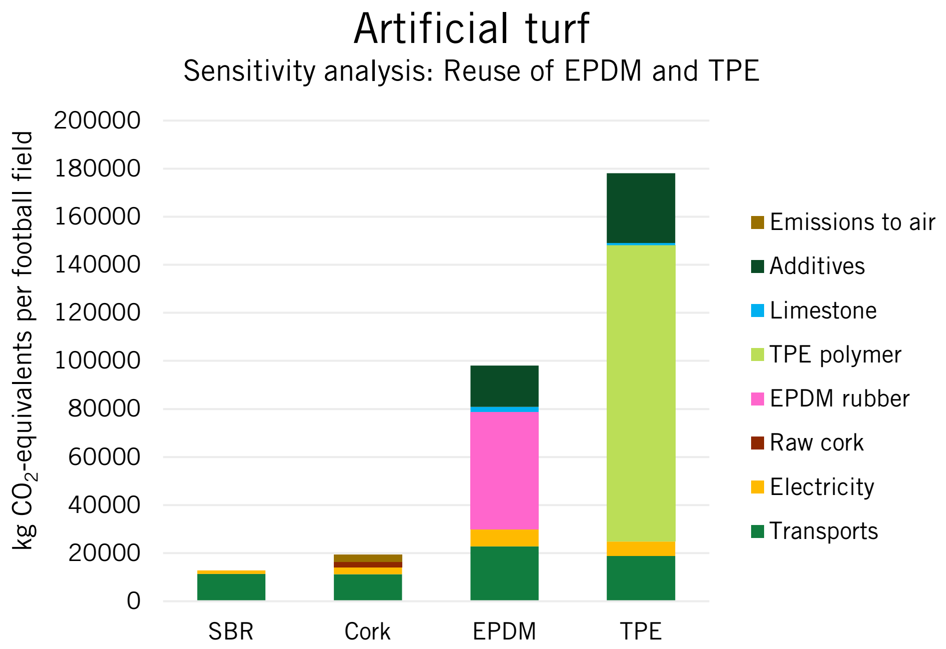


Figure 15: Sensitivity analysis testing the choice of functional unit. The life span of EPDM and TPE have been doubled compared to SBR and cork. The results are expressed in kg CO_2-equivalents per new functional unit.

Including refilling of granulate

The need for refilling of granulate varies from field to field and are affected by many parameters. In Bauer et al. (2017) estimations were made regarding the refilling needs of some types of infill. In general, fields with EPDM and TPE infills need to refill approximately 6-8% per year and fields with cork infill needs to refill 10% due to that cork is a lighter material which will discharge with water and wind more easily. No estimation regarding the refilling need of SBR was made in the report. Due to similar material properties between SBR and EPDM, it was estimated that SBR requires similar refilling as EPDM, i.e. 6-8%.

Table 13: Total amounts of infill needed if refilling of the granulate is included within the assessment.

Infill type	Amount of refilling per year	Total amount of infill needed
SBR	6%	55 tons
Cork	10%	23 tons
EPDM	6%	82 tons
TPE	6%	69 tons

The results of the sensitivity analysis are presented in Figure 16 below, for the impact category climate change. The assumed amounts of refilling needed do not have a major impact on the total results and do not affect the ranking of the infills. Whether the granulate are lost to the aquatic environment or simply compacted on the field have not been further assessed here.

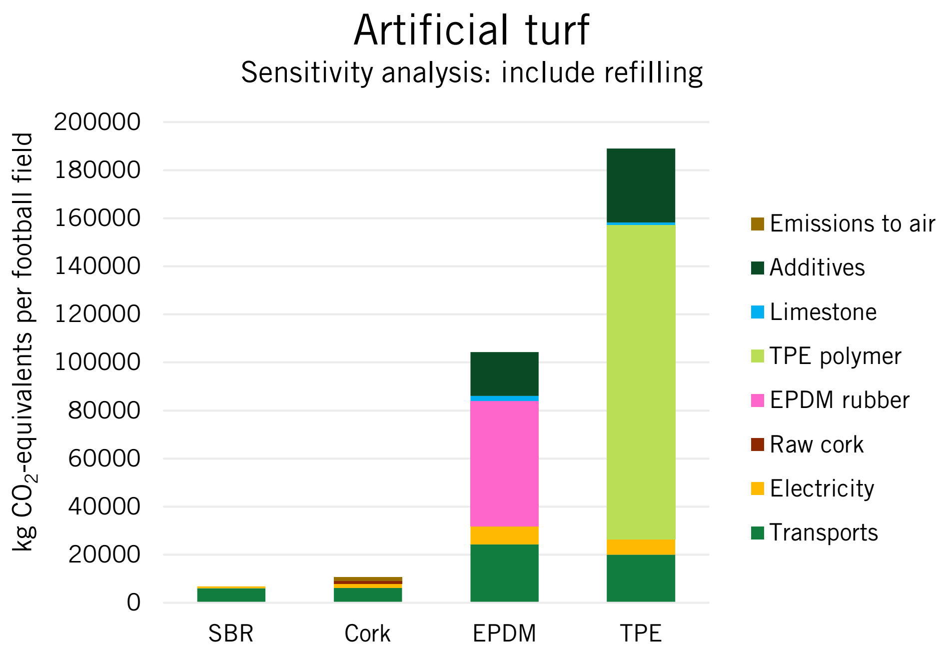


Figure 16: Sensitivity analysis testing the impact of the need for refilling of the granulate. The results are expressed in kg CO_2-equivalents per functional unit.

3.5 Interpretation and discussion

There are many parameters to consider when choosing infill material: low material and maintenance costs, good playability, long durability, high availability and low environmental impact to mention a few. Hopefully this LCA will shed some light on the last mentioned aspect and help deciding what types of environmental aspects are important to consider and which infill material has the lowest environmental impact.

3.5.1 General discussion

One of the motivations of performing this LCA was to make an update of an LCA from 2012 authored by Alongi Skenhall et al. The study compared granulated tyres with EPDM and TPE infills. To validate the results from this LCA some of the results are compared to the LCA from 2012, presented in Table 14 and Table 15 below. The infill material cork was not included by Alongi Skenhall et al (2012) and the results can therefore not be validated. One clear trait is that the GWP of infill production in this LCA is in general higher than the results from 2012. There are many possible explanations for this:

- Use of different databases (ecoinvent versus GaBi database PE Int)
- Different bulk densities of the materials and different height of the infill layer resulting in different total amounts of infill needed per football field
- Half of EPDM and TPE assumed to be shipped from China (2012), transport by lorry from Central Europe in this LCA

- Other characterisation factors were used in 2012 (the method CML 2001 was used then, IPCC 2013 used here)

Table 14: Comparison between the GWP results from this LCA and GWP results from Alongi Skenhall et al. (2012).

Infill material	GWP from Alongi Skenhall et al. (2012) [kg CO_2-eq.]	GWP from this LCA [kg CO_2-eq.]	Difference in GWP [in %]
SBR	5 000	6 400	+28%
EPDM	55 000	98 000	+78%
TPE	165 000	178 000	+8%

Table 15: Comparison of the amounts of infill per functional unit between this LCA and Alongi Skenhall et al. (2012).

Infill material	Amount of infill, from Alongi Skenhall et al. (2012) [tons]	Amount of infill from this LCA [tons]	Difference in amounts [in %]
SBR	51	52	+2%
EPDM	61	77	+26%
TPE	87	65	-25%

The largest difference when comparing the GWP results is for EPDM infill. One reason for this is that a larger amount of infill was assumed in this LCA (77 tons compared to 61 tons). In general, the access to different data sources or databases is a major influence which can lead to a different result. The ranking of the results is however the same, meaning that similar conclusions can be drawn from this LCA as the one from 2012 regarding the comparison of infill materials.

In both LCAs, a shock pad has been assumed to be a part of the construction. A shock pad is required for cork, or any natural infills, to provide better shock absorbance. It is also common to use a shock pad when EPDM or TPE infills are used. The main reason for this is economical since EPDM and TPE are a lot more expensive than SBR and cork. In Figure 17 below, the global warming potential and the cost for the different infill materials are presented together.

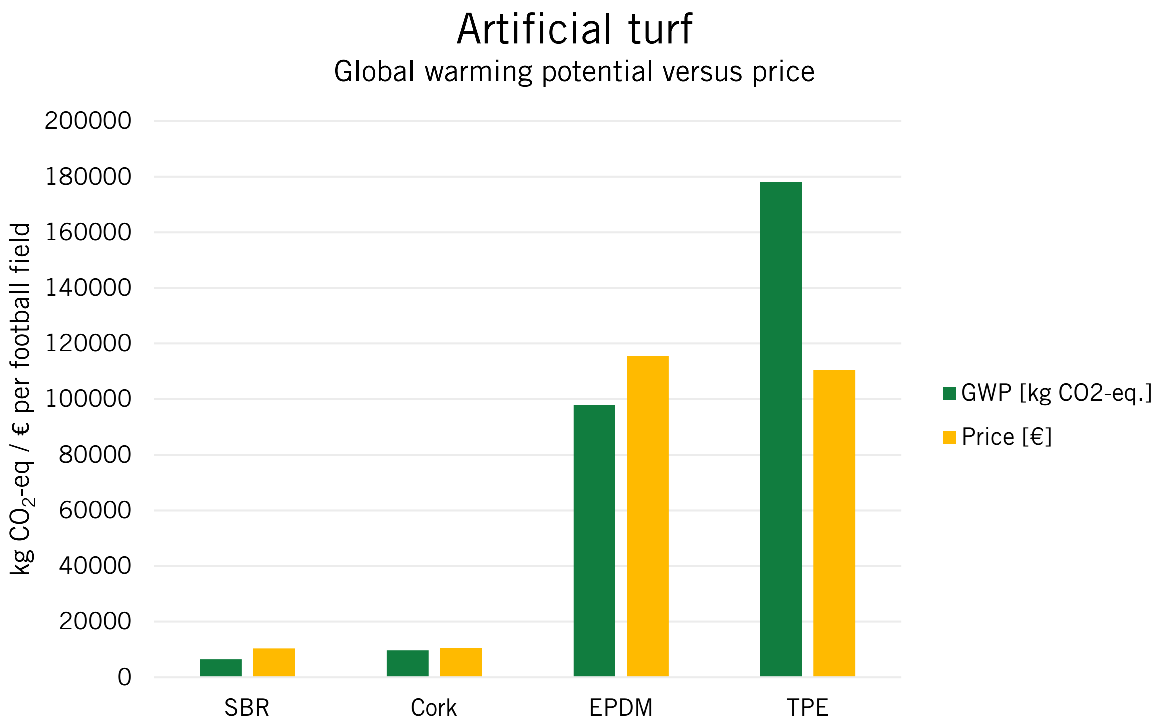


Figure 17: Figure presenting the global warming potential and the cost for different infill materials, expressed in kg CO_2-equivalents and Euro per football field.

3.5.2 Limitations of this study

The aim of this LCA is to give a general picture of the environmental impacts related to production of four infill materials available on the Swedish market. There are many possible variations regarding the construction of the artificial turf, for example if a shock pad is required or not. And there are many variations of the studied infill materials, for example the raw materials, processing of the material, quality and expected life span of the materials. It is difficult to draw general conclusions regarding the characteristics and production of infill materials, and maintenance of the field, but an attempt has been made in this LCA.

Due to limited access to databases some data on raw material production were lacking, specifically production of the TPE SEBS. To avoid data gaps production of another ABS was assumed. This might affect the final results, to what extent is not known. Having access to both software and more LCA databases could improve the results of this and future LCAs.

There are a number of natural infills available on the market today: cork, coconut husk, walnut husk and sand. Only one type have been included here (expanded cork). More types of infill materials would be interesting to compare. Coconut husk, for example, is transported longer distances and requires irrigation to maintain playability. Blends of infills are increasing in popularity as well, for example mixes of a natural infill and a plastic or rubber-based material, to enhance playability.

Depending on how well the field is maintained and what type of infill material is used the need for refilling of granulate varies. Some fields need to refill a lot and some not at all. There is a difference between natural infills and rubber or plastic based granulate since natural infills are biodegradable and do not contribute to the dispersion of microplastics. LCA as a method focuses mainly on environmental effects on a global scale, for example depletion of fossil fuels and emissions contributing to climate change.

No conclusion can be made from this LCA regarding the environmental benefits or disadvantages of a natural turf compared to artificial turfs. This comparison would require other system boundaries, including the entire construction of the artificial turf, maintenance, the availability and end-of-life treatment to be able to make a comparison.

3.6 Conclusions

The goal of this LCA was to compare the environmental impacts of four different infill materials used in artificial turfs. The results of the LCA showed that SBR had the lowest environmental impact of all infill materials.

With regards to the land use cork had the highest impact where 88 hectares of cork forests are needed to produce infill for one football field with an expected life span of 10 years. Due to its short life span cork has a slightly larger carbon and water footprint than SBR.

Production of EPDM and TPE contribute the most to climate change, releasing almost 15 and 28 times as much greenhouse gases as SBR.

4 Rubberized asphalt

4.1 Background

Rubberized asphalt, or asphalt rubber, is a concept where rubber granulates are blended into asphalt mixtures. There are two types of production processes available today: the wet process and the dry process. The wet process is the most common and implies that fine-grained rubber granulate is mixed into bitumen at high or medium temperatures and the resulting rubber modified bitumen (RMB) is then mixed with aggregates at conventional asphalt plants. If the rubberized asphalt is produced through the dry process coarse-grained rubber granulate is mixed with aggregates before standard bitumen is added as a binder (Viman, 2011).

The technology of rubberized asphalt was developed in Arizona, US (Trafikverket, 2015). In Sweden, Trafikverket (Swedish Transport Administration) has tested the concept of rubberized asphalt for Swedish conditions since the year 2006. The main application of asphalt rubber so far has been in wearing courses, the top layer of paved roads. One of the asphalt rubber projects conducted in 2011 in Vänersborg, Sweden, has been chosen as an object for study in this LCA and is further described in chapter 4.3 Life cycle inventory.

The reason for introducing asphalt rubber in Sweden was based on international experience which had shown that asphalt rubber pavements could have longer life, noise-reducing effects and reduce the ability of crack propagation (Viman, 2011). According to Nordgren[11] the longer life for asphalt rubber has not been proven for Swedish conditions, mainly due to the extensive use of studded tyres. The use of asphalt rubber in alternative layers (binder course and base course) has been tested in Sweden but not yet evaluated.

There is an on-going asphalt rubber project by RISE (Research Institutes of Sweden) where the purpose is to achieve "soft" bike- and walking paths with a decreased risk of fractures. The production technique is similar to the dry process where the rubber granulate is used as an aggregate. The rubber content in the finished product is high (around 20 w%) compared to the wet process (1,5-2%). This type of asphalt rubber has not been included in this LCA.

4.2 Goal and scope of the LCA

4.2.1 Goal definition

The goal of this LCA is to analyse and compare the environmental impacts related to asphalt rubber pavements to conventional asphalt pavements without rubber modification. The assessment focuses on asphalt rubber for Swedish conditions.

4.2.2 Function and functional unit

The primary function studied in this LCA is the manufacturing and construction of asphalt pavements. Therefore the chosen functional unit is one stretch of paved road, which is defined as a road with a length of 40 m and a width of 6 m. Calculations regarding the life span of the pavements have been included in the functional unit, resulting in the unit 240 m^2*year. There may be some functional differences between the studied pavement constructions in terms of noise and emission levels. These have not been assessed in the LCA.

[11] Torsten Nordgren, Project manager, Swedish Transport Administration, personal communication in April 2018

4.2.3 System boundaries

The system starts with the extraction of raw materials, refining into products and ends with transports of the products to the place of use. The use phase and end-of-life phase are not included within the system boundaries. The system boundaries for the rubber granulate production starts with the collection of used tyres, the same as in the artificial turf scenario.

The main focus of this LCA is on the production phase, and the primary goal is to compare the differences between asphalt rubber and conventional asphalt with respect to production and life span, which is included in the functional unit. The whole road construction is not included, i.e. the subbase layer, since this is assumed to be equal between the studied scenarios. Machines needed for the laying of asphalt have not been included since it is assumed to be equal between the asphalt rubber and conventional asphalt.

Data on emissions and leaching from the roads were not available, the same goes for maintenance of the roads which has also been excluded. The use phase of the road is of great importance concerning emissions from the vehicles which is a large source of greenhouse gases contributing to the global warming potential. However this is not relevant in the comparison between rubberized and conventional asphalt since this does not affect the amount of traffic or the emissions.

The test roads included in this LCA are located outside Ragn-Sells' granulate factory in Vänersborg, Sweden. The production sites of the aggregates and asphalt are assumed to be located in the vicinity.

4.2.4 Impact assessment categories

The impact categories considered to be relevant in this study are climate change, fossil fuel depletion, terrestrial acidification, freshwater and marine eutrophication and photochemical oxidant formation. Characterisation factors for the ReCiPe 2008 method (hierarchist perspective) were used, apart from the category climate change, where the most recent characterisation factors from IPCC 2013 were used. Long-term effects are excluded. The impact categories are listed in Table 16 below, together with impact assessment models and units.

Table 16: List of included impact categories, indicators, impact assessment models, units and examples of relevant contributors to each impact category.

Impact category	Indicator	Impact assessment model	Unit	Contributors
Climate change	Global warming potential	IPCC 2013	kg CO2-eq	Carbon dioxide, methane, nitrous oxide etc.
Fossil fuel depletion	Fossil depletion potential	ReCiPe 2008	kg oil-eq	Fossil fuels (crude oil, natural gas, coal)
Acidification	Terrestrial acidification potential	ReCiPe 2008	kg SO2-eq	Sulphur dioxide, nitrogen oxides, ammonia
Eutrophication	Freshwater eutrophication potential	ReCiPe 2008	kg P-eq	Phosphorus and phosphate emissions to water
	Marine eutrophication potential	ReCiPe 2008	kg N-eq	Emissions of nitrogen compounds to air and water
Photochemical oxidant formation	Photochemical oxidant formation potential	ReCiPe 2008	kg NMVOC	Volatile organic compounds (alcohols, aldehydes etc.) and nitrogen oxides

4.2.5 Data quality

As in the artificial turf LCA, data on rubber granulate production were provided by Ragn-Sells. Some data regarding energy consumption of production of asphalt masses and densities of the asphalt were collected from Stripple (2001) and provided by Nordgren[12]. Data on construction of the test surfaces under study were collected from Said et al. (2014). All background data, for example production of aggregates, bitumen and electricity, were gathered from the LCA database ecoinvent version 3.4 (Wernet et al., 2016) and are listed in Appendix A.

[12] Torsten Nordgren, Project manager, Swedish Transport Administration, personal communication in June 2018

4.3 Life cycle inventory

4.3.1 Construction of asphalt rubber pavements

Three asphalt rubber test surfaces using different constructions have been compared with a reference surface without rubber modification. The constructions are based on an actual asphalt rubber project outside Ragn-Sells' rubber granulate factory in Vänersborg, Sweden. The different constructions are presented in Figure 18 below. AR 1, AR 2 and AR 3 represents test surfaces containing asphalt rubber in different layers and REF 4 represents the reference surface containing no rubber. The figure is a simplification based on figure 10 in Said et al. (2014), and does not separate between wearing course, binder course and base course. However this has been included in the calculations of the LCA. Asphalt rubber normally contains a higher share of binder than conventional asphalt. According to Said et al. (2014) the asphalt rubber used in this project contains approximately 1,5% more binder than planned in the recipe. The effect of this has been tested in a sensitivity analysis.

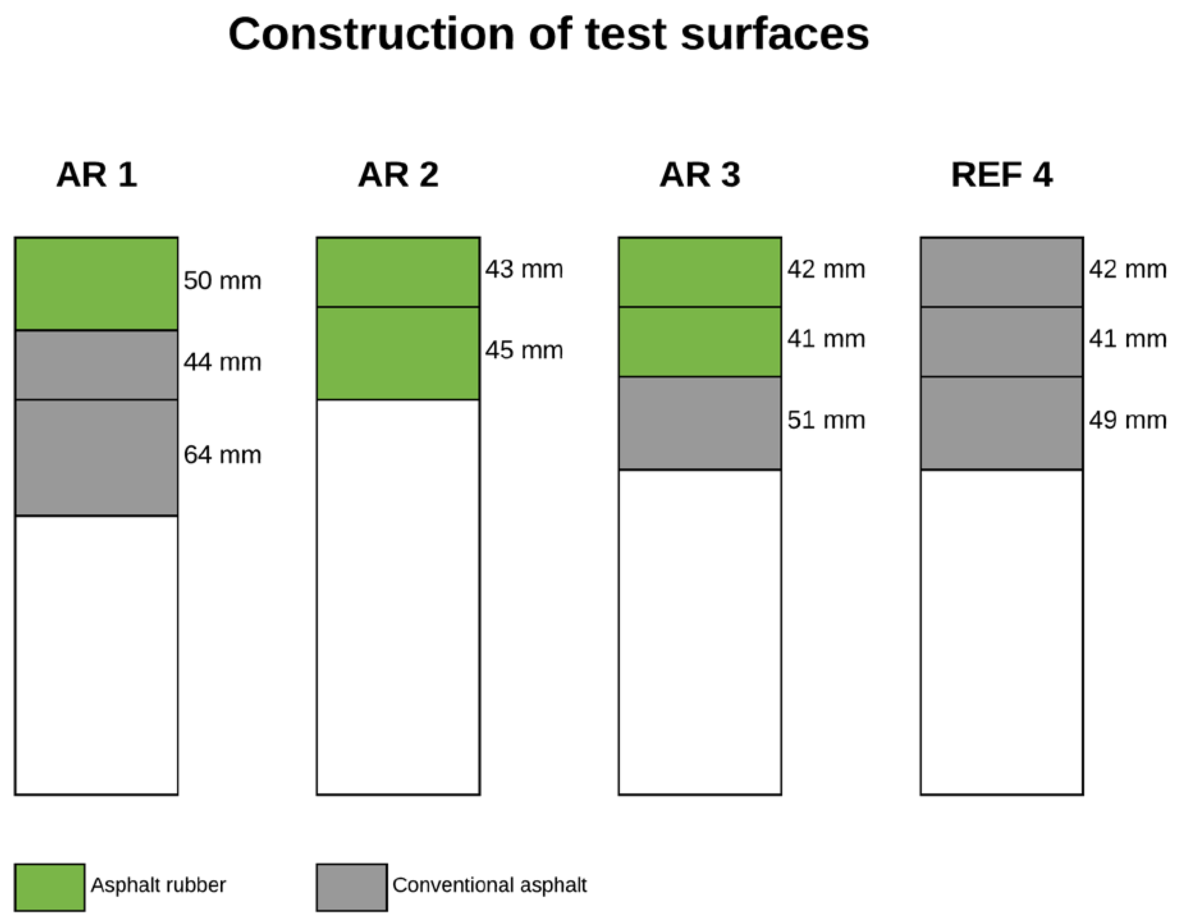


Figure 18: Presentation of the construction of the four test surfaces. Surface number 4 is a reference surface without any rubber modification. The figure is a simplification based on Figure 10 in Said et al. (2014).

4.3.2 Production of asphalt rubber

Compared to conventional asphalt, production of asphalt rubber requires a higher processing temperature as well as a higher temperature to produce the RMB, before it is mixed with the crushed rock or aggregates. According to Nordgren[13] this resulted in an added heating oil consumption of 5-7 litres per ton of bitumen for the AR project under study. The RMB in this case contains 17% rubber. The RMB is produced at a separate station which can be docked to the asphalt plant. This station entails a higher electricity consumption for asphalt rubber compared to conventional asphalt. Nordgren could not make an estimation of this electricity consumption. Instead a rough estimation of an increased electricity consumption by 50% compared to conventional asphalt was made.

Consumption of heating oil and electricity needed for the asphalt production was taken from Stripple (2001). In Table 17 below the resources needed for production of the different types of layers are listed. The extra heating oil and electricity required for asphalt rubber production have been added on top of the figures from Stripple (2001).

Table 17: Inventory analysis of wearing courses, binder courses and base courses: rubber modified and conventional. The results are expressed as per 1 ton of asphalt.

Layer	Type	Aggregates [kg]	Standard bitumen [kg]	Rubber granulate [kg]	Heating oil [MJ]	Electricity [kWh]	Density [kg/m^3]
Wearing course	GAP 11 (RM)	914	71	15	304	15	2423
	ABS 11	934	66	-	285	10	2552
Binder course	ABb 16 (RM)	928	60	12	301	15	2480
	ABb 16	946	54	-	285	10	2571
Base course	AG 22 (RM)	932	56	12	300	15	2488
	AG 22	955	45	-	285	10	2586

The binder content of asphalt rubber was listed in Said et al. (2014). The binder content of the conventional asphalt masses was estimated by using calculation values of standard ABS 11, ABb 16 and AG 22 mixes from Vägverket (2005). Nordgren[14] provided values on densities of binders (1020 kg/m^3) and aggregates (2660 kg/m^3) to convert mass to volume.

4.3.3 Life span

In the studied asphalt rubber project (the granulate factory) there were indications of a possible longer life span for the pavements containing layers of asphalt rubber compared to those without. Strain measurements performed during the first year after construction concluded that the asphalt

[13] Torsten Nordgren, Project manager, Swedish Transport Administration, personal communication in June 2018
[14] Torsten Nordgren, Project manager, Swedish Transport Administration, personal communication in June 2018

rubber could have a positive effect on the fatigue cracking of the pavements. The strain was measured at the bottom of the base course which is assumed to be dimensioned with regards to crack propagation.

It is likely that constructions containing asphalt rubber will give rise to larger surface deformations since asphalt rubber has lower stiffness than conventional pavements. Thin constructions, e.g. AR 2, will probably lead to higher strains in the subbase layer. Wheel tracking is an effect caused by deformations in the subbase layer. Only bound layers are included within the system boundaries of this LCA and the possible effect of strains in the subbase layer has not been included.

The type of traffic on the roads in question are mainly tyre delivery lorries and lorries collecting produced material (tyre cuts and rubber granulate). According to Roth[15] road number 1 and 2 are mainly trafficked by heavy lorries delivering tyres to the granulate factory with an average load weight of 28 tons. Road number 3 and 4 are trafficked mainly by lighter lorries collecting material from the factory with an average load weight of 17 tons. Maps specifying locations of the roads under study at the factory premise is attached in Appendix C. Based on information given by Roth and information about the number of strains until crack propagation obtained from Said et al. (2014), estimations of the life spans could be made. To be able to make a proper comparison the amount of traffic has been adjusted, and an average load per year have been calculated for the roads 1, 2, 3 and 4.

The full calculations of the traffic to and from the factory are presented in Appendix D, and the resulting life span estimations are presented in Table X below.

4.3.4 Inventory analysis

In Table 18 below the inventory analysis for all four test surfaces are presented. The amounts are expressed as per 240 m^2 road.

Table 18: Inventory analysis of the asphalt rubber test surfaces included in the LCA, expressed per 240 m^2 road.

Test surface	Rubber granulate [tons]	Standard bitumen [tons]	Aggregates [tons]	Heating oil [GJ]	Electricity [MWh]	Life span [years]
AR 1	0,43	5,33	90,2	27,9	1,10	5,8
AR 2	0,68	3,30	47,9	15,7	0,78	8,3
AR 3	0,66	4,63	75,2	23,8	1,05	8,3
REF 4	-	4,43	77,0	23,2	0,81	4,6

In Table 19 below, some estimations regarding transport distances are presented. The location of the road stretches is at Ragn-Sells granulate factory in Vänersborg, Sweden. The distance between the

[15] Veronica Roth, Customer supper manager/transports- and logistics manager, Ragn-Sells Tyre recycling, personal communication in June 2018

factory and the asphalt plant is assumed to be 100 km, and the aggregates are assumed to be produced locally. The bitumen is assumed to be transported a longer distance, 750 km.

Table 19: Transport distances for intermediate products and final product (asphalt). The asphalt rubber is produced at the same location as the conventional asphalt, resulting in equal transport distances for the final product.

Material	Transport distance [km]
Aggregates	50
Bitumen	750
Rubber granulate	100
Asphalt	100

Data on production of rubber granulate, used as a binder additive in asphalt rubber, are presented in Table 20 below. The same data was presented in Chapter 3.3 concerning artificial turf infill production, however another transport distance has been assumed for this LCA. Unlike the artificial turf scenario, the fine fraction (0-1,2 mm) of rubber granulate are used for asphalt rubber production. No separation of the granulate size fractions has been made.

Table 20: Inventory analysis of rubber granulate production at Ragn-Sells' granulate factory in Vänersborg, Sweden.

Unit process: production of rubber granulate		
Reference products	**Quantity**	**Unit**
Rubber granulate	1	kg
Steel	0,34	kg
Textile	0,34	kg
Inputs		
Used tyres	1,73	kg
Electricity	0,37	kWh
Outputs		
Steel studs, gravel, dust	0,05	kg
Transports		
Collection of tyres (lorry 16-32 tons)	150	km
Granulate to asphalt plant (lorry 16-32 tons)	100	km

4.4 Life cycle impact assessment

In this chapter the results of the impact assessment are presented, divided into all impact categories. Three impact categories: freshwater eutrophication, marine eutrophication and photochemical oxidant formation, are presented in Appendix B. This is because the results are similar to the results from the other impact categories. Three road constructions containing asphalt rubber are compared to one reference road containing no rubber.

4.4.1 Global warming potential

When comparing the global warming potential of asphalt rubber and conventional asphalt, which is presented in Figure 19 below, there are three large contributors. Emissions from transports, heating oil combustion and production of bitumen contribute nearly equally to the GWP. Transport distances are based on rough estimations and the results in the figure below should be evaluated strictly.

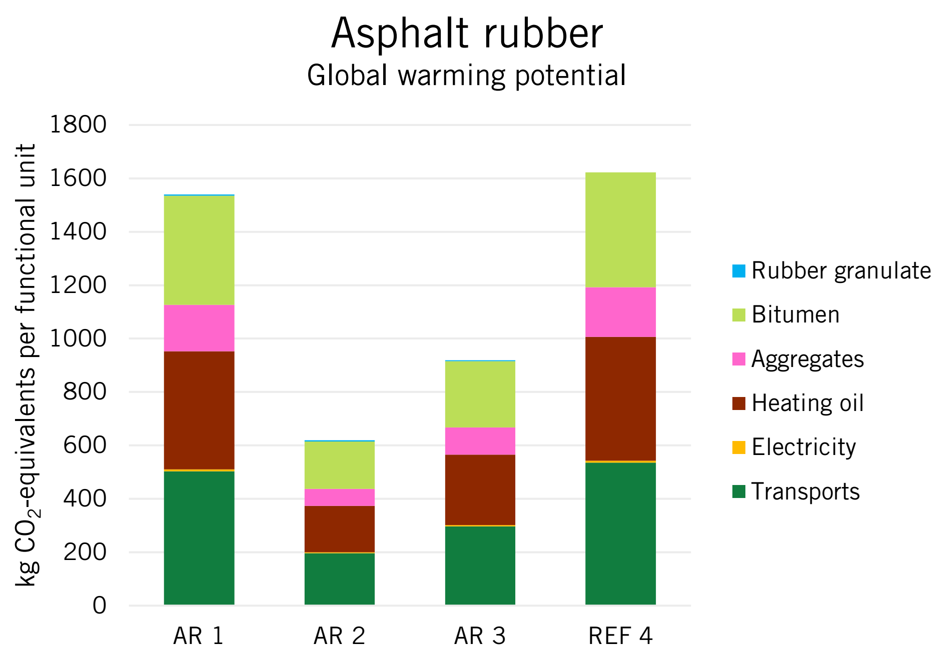


*Figure 19: Comparison of global warming potential of three asphalt rubber pavements to one conventional pavement. The results are expressed in kg CO_2-equivalents per 240 m^2*year road.*

The test surface named AR 2 has the lowest contribution to the global warming potential, partly because it is the thinnest construction of the four and partly because it has the longest life span. Due to its thin construction some pressure might be put on the subbase layer, however this has not been included in the assessment.

The asphalt rubber pavement AR 3 and the reference pavement REF 4 have similar structures, however the estimated life span for AR 3 is almost twice as long as for REF 4 resulting in almost half of the GWP contribution as the reference. AR 1 and REF 4 have similar footprints although the AR 1 is 26 mm thicker than REF 4.

4.4.2 Fossil depletion potential

The fossil depletion potential maps the use of fossil fuel resources, not the actual emissions caused by them, which is presented in the chapter above. The fossil depletion potential are usually closely related to the global warming potential since combustion of fossil fuels are a major contributor to climate change. In this LCA the results varies some: production of bitumen is a major contributor since it both causes emissions affecting the GWP and since it is made up of petroleum.

Asphalt rubber masses have a higher share of binder content than conventional asphalt masses. This is partly due to a production fault, resulting in a 1,5% higher binder content than in the original recipe. This has been tested in a sensitivity analysis and is presented in chapter 4.4.5.

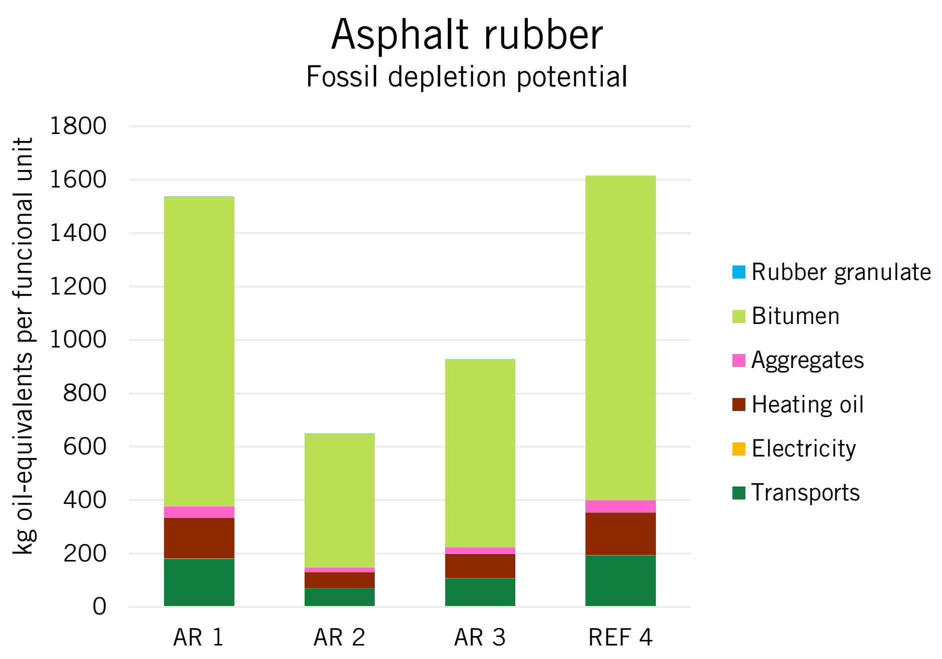


*Figure 20: Comparison of fossil fuel depletion of three asphalt rubber pavements to one conventional pavement. The results are expressed in kg oil-equivalents per 240 m^2*year road.*

4.4.3 Acidification

Terrestrial acidification is caused by emissions of NH_3, SO_2 and NO_X to air. Combustion of fossil fuels is a major source of acidifying emissions, which is visible in Figure 21 below. Production of bitumen is by far the largest contributor to acidification, but also transports and combustion of heating oil used in the asphalt production. The ranking of the test surfaces is similar as in the impact categories presented above.

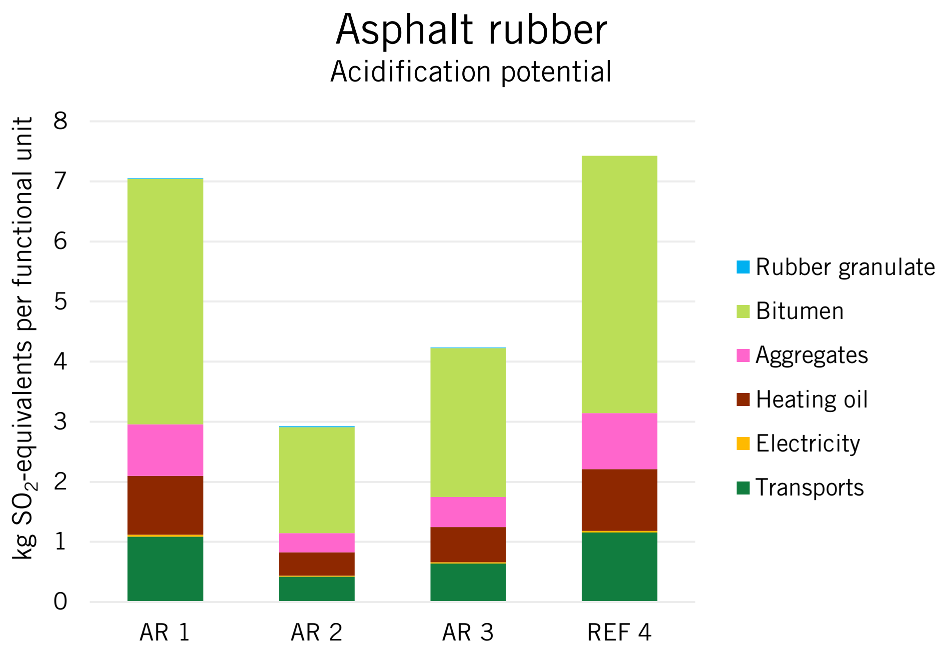


Figure 21: Comparison of acidification potential of three asphalt rubber pavements to one conventional pavement. The results are expressed in kg SO_2-equivalents per 240 m^2 road.

4.4.4 Normalisation

As in the case for artificial turfs, the results of the asphalt rubber LCA have been normalised as well. The purpose is to express the results in a wider perspective and to decide which impact categories is of importance and, if possible, to decide where improvements with regards to the pavements' environmental footprint can be made.

The functional unit in this LCA is expressed in terms of an area but due to lack of data the results have been normalised towards the amount of asphalt mass produced per year in Sweden. Preferably data on the total amount of paved surface per year in Sweden would be used to match the functional unit but this has not been accessed. Instead, the results are normalised with regards to the amount of asphalt mass expressed as tons per year in Sweden. According to Andrén & Hedin (2018) 8±0,5 million tons of asphalt mass are produced each year in Sweden.

In Figure 22 below, the results of the normalisation is presented. The result is expressed as person equivalents per year, in percent, and describes the environmental impact asphalt production has per person and year in Sweden. The graph only compares a rubber modified and a conventional wearing course (named GAP 11 and ABS 11 here). Comparisons of binder courses and base courses show similar results. One difference is perhaps that binder courses and base courses have a lower binder content and therefore the fossil depletion potential is lower than for wearing courses.

Presented in the figure below, it is clear that production of rubberized asphalt has a higher environmental impact than production of conventional asphalt without rubber modification. The reason for this is that asphalt rubber production is more resource demanding than conventional, in terms of heating oil and electricity consumption and a higher binder content.

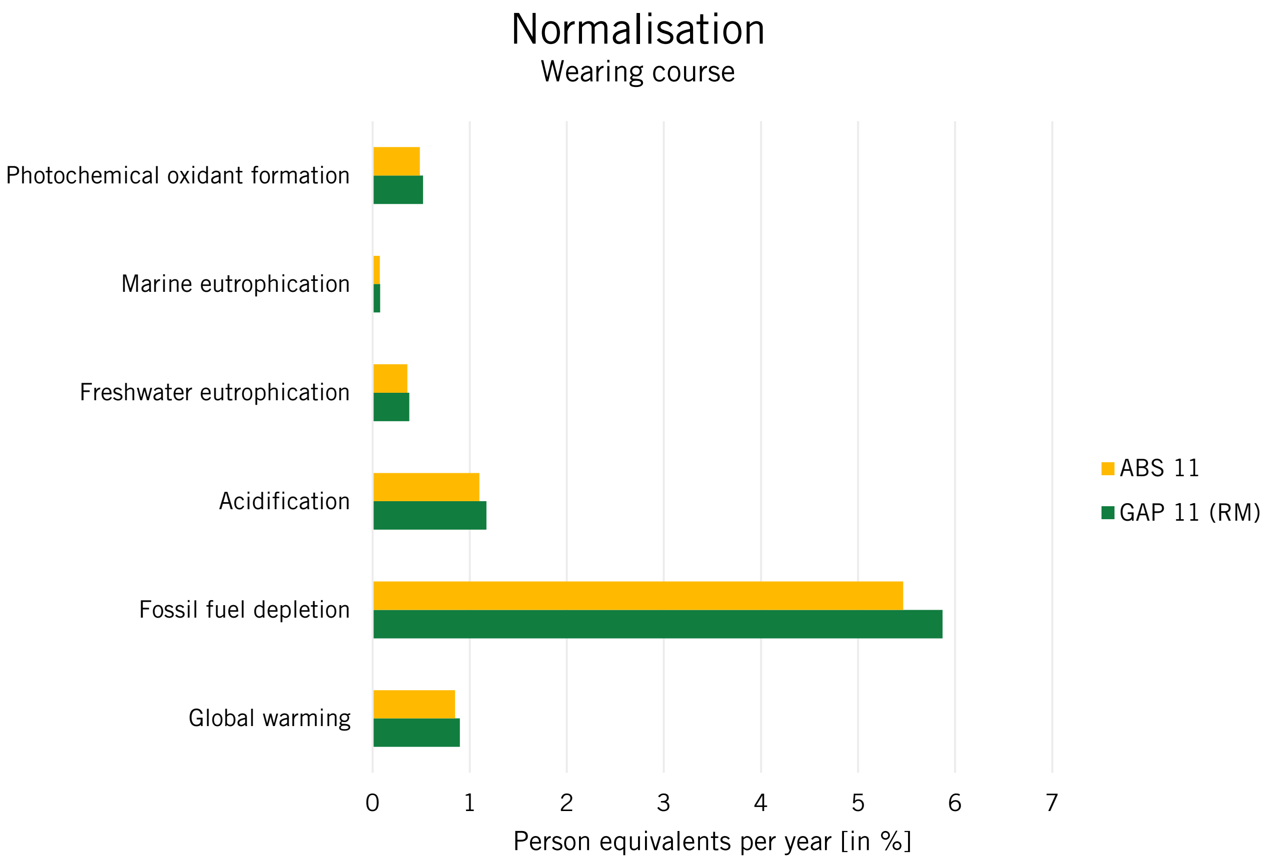


Figure 22: Normalisation of the results from the asphalt rubber LCA. The results have been normalised towards the amount of produced asphalt mass per year in Sweden, not the total area of paved surface. The results are expressed as person equivalents per year, in percent.

Due to that the results are normalised towards the amount of asphalt (expressed in tons per year) rather than the surface of paved roads (expressed in m^2 per year) some characteristics of asphalt rubber are lost. For example, it is possible to construct thinner pavements compared to conventional asphalt and the life span of the road can increase, with regards to crack initiation in the base course.

A result from the normalisation presented above is that the fossil depletion potential is the parameter that could be improved most. Replacing the fossil resources (where bitumen is by far the largest contributor) is one action to decrease the environmental impact from asphalt production. Although 17% of the binder consists of rubber rather than bitumen in AR masses, they have a higher binder content than conventional masses, resulting in a larger fossil depletion potential. Due to a production fault the binder content in AR masses is 1,5% too high, this has been tested in a sensitivity analysis in chapter 4.4.5 and the new results are normalised as well.

4.4.5 Sensitivity analysis

Implement planned amount of binder content in asphalt rubber

In the studied asphalt rubber project, the share of binder content in the asphalt rubber masses were 1,5% higher than planned due to a production fault. This was tested in a sensitivity analysis, adjusting the binder content for the asphalt rubber masses. In Figure 23 below the results for the climate change category are presented.

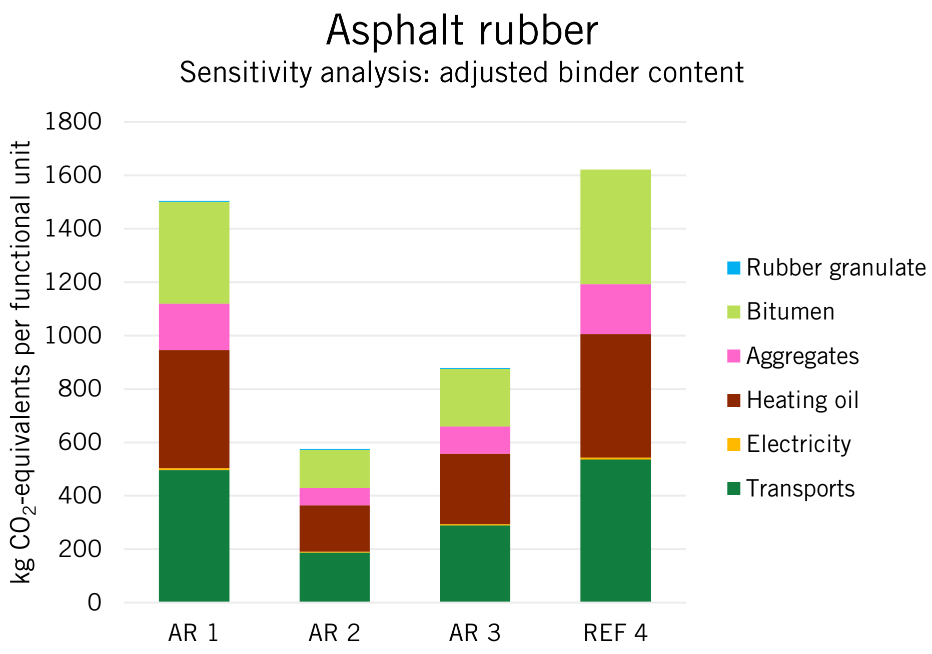


Figure 23: Comparison of GWP of three AR pavements and one conventional. The results have been adjusted, containing the planned amount of binder in the AR masses, which is 1,5% lower than in the base case.

When comparing to the base case, where the binder content is higher, the carbon footprints of the pavements containing asphalt rubber are lowered:

- -2,3% for AR 1
- -7,0% for AR 2
- -4,4% for AR 3.

The footprint of the reference surface is unchanged. Unsurprisingly the surface containing 100% asphalt rubber (AR 2) experiences the largest decrease in GWP if the binder content is changed. It is assumed that the life spans of the pavements are equal as in the base case, however this might be a simplification.

To express the impact this change in binder content has, the new results are normalised. In Figure 24 below, the reference wearing course, the rubber modified wearing course containing the real amount of binder and one with the planned amount of binder are presented. The adjusted asphalt rubber masses still contain a higher share of binder than the conventional alternative, which is standard for asphalt rubber. However in the new normalisation, the effect of replacing 17% of the bitumen with rubber powder is visible. The fossil depletion potential is lowered with nearly 1% per person and year, if the binder content is lowered. It is assumed, as earlier, that all asphalt masses are wearing courses which in reality is not the case.

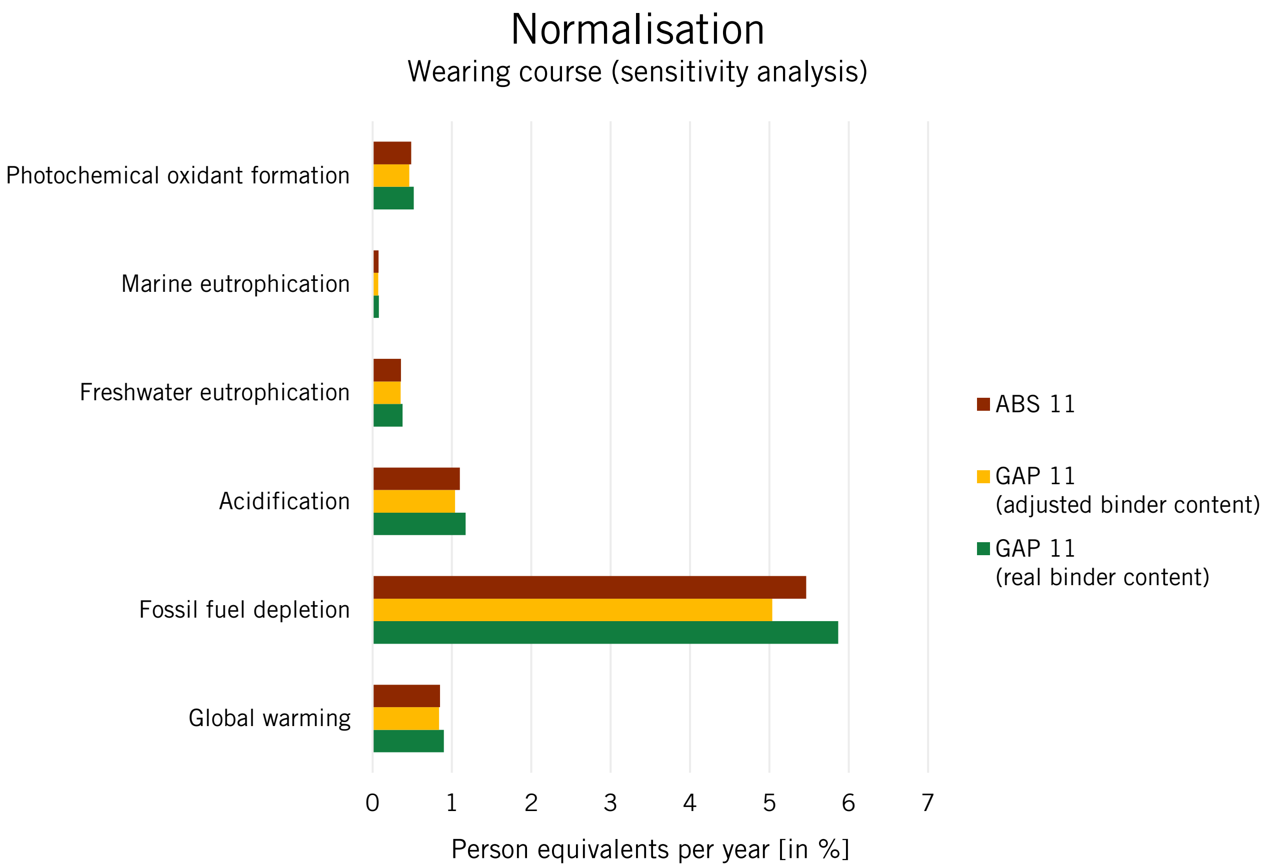


Figure 24: Normalisation of the results from the sensitivity analysis comparing wearing courses on a common reference unit (person equivalents per year). ABS 11 is a conventional wearing course and GAP 11 is rubber modified.

Excluding life span from functional unit

To test what impact inclusion of the life spans has, the exclusion has been tested in a sensitivity analysis. The functional unit has therefore been changed from 240 m^2*year to 240 m^2 and the life spans of the pavements have been assumed to be equal. In reality, it is likely that the test roads are exchanged at the same time due to their location and perhaps to reduce costs.

The estimated life spans, presented in Table 18, are based on the pavements' ability to withstand crack formation in the bottom of the base layer. There are other phenomena affecting the life spans which are not included in the estimation. For example, wearing of the top layer due to studded tyres or wheel tracking due to thin constructions and weak subbase layers.

The result of this is presented in Figure 25 below. The comparison between asphalt rubber and conventional asphalt with regards to environmental impacts is less clear if the differences in life spans is excluded. The environmental footprint, in this case the carbon footprint, is highly dependent on the thickness of the layers. Only AR 2, which is the thinnest construction, has lower impact than REF 4. AR 3 and REF 4 are constructed similarly, and the differences between them are minimal. AR 3 has a slightly higher carbon footprint due to the increased consumption of heating oil and bitumen required for the asphalt rubber production.

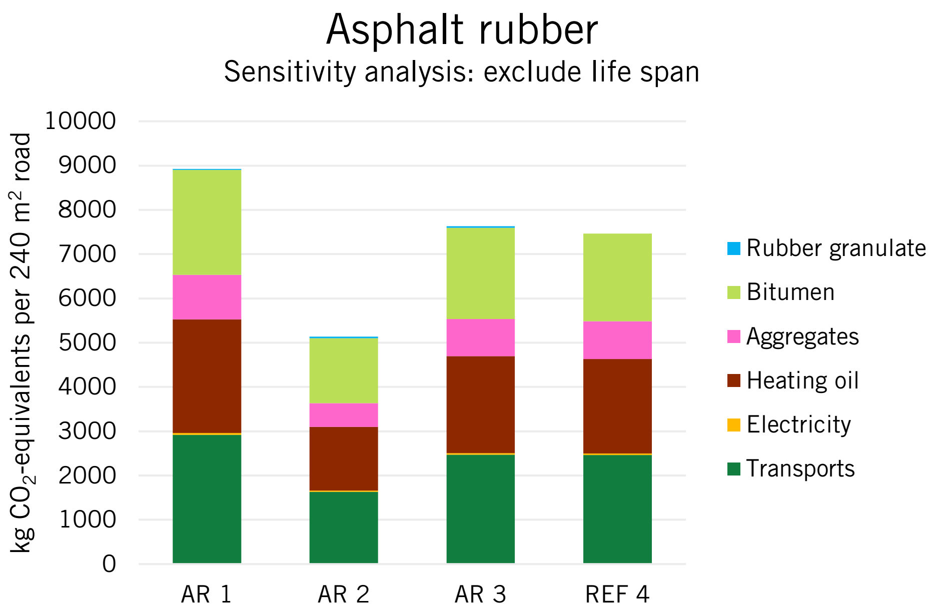


Figure 25: Results from sensitivity analysis where the estimated life spans have been excluded. The results are expressed as kg CO_2-equivalents per 240 m^2 road.

4.5 Interpretation and discussion

4.5.1 General discussion

Depending on the definition of the functional unit, the environmental comparison between asphalt rubber and conventional asphalt differs. If the assessment only considers the production of asphalt rubber compared to conventional asphalt, expressed as per ton of asphalt mass, asphalt rubber has a higher environmental footprint than conventional asphalt. The main reason for this is that asphalt rubber production has a higher demand for heating oil, electricity and a higher share of binder.

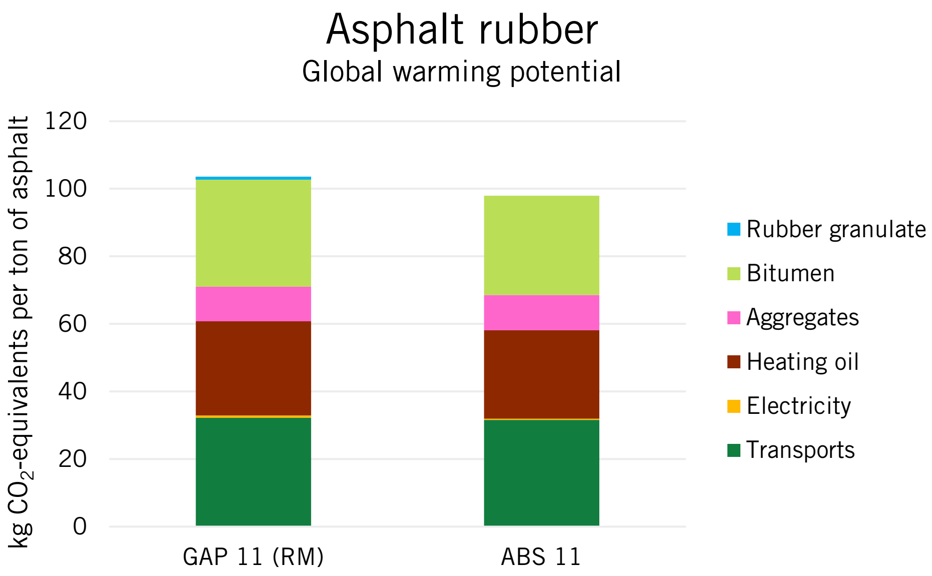


Figure 26: Comparison of 1 ton of asphalt rubber (GAP 11) to 1 ton of conventional asphalt (ABS 11).

It was established in a sensitivity analysis that if the planned amount of binder were to be used in the asphalt rubber production, the replacement of bitumen by rubber would result in a decreased depletion of fossil fuels compared to a conventional asphalt.

When considering the whole construction of the road (functional unit 240 m^2), asphalt rubber could imply a lower environmental footprint due to the possibility of constructing thinner layers of asphalt. This is presented in Table 21 below. However thinner pavements puts more pressure on the lower, unbound layer which has not been included within the system boundaries.

Table 21: Difference in GWP for all asphalt rubber test surfaces compared to the reference surface. The functional unit of the comparison is 240 m^2 road.

Test surface	Difference in GWP compared to reference surface
AR 1	+20%
AR 2	-31%
AR 3	+2%
REF 4	-

When considering the construction and expected life span of the road (functional unit 240 m^2*year) asphalt rubber has a lower environmental footprint than conventional asphalt. The results are presented in Table 22 below. This is mainly due to the increased life span that the asphalt rubber implies, when compared to the reference pavement. AR 2 and AR 3 which both have a high share of asphalt rubber in the respective construction, have almost twice the life span of the reference pavement with regards to fatigue cracking in the bottom layer.

*Table 22: Difference in GWP for all asphalt rubber test surfaces compared to the reference surface. The functional unit of the comparison is 240 m^2*year.*

Test surface	Difference in GWP compared to reference surface
AR 1	-5%
AR 2	-62%
AR 3	-43%
REF 4	-

4.5.2 Limitations of this study

It is difficult to draw any general conclusions regarding the environmental benefits or disadvantages of asphalt rubber compared to conventional asphalt. Depending on the production technology, layer thicknesses and life spans of the pavements the results will vary. Only one type of production technology of rubberized asphalt has been tested in this LCA and more would be interesting to compare: technologies that work at lower temperatures or uses different mixes of rubber, bitumen and aggregates, for example.

A result from the studied project was that the test surfaces containing asphalt rubber in different layers gave indications of longer life spans. The life spans were measured as the number of strains until crack initiation in the bottom of the base course. The measure does not include other effects on the road that might affect the life spans, for instance wheel tracking, which could be an issue for the thinnest test surface AR 2. More pressure is being put on the subbase course, which could lead to deformations and wheel tracking. Wearing caused by studded tyres is not considered here as well. This might however not be an issue for the studied objects since the main traffic is lorries and tyre collection vehicles. If another stretch of road, with more intense traffic, was to be assessed in an LCA the decreased life span of the road due to wearing would be a more important parameter than in this LCA. It is therefore important to remember when interpreting the results that the estimated life spans does not cover all effects on the road.

4.6 Conclusions

The goal of this LCA is to compare the environmental impacts of asphalt rubber and conventional asphalt. It can be concluded from this LCA that pavements containing asphalt rubber have lower environmental impact than conventional asphalt. This is possible due to thinner constructions and a longer technical life span.

It was established that if the life spans were excluded, asphalt rubber pavements with similar constructions had a slightly higher environmental impact than conventional pavements. To increase the life span, or construct thinner pavements, is thus important factors to decrease the environmental impact of asphalt rubber in a life cycle perspective.

Finally, it was established through normalisation that the highest impact, and where the most improvement potential is, is regarding the depletion of fossil fuels. The largest contributor in that category is by far the production and use of bitumen as a binder in asphalt. To decrease the fossil depletion potential concerning the production of asphalt one important action is to replace the bitumen in binders with alternative materials, for instance rubber granulate from recycled tyres. This conclusion could however not be made for the studied objects due to a production fault which resulted in a binder content that was too high. If the binder content was adjusted to the intended recipe the replacement of bitumen with rubber granulate contributed to a decrease in fossil fuel depletion.

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Appendix A: List of datasets from ecoinvent

Presented below is a table featuring all datasets used from the ecoinvent database, version 3.4 (Wernet et al., 2016). The system model used is "allocation, cut-off by classification" in all cases.

Table 23: List of datasets from ecoinvent used in the LCA.

Material/input	ecoinvent dataset
Aggregates	Gravel production, crushed – RoW
Bitumen	Petroleum refinery operation, pitch – EwS
Electricity	Market for electricity, medium voltage – SE
	Market for electricity, medium voltage – PT
	Market group for electricity, medium voltage – ENTSO-E
EPDM	Market for synthetic rubber production – GLO
Heating oil	Heat production, light fuel oil, at industrial furnace 1 MW – EwS
Limestone	Lime production, milled, loose – RoW
Machine operation	Machine operation, diesel, >=74,57 kW, steady-state – GLO
Mineral oil	Market for lubricating oil production – GLO
Phtalates	Market for polyester resin production, unsaturated – GLO
Raw cork	Cork forestry – PT
TPE	Market for acrylonitrile-butadiene-styrene-copolymer production – GLO
Transports	
Barge	Transport, freight, inland waterways, barge tanker – RER
Lorry	Transport, freight, lorry 7,5 – 16 metric ton, EURO6 – RER
	Transport, freight, lorry 16 – 32 metric ton, EURO6 – RER

Appendix B: Additional results

Artificial turf

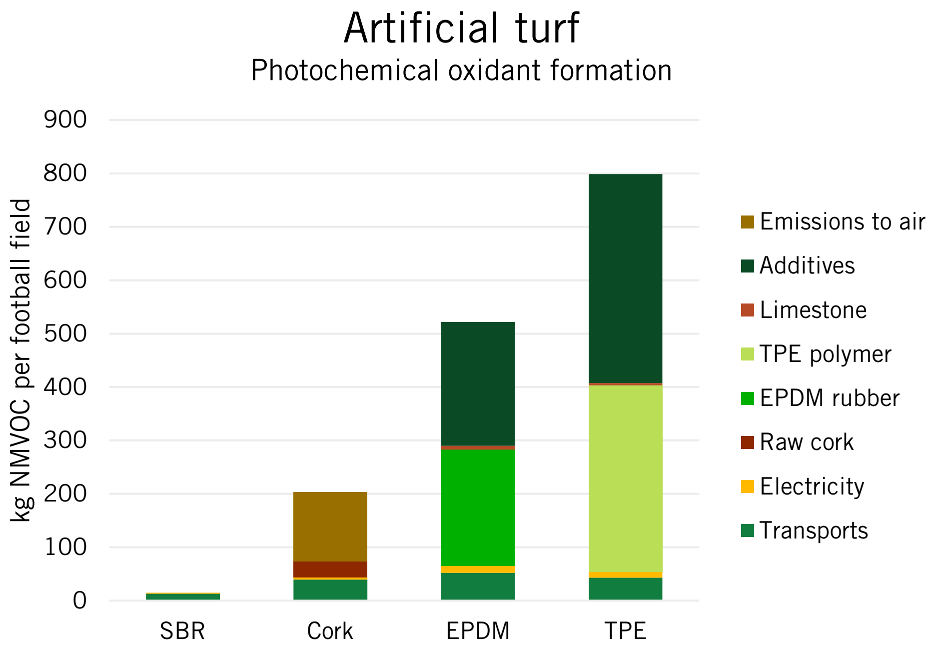

Figure 27: Comparison of infill materials in the impact category photochemical oxidation formation potential. The results are expressed in kg NMVOC per football field.

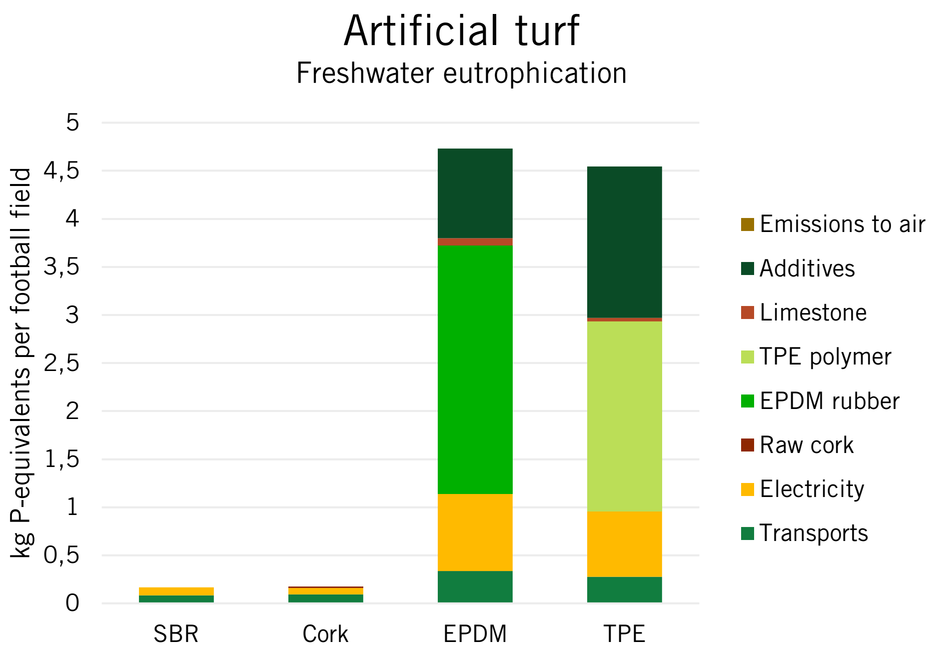

Figure 28: Comparison of infill materials in the impact category freshwater eutrophication potential. The results are expressed in kg P-equivalents per football field.

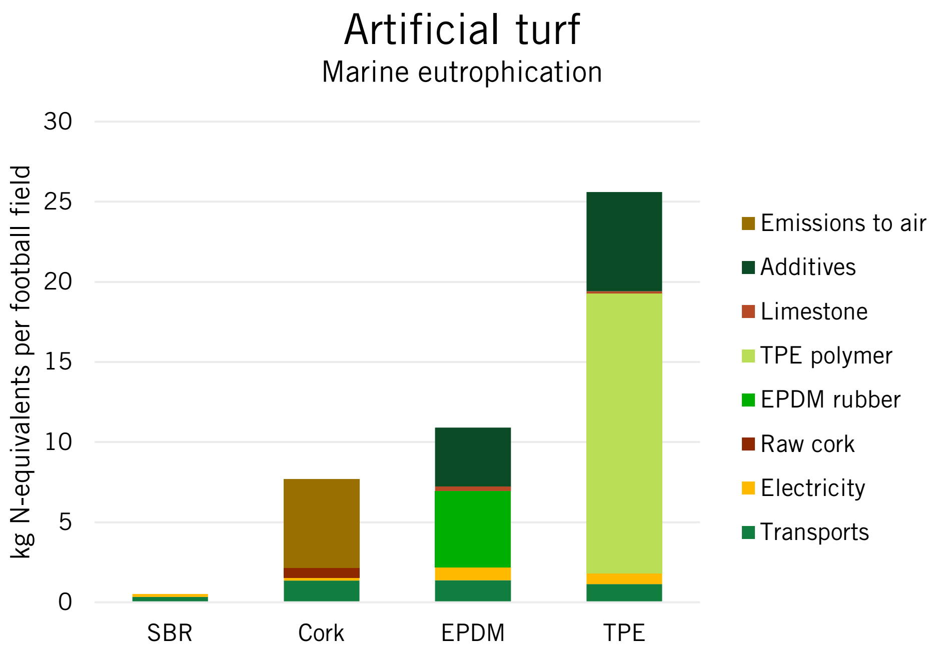

Figure 29: Comparison of infill materials in the impact category marine eutrophication potential. The results are expressed in kg N-equivalents per football field.

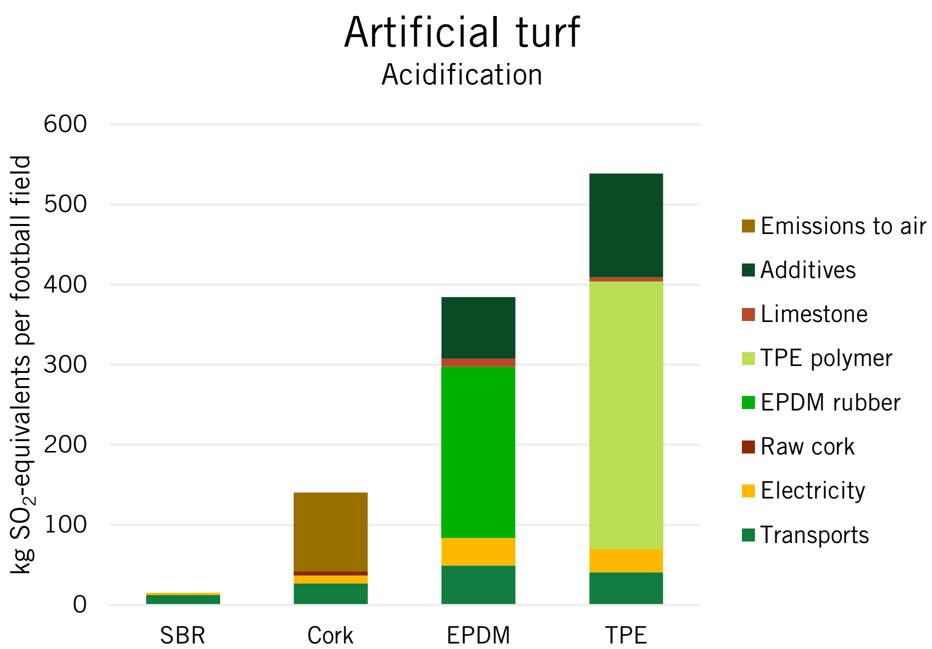

Figure 30: Comparison of infill materials in the impact category terrestrial acidification potential. The results are expressed in kg SO_2-equivalents per football field.

Asphalt rubber

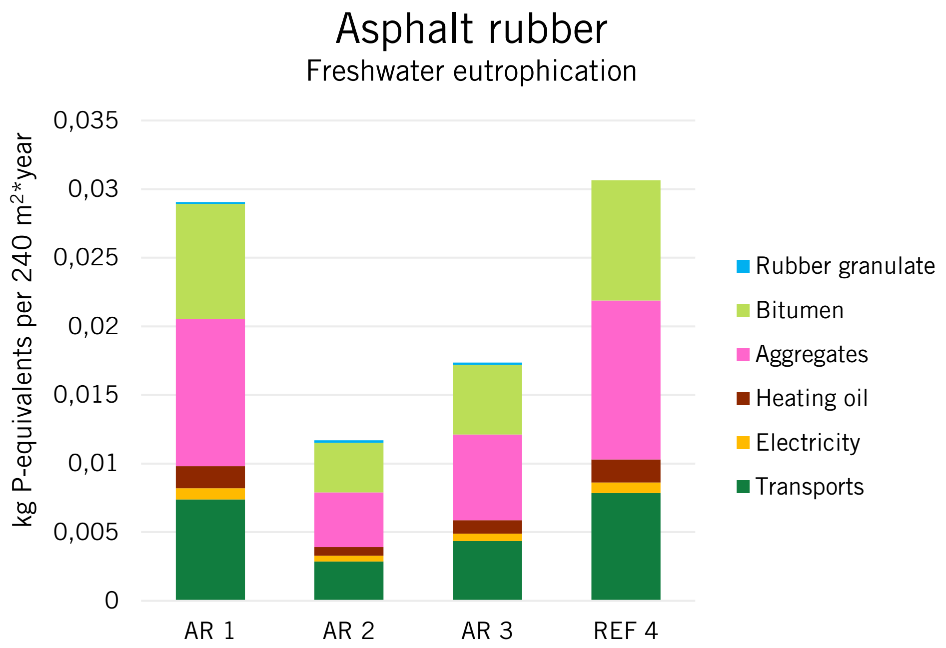

Figure 31: Comparison of test surfaces containing asphalt rubber to a reference pavement in the impact category freshwater eutrophication potential. The results are expressed in kg P-equivalents per functional unit.

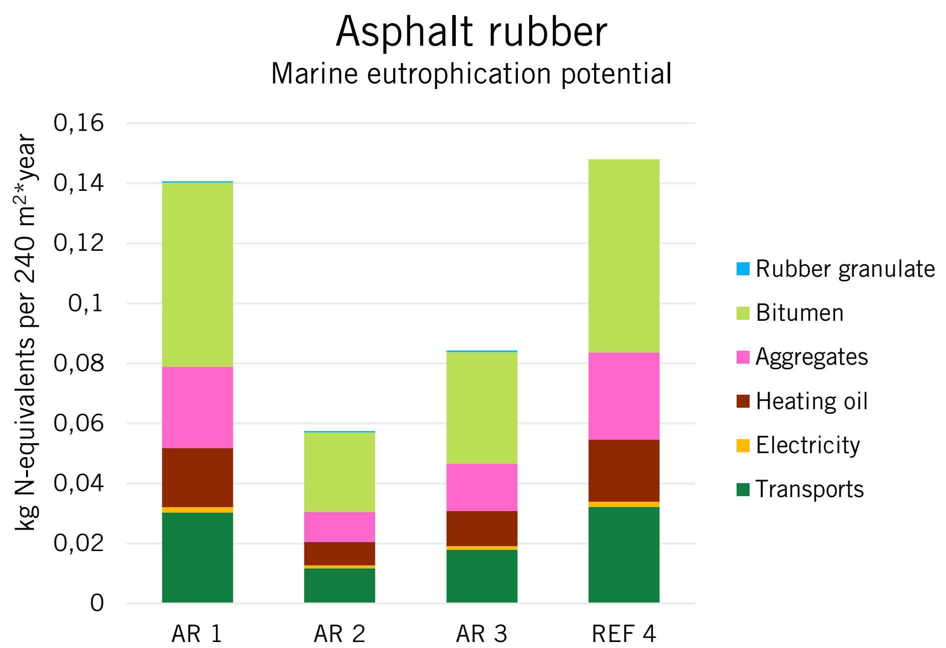

Figure 32: Comparison of test surfaces containing asphalt rubber to a reference pavement in the impact category marine eutrophication potential. The results are expressed in kg N-equivalents per functional unit.

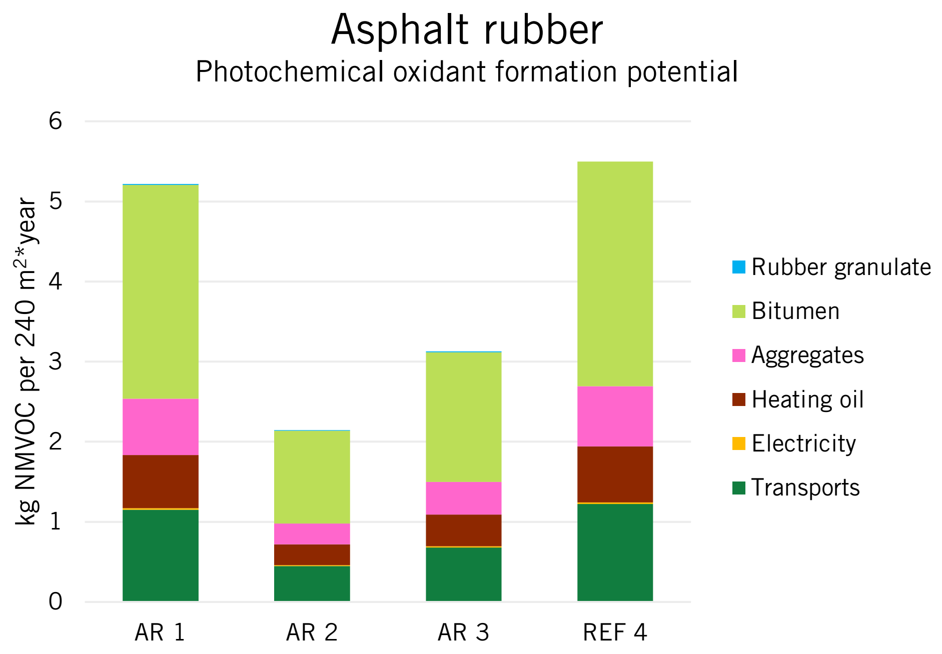

Figure 33: Comparison of test surfaces containing asphalt rubber to a reference pavement in the impact category terrestrial acidification potential. The results are expressed in kg SO_2-equivalents per functional unit.

Appendix C: Locations of asphalt rubber test surfaces

The two figures below show where the test surfaces are located in relation to the granulate factory in Vänersborg, Sweden. Both figures are taken from Said et al. (2014).

Figure 34: Location of test surfaces AR 1 and AR 2 at the premise of Ragn-Sells' granulate factory in Vänersborg, Sweden. The road is mainly used by lorries delivering tyres to the factory.

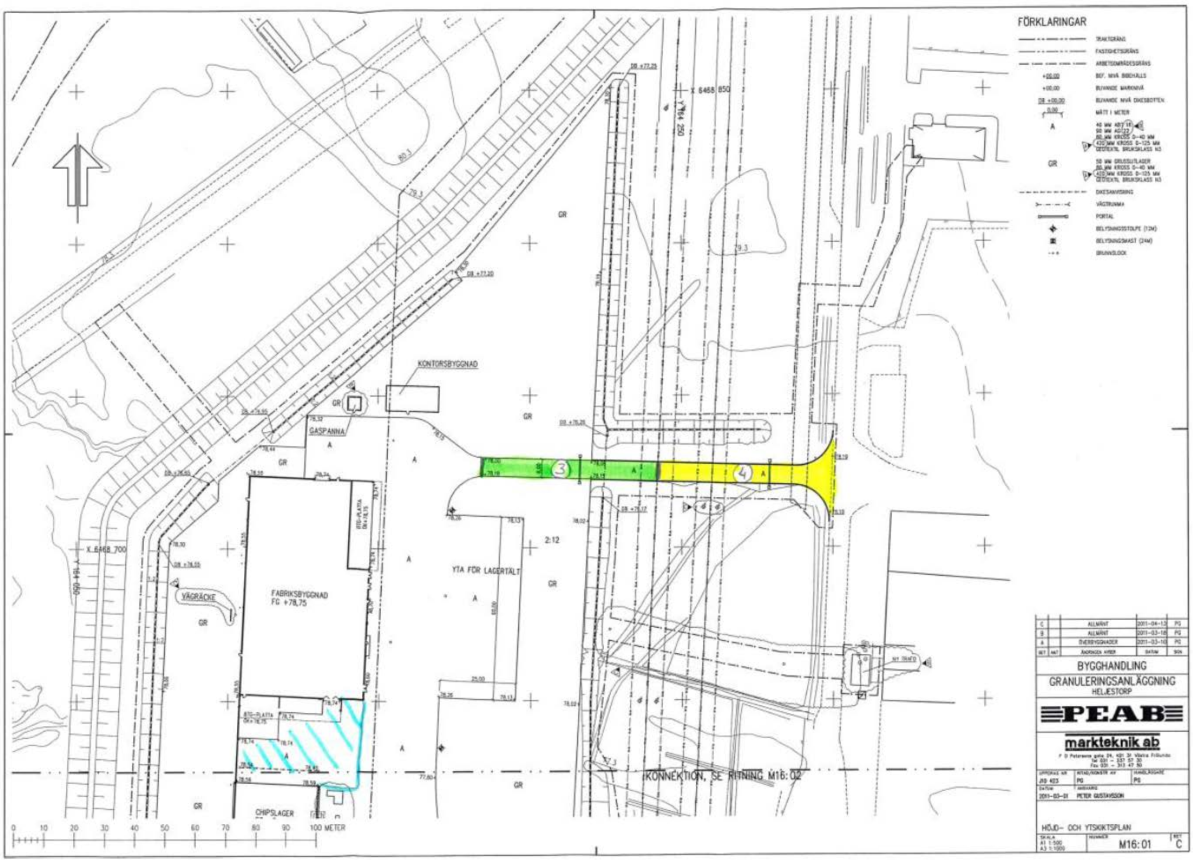

Figure 35: Location of test surfaces AR 3 and REF 4 at the premise of Ragn-Sells' granulate factory in Vänersborg, Sweden. The road is mainly used by lorries collecting processed materials (tyre cuts and rubber granulate).

Appendix D: Calculation of life spans of asphalt pavements

Traffic amounts

Information provided by Veronica Roth, Customer support manager/transports- and logistics manager, Ragn-Sells Tyre recycling.

Road 1-2:

- 1680 loads with an average weight of 28 tons.
- Traffic mainly consists of lorries delivering material (tyres).
- Average weight of empty tyre collecting lorry: 34 tons.
- Lorries are full entering the factory and some lorries transport material out of the factory as well – estimation: 75% of transports are full, 25% empty.

$$1680\ loads * (28\ tons + 34\ tons) + 560\ loads * 34\ tons = 123\ 200\ tons\ per\ year$$

Road 3-4:

- 3100 loads with an average weight of 17 tons.
- Traffic mainly consists of lorries collecting material (tyre cuts and granulate).
- Average weight of empty lorry: 30 tons.
- Most lorries are empty entering the factory and full on the way out – estimation: 70% of transports are full, 30% empty.

$$3100\ loads * (17\ tons + 30\ tons) + 1330\ loads * 30\ tons = 185\ 600\ tons\ per\ year$$

Average 1-2-3-4:

$$(123\ 200 + 185\ 600) tons\ per\ year/2 = 154\ 400\ tons\ per\ year$$

Strain measurements

Measurements from Said et al. (2014). One strain is defined as 50 kN which is equal to a 10 ton standard axle.

Surface	Number of strains
AR 1	89 660
AR 2	127 800
AR 3	128 500
REF 4	71 700

Conversion to years

Formula to convert average load and number of strains to a life span expressed in years.

$$\frac{Number\ of\ strains * 10\ tons}{Average\ load\ per\ year} = Estimated\ life\ span\ [in\ years]$$

Surface	Life span
AR 1	5,8 years
AR 2	8,3 years
AR 3	8,3 years
REF 4	4,6 years