DNV

Sustainability study

Life-cycle assessment of external paving

NATUR
STEIN
Jedes Stück ein Unikat

Table of contents

Sustainable construction using natural stone

1

Sustainable construction has gained in importance in recent years. Sustainable construction is defined as the consideration of ecological, economic and social aspects in planning and construction processes and property management. Germany has been working on the fundamentals and guidelines for the Sustainable Building Round Table, established by the Federal Ministry of Building, in 2001. One of the results of this work is the Guide to Sustainable Building by the Federal Ministry of the Interior, Building and Community, which is used as a planning guideline for public construction projects.

A certification system for sustainably designed and constructed buildings and developments has been created, in particular thanks to the activities of the German Sustainable Building Council (DGNB – Deutsche Gesellschaft für Nachhaltiges Bauen). With its certification system for sustainable developments, the DGNB offers a globally recognised planning and optimisation tool that helps to implement these kinds of comprehensive sustainability credentials in a targeted, systematic and economical way. It delivers the right answers to the key questions we will face in the future in terms of planning and construction practice.

Internationally, sustainable construction is often equated with the term green building. A similar certification system has existed in Great Britain for many years. The BREEAM system also assesses the buildings environmental performance, including social and health aspects, but does not evaluate economic performance. In the US, the LEED system was developed by the US Green Building Council. The system is now also used outside the United States for planning energy-efficient and green buildings. To date, the LEED system does not use a total building life-cycle assessment to evaluate the ecological performance of a building, but instead bases the ecologically motivated selection of materials on the evaluation of individual properties. For example, in the LEED system, a rating is given for materials and construction products that are transported less than 800 km to the construction site.

A warming planet and the changes in the climate associated with this will also require a major rethink in terms of construction, with increasing importance assigned to climate-friendly construction practices. Avoiding materials that emit high amounts of CO_2 during their manufacture is emerging as a major environmental aspect. Because the construction sector makes a major contribution to global CO_2 emissions and energy consumption, construction products should also have the lowest possible environmental impact in their manufacture and use, right through to disposal, taking economic aspects into account.

For example, the primary energy demand in the use of natural stone slabs for 1,000 m² of paving amounts to around just 505,000 MJ over a study period of 100 years. In contrast, the same area covered with concrete slabs requires approx. 2,136,000 MJ of primary energy. Based on the benchmark figure for electricity consumption for the average two-person household of 2,700 kWh/year, the amount of energy saved could supply around 170 two-person households with electricity for a whole year. Compared with clay pavers and Asphalt, the amount of primary energy saved could supply around 360 and 480 two-person households respectively with electricity for a whole year.

CO_2 emissions, which have such an impact on global warming potential, are also almost seven times lower for the production of natural stone paving slabs compared with their pre-cast concrete counterparts. For clay pavers, the ratio is as much as 7.6 times.

These results from the life-cycle assessment study are, however, also impacted by CO_2 emissions from transportation. In the following calculations, approx. 5.83 tonnes CO_2 equivalent are emitted with a transportation distance of 250 km for domestic production. If the same amount of natural stone is imported, this amount rises to approx. 46.64 tonnes for a distance of 2,000 km (Portugal/Spain) and to approx. 61.07 tonnes for imports from China. The environmental advantages of natural stone are thus severely eroded by long-distance transportation, which shows that the use of local natural stone is preferable. Offsetting transportation emissions with the purchase of carbon certificates is possible in theory, but their practical benefit is disputed.

In order to reduce raw material consumption, as much of the construction materials used in paving as possible must be directly reused or recycled.

Paving stones and slabs made from natural stone are of particular significance here because used paving stones and natural stone slabs for outdoor use are often reused and are a sought-after commodity.

For these reasons, the Deutscher Naturwerkstein-Verband e.V. (DNV – German Natural Stone Association) commissioned a study that compares the ecological impact of different modular paving materials for pavements, roads and public squares, from the production of materials, through the construction phase and whole life considerations in use.

President of the German Natural Stone Association

1 Summary

The object of this study by the Institute of Construction Materials at the University of Stuttgart is to determine the ecological performance of different pavement surfacing materials used in a variety of public realm and commercial applications.
The environmental impact of structural base and bedding layers, together with types of surfacing, was subjected to a detailed life-cycle study.
The data was collected from public environmental product declarations (EPD) issued by the various building material manufacturers and from the ÖKOBAUDAT platform managed by the German Federal Ministry for the Interior, Building and Community (BMI).

2: IBK plaza design, Maria-Theresia-Straße, Innsbruck
Nominated for a German Natural Stone Award (DNP) 2015

3+4: Plaza design: Sechsläutenplatz, Zurich
Winner of a German Natural Stone Award (DNP) 2015


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A comparison of all surfacing materials showed that paving setts and slabs produced from natural stone cause a significantly lower environmental impact in five categories – greenhouse effect **(GWP),** acidification potential **(AP)**, eutrophication potential **(EP)**, photochemical ozone creation potential **(POCP)** and total primary energy requirements – in terms of their production, installation and use than concrete paving stones and slabs as well as outdoor floor coverings involving paving bricks and Asphalt. This corresponds with the findings of the German Building Materials Association (BBS), according to which the cost of the energy consumed in processing natural stone amounts to just 3.3% of its production value.

A comparison of the pavement construction types over a 100 year service life, which is common for granite setts, for example, highlights the low energy consumption associated with pavement constructed using natural stone setts and slabs.
The energy requirements of external paving using natural stone slabs comes to approx. 470 MJ/m^2 – around 1/10th of the energy required for clay pavers (4,000 MJ/m^2) and for asphalt surfacing (5,210 MJ/m^2).

Total primary energy in MJ/m²

	Natural stone setts	Natural stone slabs	Concrete setts	Concrete slabs	Clay pavers	Asphalt
PERT [MJ]	113.2	109.1	211.6	436.1	353.9	230.7
%	**104**	**100**	**194**	**400**	**324**	**211**
PENRT [MJ]	358.7	396.4	937.3	1,700	3,641	4,979
%	**100**	**111**	**261**	**474**	**1,015**	**1,388**
Total [MJ]	471.9	505.5	1,149	2,136	3,995	5,210
%	**100**	**107**	**243**	**453**	**847**	**1,104**

Table 1: Comparative figures for PENRT and PERT over 100 years in MJ/m²

Figure 1 below shows the total energy requirements, comprising renewable energy **(PERT)** and non-renewable energy sources **(PNERT)**, for types of pavement surface construction.

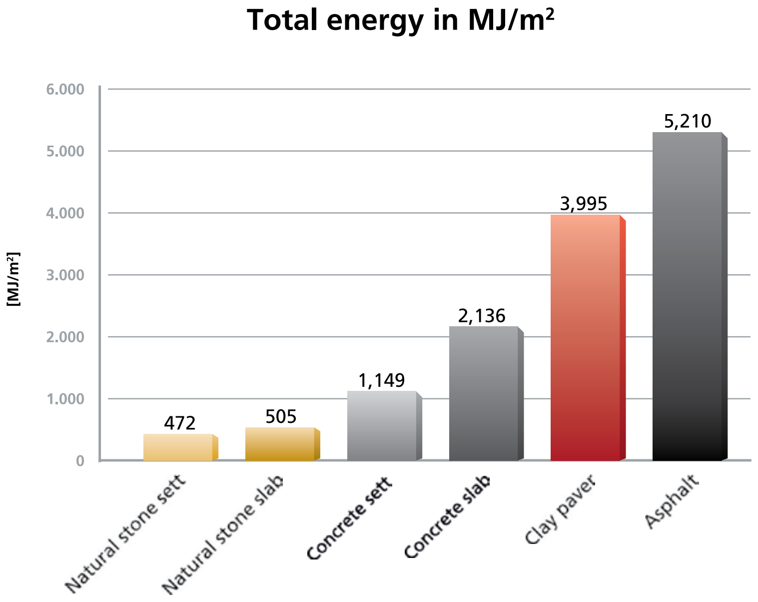


Figure 1: Total energy required by paved surfaces in MJ/m² assuming a service life of 100 years

In the especially important category of global warming potential **(GWP)** impact, the production and use of modular paving using natural stone setts and slabs generate significantly lower CO_2 equivalents than the production and use of other coverings. At 29.5 kilograms CO_2 equivalent, the lowest manufacturing emissions are attributed to the **GWP** of natural stone setts.

Global warming potential (GWP)

GWP	**Natural stone setts**	**Natural stone slabs**	**Concrete setts**	**Concrete slabs**	**Clay pavers**	**Asphalt**
kg CO_2 equiv.	29.5	33.1	139.2	225.9	253.2	135.3
%	**100**	**112**	**472**	**766**	**859**	**459**

Table 2: Global warming potential (GWP) of the paved surfaces in kg CO_2 equiv./m² within 100 years

The global warming potential **(GWP)** of clay pavers is with a value of approx. 253.2 kilograms CO_2 equiv. more than 8.5 times higher than for natural stone setts (see Figure 2).

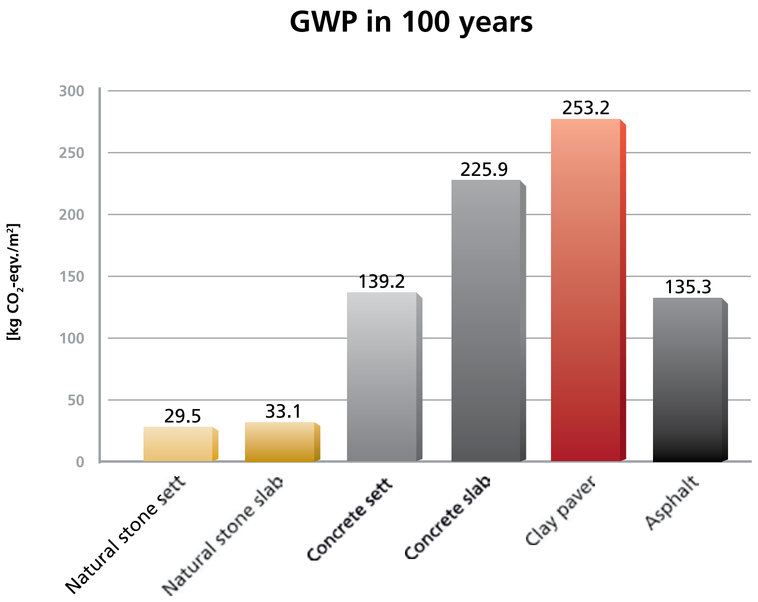


Figure 2: Global warming potential (GWP) of the paved surfaces in kg CO_2 equiv./m²

Another important aspect of using natural stone is the influence of transportation. While only 2.33 kilograms CO_2 equiv. per square metre of paving are produced when using local natural stone that is transported 100 km by lorry, or 5.83 kilograms CO_2 equiv. per sq m when transported 250 km by lorry, this increases to 23.32 kilograms CO_2 equiv./m² when transported within Europe (1,000 km by lorry) or 46.64 kilograms CO_2 equiv./m² when transported 2,000 km by lorry. Meanwhile, 61.07 kilograms CO_2 equiv. per square metre of paving are produced for natural stone from China (18,600 km by ship, 750 km by lorry).

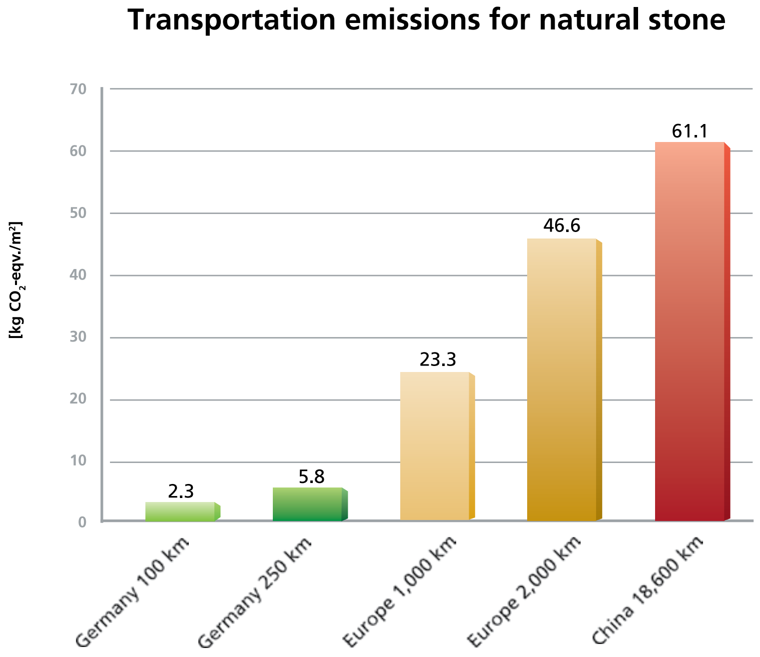
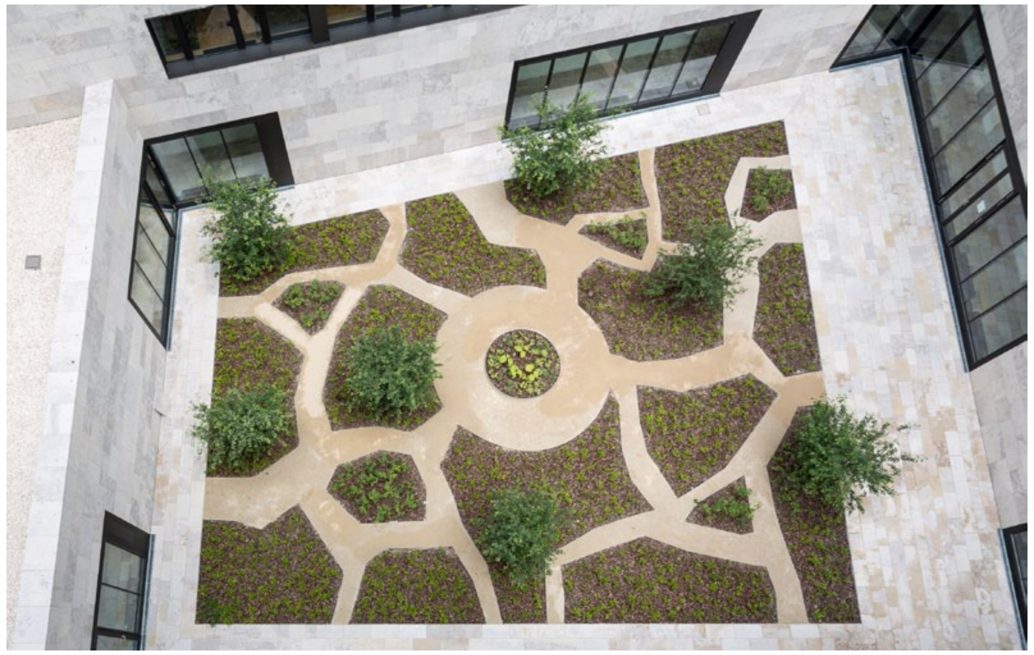


Figure 3: Transportation emissions for natural stone in kg CO_2 equiv./m²

Representative environmental product declarations (EPDs) were selected for all paving covering products studied. They contain verified values that may be anticipated for the various environmental impacts. The EPD of a product group with an available EPD was selected as being representative of the respective paving materials covering. Missing information or undeclared modules for individual life-cycle phases were supplemented with appropriate assumptions. To do this, data was employed from comparable EPDs or available databases, such as the Ökobaudat database from the Institute of Construction Materials at the University of Stuttgart, in order to create this sustainability study.



5

Max Planck Institute for European Legal History, Frankfurt am Main, Germany Nominated for a German Natural Stone Award (DNP) 2015

2 Adopted methodology

2.1 Life-cycle assessment methodology

Initially, a uniform substructure was specified for the study of the different pavement surfacing types. The layer thicknesses and the required quantities of materials were also identified. Representative environmental product declarations were researched and defined for each of the required materials. They contain verified values that may be assumed for the various environmental impacts. The EPD of a product group with an available EPD was selected as being representative of the respective pavement surfacing materials covering. Missing information or undeclared modules for individual life-cycle phases were supplemented with appropriate assumptions, employing data from comparable EPDs or available databases such as Ökobaudat for the analysis. The values determined relate to a functional unit of one square metre. The EPDs and Ökobaudat datasets are prepared according to the Environmental Product Declaration Principles for the building products category in compliance with EN 15804 [1] and therefore also conform to the life-cycle assessment principles and framework conditions in compliance with EN ISO 14040, and the requirements and instructions in compliance with EN ISO 14044 [2, 3].

6

Castle terraces Bad Alexandersbad and Alexplatz

7

Platz am Scharf Eck Winkel, Fridingen Nominated for a German Natural Stone Award (DNP) 2015

In the sustainability study, the following pavement surfacing materials coverings were compared using a representative product or product group as an example and taking into account the soil bases and necessary base courses and frost protection layers:

- Natural stone setts
- Natural stone slabs
- Concrete setts
- Concrete slabs
- Clay pavers
- Asphalt

The aim of the study is to ecologically evaluate and compare typical external pavement surfacing materials over periods of 50 and 100 years. All life-cycle phases from production to use were taken into consideration. The life-cycle assessment took into account the **global warming potential (GWP)**, the **acidification potential (AP)**, the **eutrophication potential (EP)**, the photochemical **ozone creation potential (POCP)** and energy consumption via the total **non-renewable primary energy demand (PENRT)** and the **total renewable primary energy demand (PERT)**.

2.2 Procedure

2.2.1 Pavement construction

For each surfacing material, a structural model was selected in accordance with the road construction requirements stipulated in the German Guidelines for the Standardisation of Surfaces of Road Traffic Areas (RStO) for surfaces in construction class (Bk) 1.0 that are not under constant use by heavy traffic.

2.2.2 Structure and design of natural stone setts 100/100/100 mm

Layers of substructure	Dataset (Ökobaudat)	Ökobaudat, name	Thickness [mm]	Quantity [kg/m²]
Natural stone setts	www.ökobaudat.de	Natural stone slabs, hard, outdoor use (thickness 0.08 m)	100	260
Unbound bedding	www.ökobaudat.de	Crushed rock 2/15	40	60
Gravel base course	www.ökobaudat.de	Gravel 16/32	200	280
Frost-protection layer	www.ökobaudat.de	Crushed rock 2/15 and gravel 16/32	410	697

Table 3: Natural stone setts – EPD, layer thickness and quantity

2.2.3 Structure and design of natural stone slabs 400/400/140 mm

Layers of substructure	Dataset (Ökobaudat)	Ökobaudat, name	Thickness [mm]	Quantity [kg/m²]
Natural stone Slabs	www.ökobaudat.de	Natural stone slabs, hard, outdoor use (thickness 0.08 m)	140	364
Unbound bedding	www.ökobaudat.de	Crushed rock 2/15	40	60
Gravel base course	www.ökobaudat.de	Gravel 16/32	200	280
Frost-protection layer	www.ökobaudat.de	Crushed rock 2/15 and gravel 16/32	370	629

Table 4: Natural stone slabs – dataset, thickness and quantity

2.2.4 Structure and design of concrete setts 100/100/100 mm

Layers of substructure	Data set (EPD)	EPD, name	Thickness [mm]	Quantity [kg/m²]
Concrete setts	EPD-SLG-20150317-CAE1-DE	Concrete setts, grey, with top layer	100	225
Bedding	www.ökobaudat.de	Crushed rock 2/15	40	60
Gravel base course	www.ökobaudat.de	Gravel 16/32	200	280
Frost-protection layer	www.ökobaudat.de	Crushed rock 2/15 and gravel 16/32	410	697

Table 5: Concrete setts – dataset, layer thickness and quantity

2.2.5 Structure and design of concrete slabs 400/400/140 mm

Table 6: Concrete slabs – dataset, layer thickness and quantity

Layers of substructure	Data set (EPD)	EPD, name	Thickness [mm]	Quantity [kg/m²]
Concrete slabs	EPD-KLO-20170147-IAC1-DE	Concrete tiles	140	329
Bedding	www.ökobaudat.de	Crushed rock 2/15	40	60
Gravel base course	www.ökobaudat.de	Gravel 16/32	200	280
Frost-protection layer	www.ökobaudat.de	Crushed rock 2/15 and gravel 16/32	370	629

2.2.6 Structure and design of clay pavers 100/100/100 mm

Table 7: Paving bricks/slabs – dataset, layer thickness and quantity

Layers of substructure	Data set (EPD)	EPD, name	Thickness [mm]	Quantity [kg/m²]
Clay pavers	EPD-ZWM-20160126-ICG1-DE	Paving bricks and quarter bricks	100	210
Bedding	www.ökobaudat.de	Crushed rock 2/15	40	60
Gravel base course	www.ökobaudat.de	Gravel 16/32	200	280
Frost-protection layer	www.ökobaudat.de	Crushed rock 2/15 and gravel 16/32	410	697

2.2.7 Structure and design of asphalt surfacing

Table 8: Asphalt – dataset, layer thickness and quantity

Layers of substructure	Dataset (Ökobaudat)	Ökobaudat, name	Thickness [mm]	Quantity [kg/m²]
Asphalt	www.ökobaudat.de	Mastic asphalt	40	96
Asphalt base course	www.ökobaudat.de	Asphalt base course	100	235
Gravel base course	www.ökobaudat.de	Gravel 16/32	150	210
Frost-protection layer	www.ökobaudat.de	Crushed rock 2/15 and gravel 16/32	460	782

Concrete slabs

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Asphalt with transition to natural stone setts

2.2.8 Service life of the external pavements coverings

The service life of external pavements varies considerably depending on the level of traffic and their construction. According to the guidelines of the German Federal Ministry of Transport and Digital Infrastructure (BMVI), road surfaces are generally designed to have a planned service life of 30 years.[2] Individual upper layers have different periods of use, however. In line with the latest findings, for instance, we can assume that an asphalt surface can more or less last for between 12 and 25 years, depending on the level of use and its design. Surfaces involving natural stone setts and slabs, however, have often been proven in use for centuries.

In this study, surfaces were analysed for service lives of 50 years and 100 years.
The following average service lives of the different coverings were used as a basis for the study period of 50 years:

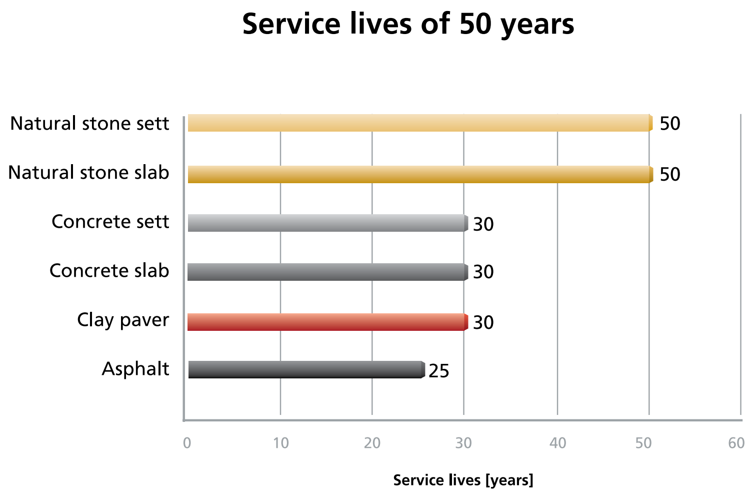

Figure 4: Average service life of paved surfaces

For a study period of 100 years, the following service lives of the surfaces were taken into account:

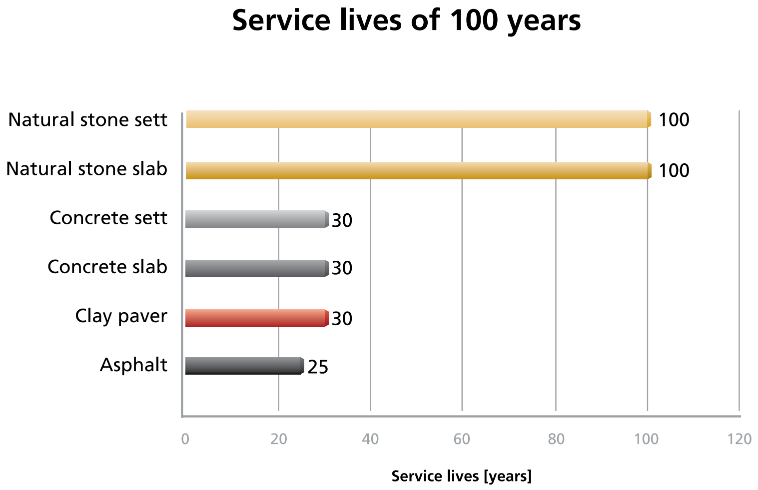

Figure 5: Service life of paved surfaces

[2] https://www.bmvi.de/SharedDocs/DE/Artikel/StB/erhaltung-von-strassen.html

3 Life-cycle assessment results

3.1 General aspects

This section compares selected impact categories for the different pavement structures.
For this comparison, a transportation distance of 100 km was assumed for natural stone, pre-cast concrete and clay pavers, while 50 km was assumed for asphalt.
The respective datasets used in the life-cycle assessment calculations are enclosed in Appendix B.

3.2 Environmental impact of GWP greenhouse effect with a life-cycle of 50 years

The table below shows the global warming potential (GWP) for the various pavement types constructions, including the base courses and frost protection layers, in kilograms CO_2 equiv. per square metre of pavement covering with a service life of 50 years.
The bottom line shows the percentage increase in comparison to the lowest emission value (=100%).

Global warming potential (GWP) in kg CO_2 equiv./m² of floor covering

GWP	Natural stone setts	Natural stone slabs	Concrete setts	Concrete slabs	Clay pavers	Asphalt
kg CO_2 equiv.	29.5	33.1	77.6	120.0	134.9	74.8
%	**100**	**112**	**263**	**407**	**458**	**254**

Table 9: Global warming potential (GWP) in kg CO_2 equiv./m² of floor covering within 50 years

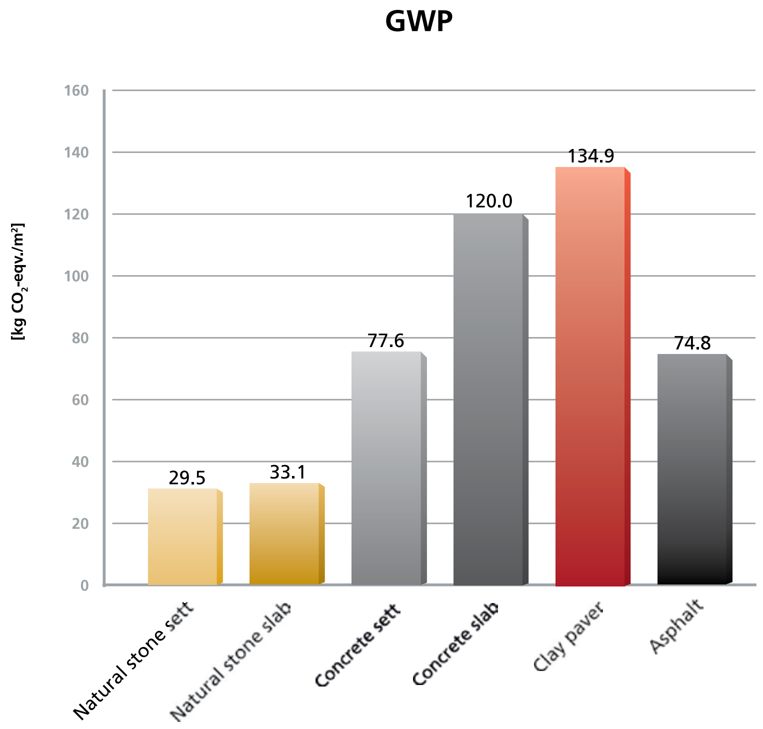

Figure 6: Global warming potential (GWP) of the paved surfaces in kg CO_2 equiv./m² within 50 years

At approx. 29.5 kilograms CO_2 equiv. per m², the lowest emissions in the impact category “climate change” (GWP) are assigned to natural stone setts, including bedding and base courses. The GWP of clay pavers is over 4.5 times higher than for natural stone setts at some 135 kilograms CO_2 equiv.

Upon closer analysis, the differences in these amounts can be explained primarily by the production stage of the surface material. The substructures all have similar thicknesses and therefore similar values. **For this reason, only the production of the upper surface is a major factor.** By way of comparison, only 7.17 kg CO_2 equiv. is generated by natural stone setts in production stages A1–A3, while clay pavers produce 53.7 kg CO_2 equiv. – a figure some 7.5 times higher. Furthermore, all top surfaces with the exception of natural stone have to be replaced after 25 to 30 years, which results in higher emissions in module B4, "Replacements" (see Appendix B).

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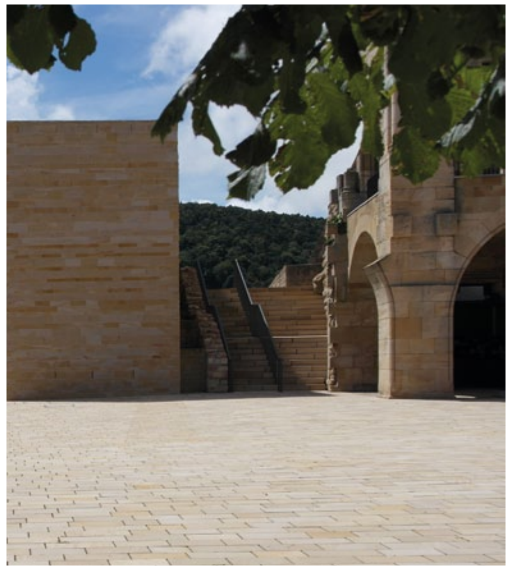


12


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10–12: Grounds of Hambach Castle, Neustadt an der Weinstraße, Winner of a German Natural Stone Award (DNP) 2013

13: View of Marktplatz in Hallstadt

3.3 Primary energy demand (PENRT and PERT) with a life-cycle of 50 years

The total primary energy demand in terms of manufacturing, installation and use, including the superstructure, is lowest for natural stone setts at 471.8 MJ and for natural stone slabs at 505.5 MJ, followed by concrete setts at 727.5 MJ and concrete slabs at 1,205 MJ. The provision of energy for natural stone and concrete constructions is generally covered by non-renewable primary energy sources (PENRT), with the proportion of renewable energy sources (PERT) only accounting for approx. 22–24%. When it comes to paving bricks and Asphalt, renewable energy sources only account for as little as approx. 5–10%. Asphalt has the highest total energy consumption with a value some 6.38 times higher than natural stone setts at 3,012 MJ (see Table 10).

Total primary energy in MJ/m²

	Natural stone setts	Natural stone slabs	Concrete setts	Concrete slabs	Clay pavers	Asphalt
PERT [MJ]	113.2	109.1	157.9	266.3	229.4	164.7
%	104	100	120	166	153	121
PENRT [MJ]	358.6	396.4	569.7	938.9	1,926.7	2,847.1
%	100	111	159	262	537	794
Total [MJ]	471.8	505.5	727.5	1,205.2	2,156.1	3,011.8
%	100	107	154	255	457	638

Table 10: Comparative figures for PENRT and PERT within 50 years

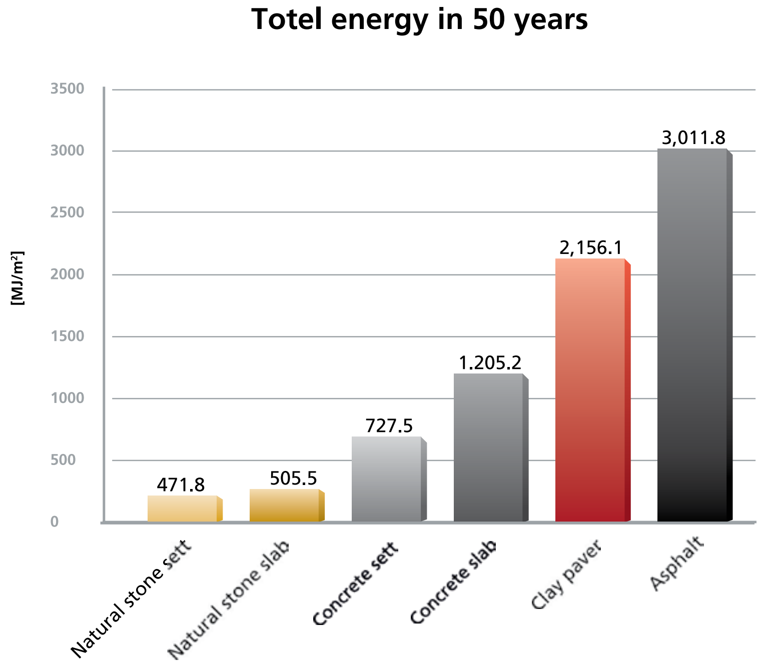

Figure 7: Primary energy demand for surface construction (PENRT and PERT) in MJ within 50 years

3.4 Environmental impact of GWP greenhouse effect with a life-cycle of 100 years

Within the “climate change” (GWP) impact category, emissions for natural stone remain unchanged over a period of 100 years compared with a period of 50 years because they do not have to be replaced during the study period of 100 years. By contrast, the environmental impacts of the other surfacing materials have increased further, because they have much shorter life-cycles (25–30 years) and thus need to be replaced three times during the same time frame. As a result of the replacement (B4) (see Appendix B), the emissions increase by between 80% and 90% compared with the study period of 50 years. The worst performer is the clay paver, for which emissions are nearly nine times as high as for natural stone setts (see Figure 8).

Global warming potential (GWP)

GWP	Natural stone setts	Natural stone slabs	Concrete setts	Concrete slabs	Clay pavers	Asphalt
kg CO_2 equiv.	29.5	33.1	139.2	225.9	253.2	135.3
%	100	112	472	766	859	459

Figure 11: Global warming potential (GWP) of the paved surfaces in kg CO_2 equiv./m² within 100 years

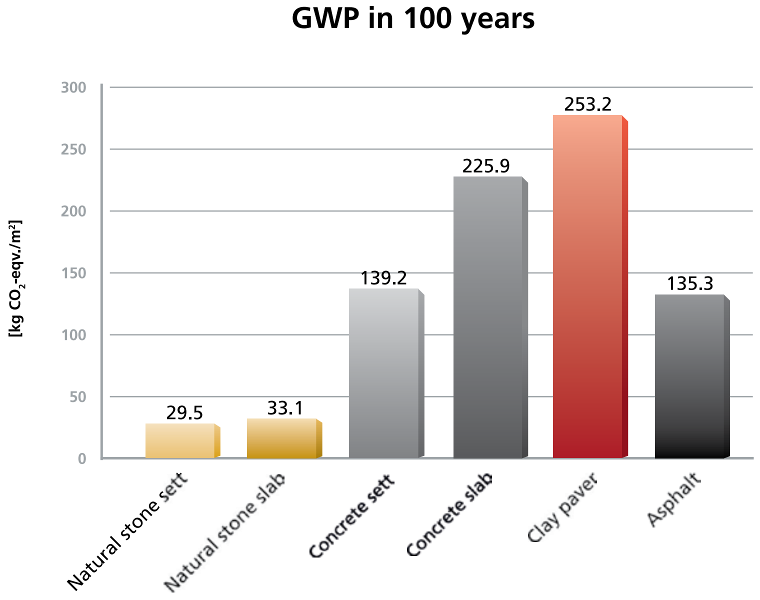

Figure 8: Global warming potential (GWP) of the paved surfaces in kg CO_2 equiv./m² within 100 years

3.5 Primary energy demand (PENRT and PERT) with a life-cycle of 100 years

The values for natural stone also remain unchanged with regard to total primary energy supply. Since pre-cast concrete and clay modular paving, also asphalt need to be replaced, they require more energy in percentage terms for manufacture, installation and use over a period of 100 years. Asphalt is the worst performer here, with emissions around 11 times as high as for natural stone setts (see Figure 9).

Total primary energy in MJ/m²

	Natural stone setts	Natural stone slabs	Concrete setts	Concrete slabs	Clay pavers	Asphalt
PERT [MJ]	1.132E+02	1.091E+02	2.116E+02	4.361E+02	3.539E+02	2.307E+02
%	**104**	**100**	**194**	**400**	**324**	**211**
PENRT [MJ]	3.587E+02	3.964E+02	9.373E+02	1.700E+03	3.641E+03	4.979E+03
%	**100**	**111**	**261**	**474**	**1,015**	**1,388**
Total [MJ]	4.718E+02	5.055E+02	1.149E+03	2.136E+03	3.995E+03	5.210E+03
%	**100**	**107**	**243**	**453**	**847**	**1,104**

Table 12: Comparative figures for PENRT and PERT within 100 years

Total energy in MJ/m²

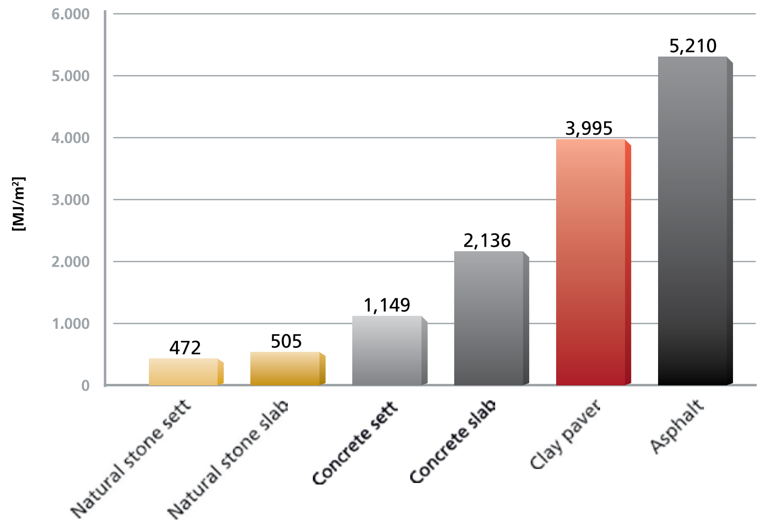

Figure 9: Primary energy demand for floor construction (PENRT and PERT) within 100 years

3.6 Comparison of transportation emissions

The transportation emissions for natural stone in various scenarios are illustrated in chart form below. The first scenario shows transportation within Germany (100 or 250 km) by lorry. The second scenario is for transportation within Europe (1,000 or 2,000 km), also by lorry. The third scenario illustrates transportation from China with a shipping route of 18,600 km and a lorry route from the quarry to the port of 250 km and, after the ship docks in Germany, another lorry route of 500 km to the construction site. The comparison is made using the CO_2 equivalent resulting from these transportation routes.

Environmental impact: transportation

	Transportation emissions to the site						
Natural stone	Emissions per m²						
Distances		Germany	Germany	Europe	Europe	China	
		100 km lorry	250 km lorry	1,000 km lorry	2,000 km lorry	18,600 km container ship	750 km lorry
GWP	kg CO_2 equiv.	2.33	5.83	23.32	46.64	43.58	17.49
∑	kg CO_2 equiv.	2.33	5.83	23.32	46.64	61.07	

Table 13: Transportation emissions

Transportation emissions for natural stone

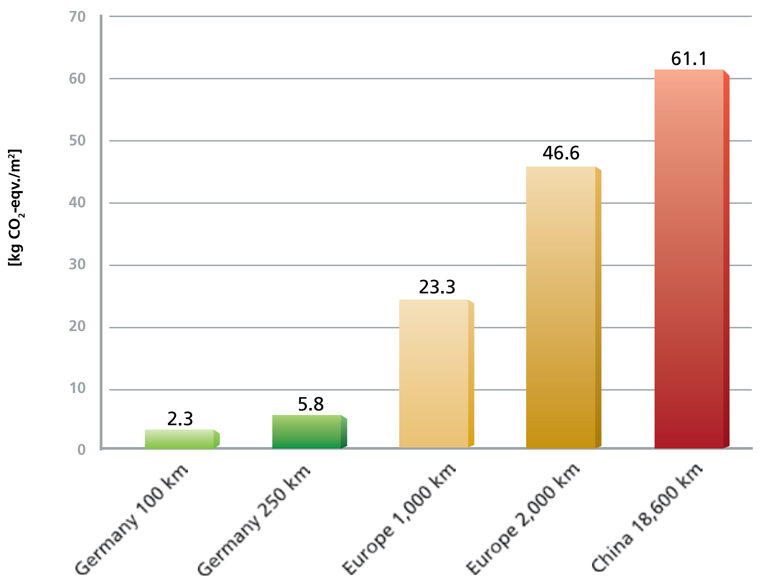

Figure 10: Transportation emissions for natural stone in kg CO_2 equiv./m²

4. Benefits of natural stone

The results of the external paving study show that natural stone setts and slabs for outdoor use have significant ecological advantages over all other paving materials.

Natural stone used a pavement surfacing material that has evolved over millions of years and is provided by nature as a ready made building material in its natural state. No energy is needed for its creation. Energy is only consumed during processing and transportation.
At 3.3% for working and processing natural stone, the share of energy costs in the gross production value is extremely low (see bbs 2016 figures).

Extraction in the quarry is kind to natural resources and does not require maximum fragmentation blasting. The unused rock utilised to backfill excavated sections of the quarry or economically processed into the bedding and base materials needed to construct the pavement, also used in landscaping and masonry. Nothing is lost in the entire cycle of natural stone extraction, processing and return to nature.

As a construction material, natural stone contains no harmful substances and can be safely used in conjunction with foodstuffs. Even in case of fire, natural stone releases no harmful substances. It is incombustible and corresponds to building material class A in accordance with DIN 4102.

The freedom of choice for format, shape and size, the variety of different stone colours and patterns, as well as the diverse range of surface treatments, allow almost unlimited design options when using natural stone. Because of the availability of square, rectangular, polygonal and even circular natural stone slabs and a wide range of bond styles, a great variety of patterns are made possible in the pavement surface design.

Building materials such as natural stone are back in focus with regard to sustainable construction methods because they effectively meet the demands for sustainable building materials. In detail, the most important ecological aspects of sustainable construction are:

Marktplatz in Hallstadt

14

A. Reduction in energy demand and use of operating resources

No energy is required to manufacture natural stone – it has been provided for us by nature. Natural stone is available as a finished product in the quarry and does not need to be manufactured using a mixture of raw materials and, as is the case for clay pavers, fired at very high temperatures. Only relatively low energy input is needed during extraction in the quarry and subsequent finishing in a processing plant in order to manufacture finished products of natural stone.
Limestone and even most sandstones maintain their natural role as a permanent store of carbon dioxide, just like timber.

B. Minimising the transportation of building materials

There are natural stone resources in every country. Germany in particular has large quantities of workable natural stone. As a result of the great diversity of domestic granites, sandstones, limestones, schists, etc., the demand for dimension stone can generally be met by domestic resources. The use of local natural stone obviates the impact of long-distance transportation and promotes construction projects that are in harmony with the local landscape.
Natural stone transportation from the stone processing plant to the construction site plays a substantial role in terms of environmental impact. This becomes obvious when comparing different production facilities (see section 3.6).

C. Use of reusable/recoverable building products

Natural stone products can be endlessly reused and recycled after the end of the structure’s use phase. Used natural stone setts and paving slabs are highly sought-after commodities and are reused many times, particularly in the design of historical districts. Natural stone setts and paving slabs are typically in their first place of use for more than 100 years and we see many examples still in service after millennia.
Any natural stone products that cannot be reused can be broken up into gravel, chippings or frost protection layers and used in road construction, paths, for gardening or landscaping.

D. Extension of the service life of building products and structures

Natural stone demonstrates exceptionally long periods of use, measured in centuries. Natural stone surfaces showing signs of heavy wear can be easily reprocessed in situ, resulting in a practically new surface, with minimal impact.

E. Non-hazardous return of building materials to the natural material cycle

Natural stone contains no pollutants and can easily be returned to the natural material cycle.

15

River Rhine promenade, Konrad-Adenauer-Ufer, Koblenz Nominated for a German Natural Stone Award (DNP) 2013

5 Bibliography

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[1] DIN EN 15804: Sustainability of construction works – Environmental product declarations – Core rules for the product category of construction products (EN 15804:2012).

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Grounds of Hambach Castle, Neustadt an der Weinstraße, Winner of a German Natural Stone Award (DNP) 2013

16

Appendix A Description of assessed variables

Appendix A 1 Primary energy demand

Primary energy demand can be met by different types of energy sources. The primary energy demand is the amount of energy or energy source directly extracted from the hydrosphere, atmosphere or geosphere which has not yet undergone anthropogenic transformation. With regard to fossil fuels and uranium, for example, this equates to the quantity of resource extracted, expressed as an energy equivalent (energy content of energy resources). With regard to renewable energy sources, for example, the quantity of biomass used, characterised by its energy content, is described. In terms of hydropower, we refer to the quantity of energy gained from the change in potential energy (from the elevation difference) of the water. Aggregated values include the following primary energy sources:

The cumulative value for **non-renewable total primary energy supply** in MJ essentially characterises the use of the following energy sources: natural gas, crude oil, lignite, anthracite and uranium. Natural gas and crude oil are used both for power generation and as a constituent of plastics, for example. Coal is predominantly used for power generation. Uranium is used exclusively for power generation in nuclear power stations.

The cumulative value for **renewable total primary energy supply**, given in MJ, is generally given separately and comprises wind and hydropower, solar energy and biomass.

It is important that the final energy consumed (for example, 1 kWh of electricity) and the primary energy used to achieve this are not offset against each other, otherwise the final energy production efficiency would not be taken into consideration.

The energy content of the manufactured products is reported as material-related energy content. It is characterised by the net calorific value of the product. It represents the remaining usable energy content.

Appendix A 2 Global warming potential (GWP)

The active mechanism of the greenhouse effect can be observed on a smaller scale, as the name implies, in greenhouses. This effect also occurs on a global scale. Incoming short-wave solar radiation strikes the earth's surface, where it is partially absorbed (which leads to direct warming) and partly reflected as infrared radiation. The reflected proportion is absorbed in the troposphere by what are known as greenhouse gases and radiated again in all directions, meaning that it is partially reflected back to earth. This leads to additional warming.

The global warming potential is given as a carbon dioxide equivalent (CO_2 equiv.). This means that all emissions are given with reference to CO_2 in terms of their potential greenhouse effect.

Appendix A 3 Acidification potential (AP)

The acidification of soils and water bodies is caused mainly by the conversion of air pollutants into acids. This results in a reduction in the pH of rainwater, mist and fog from 5.6 to 4 and below. Relevant inputs are delivered by sulphur dioxide and nitrogen oxides with their acids (H_2SO_4 and HNO_3). This causes damage to ecosystems, the foremost effect being forest dieback.

The acidification potential is given as a sulphur dioxide equivalent (SO_2 equiv.)

Appendix A 4 Eutrophication potential (EP)

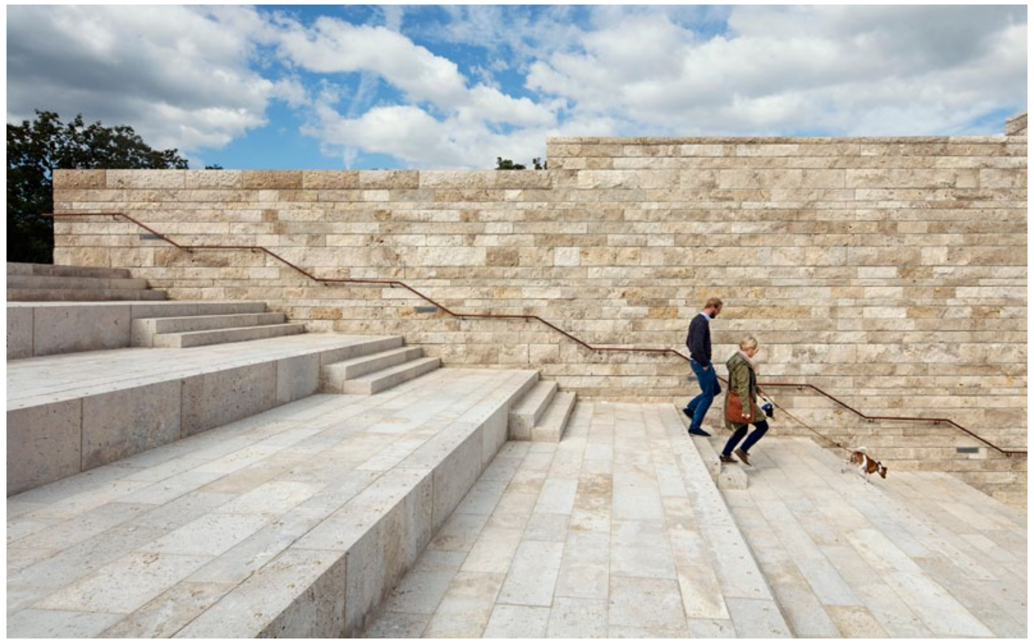
By eutrophication or nutrient input, we refer to an accumulation of nutrients at a specific location. We differentiate between aquatic and terrestrial nutrient input. Atmospheric pollutants, waste water and agricultural fertilisers all contribute to eutrophication.
The eutrophication potential is given as the phosphate equivalent (PO_4 equiv.)

Appendix A 5 Photochemical ozone creation potential (POCP)

In contrast to the protective function in the stratosphere, ground-level ozone is classified as a harmful trace gas. Photochemical ozone formation in the troposphere, also referred to as summer smog, is suspected of causing damage to vegetation and other materials. Higher concentrations of ozone are toxic to humans.
The photochemical ozone creation potential (POCP) is given as an ethylene equivalent (C_2H_4 equiv.) in the life-cycle assessment.

Appendix A 6 Ozone depletion potential (ODP)

Ozone is created at high altitudes by the irradiation of oxygen molecules by short-wave UV light. This leads to the formation of the so-called ozone layer in the stratosphere (15–50 km altitude). About 10% of the ozone passes into the troposphere through mixing processes. Despite its low concentration, the effect of ozone is important for life on earth. Ozone absorbs short-wave UV radiation and re-emits a longer wavelength in all directions, hence only some of the UV radiation reaches the earth. Anthropogenic emissions lead to the depletion of the ozone layer.
The ozone depletion potential of the respective substance is given as an R11 equivalent.



**Grimmwelt Kassel
Special mention
German Natural
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2018**

17

Appendix B Life-cycle assessment study data calculation

B.1 Substructure analysis

B.1.1 Natural stone setts, including substructure

Environmental impacts: natural stone setts construction

Size	Unit	Production stage	Installation stage	Use stage	Total emissions per m²
GWP	kg CO_2 equiv.	2.240E+01	7.210E+00	0.000E+00	**2.947E+01**
ODP	kg R11 equiv.	5.752E-13	7.802E-12	0.000E+00	**8.377E-12**
AP	kg SO_2 equiv.	3.551E-02	1.158E-02	0.000E+00	**4.710E-02**
EP	kg PO_4 equiv.	6.846E-03	2.765E-03	0.000E+00	**9.611E-03**
POCP	kg ethylene equiv.	1.814E-03	-3.802E-03	0.000E+00	**-1.987E-03**
PERT	MJ	1.094E+02	3.748E+00	0.000E+00	**1.132E+02**
PENRT	MJ	2.954E+02	6.325E+01	0.000E+00	**3.587E+02**

**Table 14:
Life-cycle assessment, natural stone setts construction**

Production stage:
The manufacturing phase information modules A1, A2 and A3 are declared and given as the aggregated module A1–A3. The emissions per square metre of natural stone were multiplied by a factor of 1.25 in order to increase the thickness of the slab from 8 cm to the requisite 10 cm. This produces the required function: emissions per square metre of natural stone slab relative to a thickness of 10 cm.

Installation stage:
Module A4 was calculated using a dataset from Ökobaudat that refers to transportation by lorry. The haulage capacity is 1,000 kg/km. To this end, the emissions were determined for a transportation distance of 100 km. The values for paving bricks were used for installation (module A5). It was assumed that the installation process for natural stone setts is virtually identical to that for clay pavers. The total of the two modules A4 and A5 was then multiplied by 260 kg/m² in order to get to the required thickness. The result is the emissions per square metre of natural stone setts relative to the layer thickness of 10 cm.

Use stage:
No environmental burdens occur during the reference service life of natural stone, because no measures for cleaning or repair are generally necessary. Furthermore, the natural stone is not replaced during the period of use studied here. For this reason, it is assumed that no, or only negligibly low, emissions are assigned to this stage.

B.1.2 Natural stone slabs, including substructure

Environmental impacts: natural stone slab construction

Size	Unit	Production stage	Installation stage	Use stage	Total emissions per m²
GWP	kg CO_2 equiv.	2.427E+01	8.815E+00	0.000E+00	**3.309E+01**
ODP	kg R11 equiv.	5.421E-13	1.092E-11	0.000E+00	**1.146E-11**
AP	kg SO_2 equiv.	3.972E-02	1.358E-02	0.000E+00	**5.330E-02**
EP	kg PO_4 equiv.	7.455E-03	3.240E-03	0.000E+00	**1.069E-02**
POCP	kg ethylene equiv.	2.224E-03	-4.435E-03	0.000E+00	**-2.211E-03**
PERT	MJ	1.047E+02	4.377E+00	0.000E+00	**1.091E+02**
PENRT	MJ	3.224E+02	7.396E+01	0.000E+00	**3.964E+02**

Table 15: Life-cycle assessment, natural stone slab construction

Production stage:
The manufacturing phase information modules A1, A2 and A3 are declared and given as the aggregated module A1–A3. The emissions per square metre of natural stone were multiplied by a factor of 1.75 in order to increase the thickness of the slab from 8 cm to the requisite 14 cm. This produces the required function: emissions per square metre of natural stone slab relative to a thickness of 14 cm.

Installation stage:
Module A4 was calculated using a dataset from Ökobaudat that refers to transportation by lorry. The haulage capacity is 1,000 kg/km. To this end, the emissions were determined for a transportation distance of 100 km. The values for clay pavers were used for installation (module A5). It was assumed that the installation process for natural stone slabs is virtually identical to that for clay pavers. The total of the two modules A4 and A5 was then multiplied by 364 kg/m² in order to get to the required thickness. This results in the emissions of the natural stone slabs per square metre relative to a layer thickness of 14 cm.

Use stage:
No environmental burdens occur during the reference service life of natural stone, because no measures for cleaning or repair are generally necessary. Furthermore, the natural stone is not replaced during the period of use studied here. For this reason, it is assumed that no, or only negligibly low, emissions are assigned to this stage.

River Main promenade, Miltenberg
Special mention
German Natural Stone Award (DNP) 2018

18

B.1.3 Concrete setts, including substructure

Environmental impacts: concrete setts construction

Size	Unit	Production stage	Installation stage	Use stage	Total emissions per m²
GWP	kg CO_2 equiv.	4.033E+01	6.431E+00	3.081E+01	**7.758E+01**
ODP	kg R11 equiv.	4.796E-10	6.752E-12	4.858E-10	**9.721E-10**
AP	kg SO_2 equiv.	5.808E-02	1.079E-02	4.817E-02	**1.170E-01**
EP	kg PO_4 equiv.	9.535E-03	2.575E-03	7.745E-03	**1.986E-02**
POCP	kg ethylene equiv.	3.790E-03	-3.547E-03	1.082E-03	**1.325E-03**
PERT	MJ	1.275E+02	3.496E+00	2.687E+01	**1.579E+02**
PENRT	MJ	3.269E+02	5.895E+01	1.838E+02	**5.697E+02**

Table 16: Life-cycle assessment, concrete setts construction

Production stage:
The manufacturing phase information modules A1, A2 and A3 are declared and given as the aggregated module A1–A3. Because the results of the EPD already refer to 1 m² and a layer thickness of 10 cm, no further calculations are required.

Installation stage:
Module A4 is not declared. It is assumed that the product is transported to the site by lorry. The haulage capacity is 1,000 kg/km. The emissions were determined for a weight of 225 kg/m² and a transportation distance of 100 km. It was assumed for module A5 that the installation process for concrete setts paving is virtually identical to that for paving bricks, and it was also multiplied by a weight of 225 kg/m². The total for both modules results in total emissions of the concrete setts paving per square metre relative to a layer thickness of 10 cm.

Use stage:
The use stage is not declared. It is assumed that there are no emissions during use (module B1). Moreover, no maintenance (module B2) or repair (module B3) is assumed within the selected study period. The emissions in the use stage only originate from the replacement (module B4). The concrete setts paving needs replacing every 30 years, i.e. once during the study period. As a result, module B4 comprises the new surface, transportation to the site, installation, transportation of the old surface for reprocessing/disposal and waste processing and is finally multiplied by a weight of 225 kg/m².

19

Concrete setts paving

B.1.4 Concrete slabs, including substructure

Environmental impacts: concrete slab construction

Size	Unit	Production stage	Installation stage	Use stage	Total emissions per m²
GWP	kg CO_2 equiv.	5.879E+01	8.329E+00	5.291E+01	**1.200E+02**
ODP	kg R11 equiv.	9.572E-11	9.872E-12	1.051E-10	**2.107E-10**
AP	kg SO_2 equiv.	9.740E-02	1.315E-02	9.425E-02	**2.048E-01**
EP	kg PO_4 equiv.	1.520E-02	3.139E-03	1.500E-02	**3.334E-02**
POCP	kg ethylene equiv.	3.031E-03	-4.305E-03	-5.699E-04	**-1.843E-03**
PERT	MJ	1.771E+02	4.247E+00	8.491E+01	**2.663E+02**
PENRT	MJ	4.865E+02	7.172E+01	3.807E+02	**9.389E+02**

Table 17: Life-cycle assessment, concrete slab construction

Production stage:
The manufacturing phase information modules A1, A2 and A3 are declared individually. The emissions stated refer to 1 m² concrete with a thickness of 8 cm. In order to achieve the desired thickness of 14 cm, the total for the modules is multiplied by a factor of 1.75. This results in the emissions of the concrete slabs per square metre relative to a layer thickness of 14 cm.

Installation stage:
Module A4 was calculated using a dataset from Ökobaudat that refers to transportation by lorry. The haulage capacity is 1,000 kg/km. To this end, the emissions were determined for a transportation distance of 100 km. The values for clay pavers were used for installation (module A5). It was assumed that the installation process for concrete slabs is virtually identical to that for clay pavers. The total of the two modules A4 and A5 was then multiplied by 329 kg/m² in order to get to the required thickness. This results in the emissions of the concrete slabs per square metre relative to a layer thickness of 14 cm.

Use stage:
No environmental impact occurs during the reference service life of concrete slabs apart from during their replacement (module B4). Neither do any measures to clean or repair the concrete need to be implemented, although the concrete slabs are replaced once during the period of use studied. As a result, the emissions for the new surface, transportation to the site, installation, transportation of the old surface for reprocessing/disposal and waste processing are added to the total once again and multiplied by a factor of 329.

Plaza with concrete slabs

20

B.1.5 Clay pavers, including substructure

Environmental impacts: construction with clay pavers

Size	Unit	Production stage	Installation stage	Use stage	Total emissions per m²
GWP	kg CO_2 equiv.	6.890E+01	6.899E+00	5.912E+01	**1.349E+02**
ODP	kg R11 equiv.	7.167E-10	1.607E-11	7.386E-10	**1.471E-09**
AP	kg SO_2 equiv.	2.080E-01	1.541E-02	2.010E-01	**4.243E-01**
EP	kg PO_4 equiv.	1.671E-02	3.219E-03	1.515E-02	**3.508E-02**
POCP	kg ethylene equiv.	1.196E-02	-3.407E-03	1.022E-02	**1.877E-02**
PERT	MJ	1.653E+02	1.872E+00	6.227E+01	**2.294E+02**
PENRT	MJ	1.002E+03	6.744E+01	8.574E+02	**1.927E+03**

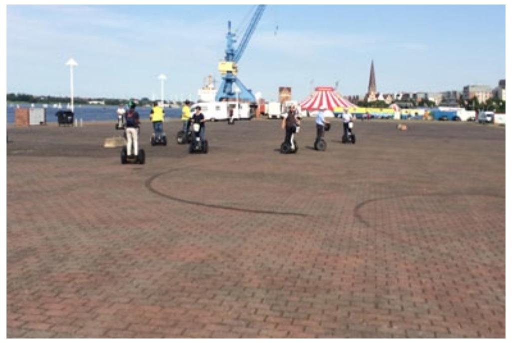
Table 18: Life-cycle assessment, construction with clay pavers

Production stage:
The manufacturing phase information modules A1, A2 and A3 are declared and given as the aggregated module A1–A3. The emissions for clay pavers refer to one tonne. For this reason, the values are multiplied by a factor of 0.21, because only 210 kg of material is required per square metre. This produces the required function: emissions per square metre of paving bricks relative to a thickness of 10 cm.

Installation stage:
The declared transportation A4 and installation A5 modules are active in the paved surface installation stage. Both modules have defined values. The A5 values are based on the waste treatment of the packaging materials. The functional unit is again achieved via multiplication by a factor of 0.21.

Use stage:
For clay pavers, the only environmental impact that occurs during the use stage is during replacement (module B4) because the surface needs to be replaced once after 30 years. The values for the new surface, transportation to the site, installation, transportation of the old surface for reprocessing/disposal and waste processing are added up once again and multiplied by a factor of 0.21. Apart from during replacement, no further emissions occur during the life-cycle, because clay pavers do not emit any substances that are harmful to the environment or to human health during use according to the EPD. No cleaning or repair measures need to be implemented either. For this reason, it is assumed that no, or only negligibly low, emissions need to be assigned.

21



Plaza with paving bricks

B.1.6 Asphalt, including substructure

Environmental impacts: asphalt construction					
Size	**Unit**	**Production stage**	**Installation stage**	**Use stage**	**Total emissions per m^2**
GWP	kg CO_2 equiv.	4.063E+01	3.940E+00	3.024E+01	**7.481E+01**
ODP	kg R11 equiv.	6.879E-13	1.783E-15	1.493E-13	**8.,390E-13**
AP	kg SO_2 equiv.	7.051E-02	9.282E-03	5.988E-02	**1.397E-01**
EP	kg PO_4 equiv.	1.251E-02	2.215E-03	1.044E-02	**2.516E-02**
POCP	kg ethylene equiv.	-6.976E-05	1.851E-02	1.904E-02	**3.748E-02**
PERT	MJ	1.286E+02	3.171E+00	3.297E+01	**1.647E+02**
PENRT	MJ	1.321E+03	5.314E+01	1.473E+03	**2.847E+03**

Table 19: Life-cycle assessment, Asphalt construction

Production stage:
The production phase information modules A1, A2 and A3 are declared and given as the aggregated module A1–A3. The emissions refer to 1 kg. For this reason, the values are multiplied by a factor of 96, because 96 kg of material is used per square metre. This produces the required function: emissions per square metre of asphalt relative to a thickness of 4 cm.

Installation stage:
Module A4 was calculated using a dataset from Ökobaudat that refers to transportation by lorry. The haulage capacity is 1,000 kg/km. To this end, the emissions were determined for a transportation distance of just 50 km instead of the 100 km used elsewhere, because the supply radius for asphalt is a maximum of 50 km [4]. As is the case for the production stage, the installation module A5 was declared in Ökobaudat as a per-kilo figure. The total of the two modules A4 and A5 was then multiplied by 96 kg/m² in order to get to the required thickness. This results in the emissions of the asphalt per square metre relative to a layer thickness of 4 cm.

Use stage:
For asphalt, the only environmental impact that occurs during the use stage is during replacement (module B4), because the surface needs to be replaced once after 25 years. The values for the new surface, transportation to the site, installation, transportation of the old surface for reprocessing/disposal and waste processing are added up once again and multiplied by a factor of 96. Apart from the replacement of the surface, no further emissions occur during the life cycle. No cleaning or repair measures need to be implemented either. For this reason, it is assumed that no, or only negligibly low, emissions need to be assigned.

Asphalt road surface

22

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