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Planning strategies for promoting environmentally suitable pedestrian pavements in cities

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ABSTRACT

This paper examines the relevance of incorporating comprehensive life-cycle environmental data into the design and management of pedestrian pavements to minimize the impact on the built environment. The overall primary energy demand and global warming potential of concrete, asphalt and granite sidewalks are assessed. A design with a long functional lifetime reduces its overall primary energy demand and global warming potential due to lower maintenance and repair requirements. However, long-lived construction solutions do not ensure a lower life-cycle primary energy demand and global warming potential than for shorter-lived designs; these values depend on the environmental suitability of the materials chosen for paving. Asphalt sidewalks reduce long-term global warming potential under exposure conditions where the functional lifetime of the pavements is less than 15 years. In places where it is known that a concrete sidewalk can have a life of at least 40 years, a concrete sidewalk is the best for minimizing both long-term primary energy demand and global warming potential. Granite sidewalks are the largest energy consumers and greenhouse gas contributors.

1. Introduction

New Urbanism puts emphasis creating a pedestrian-friendly environment where walking is promoted as a broadly accessible mode of sustainable transportation and safe recreation while facilitating commercial and social exchange and encouraging citizens to be physically active. The environmental benefits of promoting pedestrian networks are calculated based on the assumption that suitable and well-connected infrastructures can increase walking activities while limiting the demand for motorized transport. Pedestrian pavements are therefore designed to be technically, economically and aesthetically suitable for users and developers, often involving a pedestrian need hierarchy. The design process, however, fails to apply comprehensive life cycle environmental data to identify suitable construction solutions and urban management strategies that contribute to minimizing environmental impacts.

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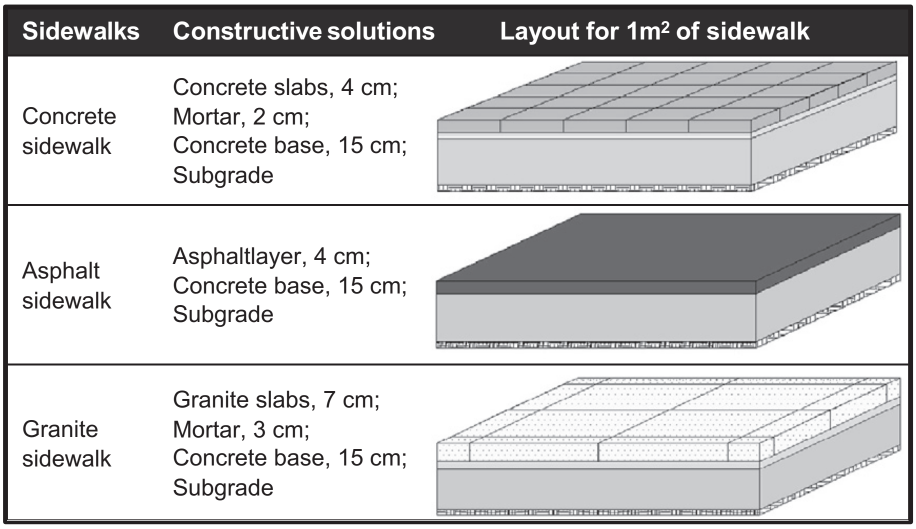


Fig. 1. Structural sections of the sidewalk designs.

Based the European Commission's (2010) goal of reducing fossil energy consumption and greenhouse gas (GHG) emissions by 20% by 2020, we focus on assessing the life-cycle embodied energy and GHG emissions of three common types of sidewalks found worldwide that use concrete slabs, granite slabs and asphalt as surface paving materials. The paper integrates the collection of a life-cycle inventory (LCI) of the energy and material flows associated with the entire life cycle of an asphalt sidewalk and updates the corresponding life-cycle inventories of the structurally equivalent concrete and granite sidewalks addressed in Oliver-Solà et al. (2009) and Mendoza et al. (2012).[1]

2. Methodology

The environmental performances of the sidewalk constructions were evaluated according to the LCA methodology (International Standardization Organization 14040, 2006).

2.1. Functional Unit

A functional unit (FU) provides a reference for accounting for and evaluating the inputs and outputs related to the life cycle of the systems under assessment. It is defined as one square meter of sidewalk located in central Barcelona, Spain, that supports pedestrian and (sporadic) light motorized traffic over a period of 45 years. Sidewalks include all pavement layers extending from the compacted soil (subgrade) to the surface (top layer).

Although sidewalks emphasize pedestrian comfort, vehicles tend to travel or park over them (i.e., during cleaning or to enter or exit a parking lot). Sidewalks designs are therefore considered to accommodate this extra loading.

Due to the high degree of uncertainty related to the average service lives of pedestrian pavements a specific benchmark must be used to define the timeframe for which life-cycle impacts are quantified. Oliver-Solà et al. (2009) set this timeframe on the assumption that an area equivalent to the entire sidewalk surface (including inner and outer, residential and non-residential urban areas) is reconstructed every 45 years in the city of Barcelona because of trenching or maintenance of underground services. We used the same assumption to define our analysis period.

2.2. Description of the sidewalks

Concrete sidewalks are the most common type worldwide because they are considered consistent, durable and economic. Asphalt sidewalks are chosen for their initial low cost, but they have a shorter service life than concrete. They are more susceptible to damage from weather and normally require more maintenance, increasing their economic cost over time (Federation of Canadian Municipalities and National Research Council, 2004). Granite sidewalks may be more aesthetically pleasing than concrete or asphalt sidewalks, but their construction cost is normally higher. Granite is the natural stone that is most commonly used for exterior paving due to its three fundamental characteristics: hardness, durability and aesthetics (Federación Española de la Piedra Natural, 2005).

[1] Oliver-Solà et al. find that, by optimizing the design of concrete sidewalks according functions, environmental impacts can be reduced by 74% per square meter. Mendoza et al. show that by using the more environmentally suitable flooring material, urban planners can reduce their environmental impacts to 139% per square meter.

The standard structural sections of the construction designs are indicated in Fig. 1. Sidewalks are named after their respective top layers.

A standard base of 15 cm of concrete with a typical compressive strength of 25 MPa is required when the sidewalk must accommodate both pedestrian and light motorized traffic. This requirement is assumed to be the same for each sidewalk design. Concrete slabs have typical dimensions of 20 × 20 × 4 cm, whereas granite slabs measure 40 × 40 × 7 cm; a layer of asphalt is necessarily 4 cm wide (pers. comm. City Council of Barcelona, 2011; pers. comm. HormiLaser Group, 2011). When concrete or granite slabs are used, a layer of mortar for fixing the slabs and cement grout for sealing the joints are required. Curbs are not included in the environmental assessment because they are frequently outside of the maintenance area; therefore, it is assumed that curbs are unaffected by M&R operations or trenching.

2.3. System boundaries

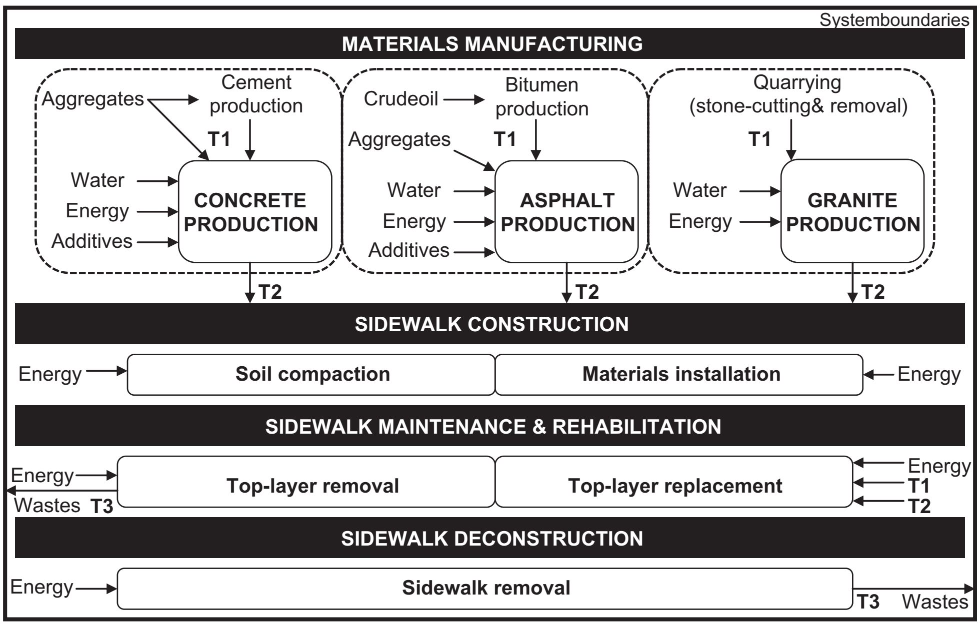
Fig. 2 shows the life-cycle stages, unit processes, energy and material flows included within the LCA.

All inputs and outputs associated with the life cycle of the sidewalks have been studied, including transportation operations, where T1 corresponds to the transportation of materials from quarry to production facilities, T2 from production facilities to the construction site, and T3 from the construction site to final disposal. It is assumed that raw materials required in production come from local suppliers, with the construction products being manufactured at facilities. Distances for goods and demolition wastes are based on the location of facilities from central Barcelona, Spain. Construction work is defined as: Soil compacted using tampers, and the concrete base is poured from a mixer truck, spread manually, compacted with vibration and smoothed by a ruler. Mortar, concrete and granite slabs are manually placed onto this base. A small paver, roller compactor and vibrating tray, however, are required to install an asphalt layer. It is assumed in the M&R schedule that the base of concrete does not need to be replaced, repaired or rehabilitated for 45 years. The top layers, with mortar and grout where appropriate, however, are assumed replaced as often as indicated by their potential service lives. The top layer of sidewalks is removed using pneumatic hammers and small power shovel for concrete and granite, whereas a small grinder and power shovel with sweeper are used for asphalt. New top layers are installed following the same processes used in sidewalk construction. Finally, the whole sidewalks are deconstructed using backhoes equipped with pneumatic hammers.

The management of the construction and demolition wastes was excluded from the environmental assessment due to uncertainties about the waste treatment techniques that will be employed when the sidewalk is demolished after 45 years. In addition, when the top layer of the sidewalks is replaced due to maintenance operations, wastes are usually poorly recycled, mainly in a landfill. Only related impacts from waste transportation to final disposal (T3) are considered.

2.4. Service life of sidewalks: case scenarios

Accuracy in the projections of the needs for, and the timing of, M&R activities cannot be expected because this is a process of estimating and/or predicting future events; however, it provides valuable input to the life-cycle environmental impact



Note: T refers to materials transportation.

Fig. 2. System boundaries and unit processes considered.

assessment (International Standardization Organization 15686-1, 2011; 15686-6, 2004). Concrete and granite sidewalks have an average service life of 20–45 years (Federation of Canadian Municipalities and National Research Council, 2004), whereas asphalt sidewalks have an average service life of 15 years. Nevertheless, the service life of a sidewalk can be longer or shorter than expected. Poorly designed or constructed sidewalks with inappropriate management standards may show significantly accelerated functional and/or structural deterioration, leading to their premature failure. However, when sidewalks are designed and managed using best practices, their serviceability can be longer than expected. For instance, the service life of a concrete or granite sidewalk can be extended to some 80 years, and to almost 45 years for an asphalt sidewalk.

Due to the potential variability of the service lives of sidewalks and the corresponding effect on the M&R schedule, different case scenarios have been considered in which sidewalks are subjected to the same exposure over a period. The service lives of sidewalks are considered to range from 5 years to 45 years, where only the top layers are assumed replaced to restore the serviceability of the infrastructure. The top layers are therefore replaced as often as necessary based on their service life. For instance, if a sidewalk's service life is 5 years, it would be replaced eight times, but no replacements would be required if the service life falls within the study timeframe.

The environmental impacts of M&R operations are quantified according to a static focus of the current state of the technology. The LCI (Table 1) of the sidewalks includes intermediate values of the current processes within the systems analyzed without analyzing their variation over time. Because M&R operations can take place 5–45 years after the construction of the sidewalk, management techniques and machinery can improve before a M&R operation takes place. Energy efficiency improvements and related GHG emissions are therefore somewhat uncertain.

Table 1
Life-cycle inventories for 1 m^2 of the sidewalk systems according to the F.U.

Sidewalk	Life-cycle stage	Flow	Materials and energy requirements	Data per F.U.
Concrete sidewalk	Materials manufacturing (top-layer)	Concrete slabs (20 × 20 × 4 cm)	Portland calcareous cement	11 kg
			Fine aggregates (gravel)	85 kg
			Admixture (plasticizers)	0.2 kg
			Water	5.5 kg
		Mortar (2 cm)	Portland calcareous cement	6.6 kg
			Fine aggregates (sand)	40 kg
			Water	3.7 kg
		Grout	Portland calcareous cement	1.9 kg
			Water	5.6 kg
	Materials transportation	T1 (truck, 28 t)	From quarry to concrete plant (cement, aggregates and additives)	75, 45 100 km
		T2 (truck, 16 t)	From facility to site (concrete, mortar)	30 km
		T3 (truck, 28 t)	From site to final disposal (wastes)	30 km
	Sidewalk construction	Energy	Diesel (compaction and material installation)	7.3 MJ
	Sidewalk maintenance	Energy	Diesel (top-layer removal and replacement)	8.8 MJ
	Sidewalk deconstruction	Energy	Diesel (system removal)	17.4 MJ
Asphalt sidewalk	Materials manufacturing (top layer)	Asphalt layer (4 cm)	Fine aggregate (sand)	64.1 kg
			Coarse aggregates (limestone)	27.5 kg
			Bitumen	4.4 kg
	Materials transportation	T1 (truck, 28 t)	From quarry to asphalt plant (bitumen, aggregates)	200, 45 km
		T2 (truck, 16 t)	From facility to site (asphalt, concrete)	100, 30 km
		T3 (truck, 28 t)	From site to final disposal (wastes)	30 km
	Sidewalk construction	Energy	Diesel (compaction and material installation)	16.4 MJ
	Sidewalk maintenance	Energy	Diesel (top-layer removal and replacement)	32.1 MJ
	Sidewalk deconstruction	Energy	Diesel (system removal)	15.7 MJ
Granite sidewalk	Materials manufacturing (top-layer)	Granite slabs (40 × 40 × 7 cm)	Granite	185 kg
		Mortar (3 cm)	Portland calcareous cement	9.9 kg
			Fine aggregates (sand)	60 kg
			Water	5.6 kg
		Grout	Portland calcareous cement	1.9 kg
			Water	5.6 kg
	Materials transportation	T1 (truck, 28 t)	From quarry to plant (granite blocks)	10 km
		T2 (truck, 16 t)	From facility to site (granite, mortar)	30 km
		T3 (truck, 28 t)	From site to final disposal (wastes)	30 km
	Sidewalk construction	Energy	Diesel (compaction and material installation)	9.3 MJ
	Sidewalk maintenance	Energy	Diesel (top-layer removal and replacement)	14.5 MJ
	Sidewalk deconstruction	Energy	Diesel (system removal)	20.7 MJ
Common element	Concrete base (15 cm)		Portland calcareous cement (CEM II 32.5R)	45 kg
			Fine aggregates (sand)	150 kg
			Coarse aggregates (gravel)	150 kg
			Admixture (plasticizers)	0.7 kg
			Water	19.7 kg

2.5. Environmental assessment

The embodied energy of the sidewalks is quantified in terms of primary energy demand (PED), expressed in megajoules equivalent (MJ-eq. from renewable and non-renewable resources [net cal. value]). GHG emissions are analyzed in terms of their contribution to global warming potential (GWP), expressed in emissions of equivalent carbon dioxide (kg CO_2-eq. [100 years]).[2]

The PED and GWP of the manufacturing process of granite slabs were quantified by using the LCI of granite quarrying and processing from the US Natural Stone Council (2009). For asphalt, a LCI of asphalt production provided by Cartif Technology Centre (pers. comm., 2011) was considered. These inventories were chosen because of their high quality, updated data and use of industrial manufacturing processes that are standard worldwide. Processes from the ecoinvent database were used for quantifying the PED and GWP of the other elements of the LCI of the sidewalks.

3. Results

Table 1 shows the life-cycle inventories for 1 m^2 of the sidewalk solutions under consideration.

The energy requirements associated with construction activities were determined using the BEDEC database (Institut de Tecnologia de la Construcció de Catalunya, 2011) and an urban planner in the pers. comm. HormiLaser Group (2011). Material inputs for concrete and granite sidewalks were compiled from Oliver-Solà et al. (2009) and Mendoza et al. (2012). Material inputs for the asphalt sidewalk were provided by the Cartif Technology Centre and City Council of Barcelona (pers. comm., 2011). Distances and type of trucks related to transportation activities were defined from a local market perspective.

Initially, to determine the life-cycle PED and GWP of the sidewalk types (Table 2 and Fig. 3), it is assumed that no M&R operations are required; sidewalks are deconstructed before they reach the end of their service lives. At this point, we do not aim to compare the environmental performance between sidewalks, but to analyze their impacts on an individual basis by avoiding the initial uncertainty related to M&R activities. The environmental impact related to the M&R schedule is addressed later.

The construction materials constitute the largest portions of both PED and GWP, accounting for 63–72% and 75–79%. The transportation stage is the second highest impact contributor, within which transportation of materials from the production facility to the construction site (T2) contributes the most. A carefully considered transportation management system can reduce the extent of this impact. The contributions of construction works are nearly negligible (less than 6%).

When analyzing the contribution of the construction materials (Fig. 3), the concrete base is shown to be the largest input to GWP in all of the sidewalk types. It also constitutes the largest input to PED in the concrete sidewalk. For the asphalt and granite sidewalks, however, their top layers have 0.2% and 92% higher embodied energy than the concrete base. Table 3 shows the PED and GWP of the top layers of the sidewalks, indicating the elements of their manufacturing processes that contribute most significantly to their environmental burden.

The impact of concrete slabs is mainly associated with the cement content; the largest impact contributor for all cement-based materials used in the sidewalks. About 0.72 kg CO_2-eq. is emitted and 3.6 MJ-eq. are consumed per kg of cement. Clinker production constitutes the largest input to PED and GWP because of the chemical reactions that occur in the clinker kiln and the fuel combustion during its production (Josa et al., 2004).

The process that contributes the most GHG emissions in asphalt manufacturing is the mixing and drying of aggregates. It contributes 51% of the overall GWP of asphalt but only accounts for 12% of its PED. Bitumen content, however, represents 86% of the total PED of asphalt and is the highest-impact constituent, with crude oil refining as its critical process. Bitumen accounts for 0.43 kg CO_2-eq. and 48.4 MJ-eq. per kilogram. Table 3 indicates that although the PED of asphalt is much higher than that of the concrete slabs (+238%), its contribution to GWP is very low (−56%). In this case, PED and GWP are not directly correlated because of the energy allocation of bitumen. As a hydrocarbon, it has approximately 40.2 MJ/kg of inherent energy (Garg et al., 2006). This chemical energy needs to be included in the energy balance of bitumen and measured as part of the total embodied energy of the asphalt to be compliant with the International Standardization Organization 14044 (2006) guidelines. However, this embodied energy has no associated GHG emissions. If this type of energy were excluded from the energy balance of bitumen, the PED of the asphalt applied in the sidewalk would be approximately 72.7 MJ-eq./m^2, lower than the PED of the concrete slabs. The exclusion or inclusion of this feedstock energy is a pivotal decision within a pavement LCA study (Santero et al., 2011a)[3].

The main contributor to the environmental burden of granite slabs is the amount of energy required for quarrying and processing (Mendoza et al., 2012). Granite is a naturally compact stone that consisting of several minerals including quartz and feldspar, with a hardness of between five and seven on the Mohs scale (EN 12670, 2001). Because of this heavy equipment is required for removing, transferring and processing it. Electric-powered diamond wire saws are used for stone-cutting, and trucks and cranes, usually diesel-powered, are used for removing and transferring the blocks. The contribution of granite slabs to GWP is also relatively low with regard to its PED. This disparity is associated with the electricity mix

[2] The environmental assessment is based on the CML baseline 2001 method (Guinée et al., 2001). The GaBi 4.4 software (PE International, 2010) and the ecoinvent database v2.1 (Swiss Centre for Life Cycle Inventories, 2009) were used as supporting analytical tools.

[3] It has been suggested that feedstock energy of bitumen should be treated differently from that of consumed energy because it is fundamentally different (University of California Pavement Research Center, 2010).

Table 2
Life-cycle PED and GWP of the sidewalks without considering M&R requirements.

Sidewalk type	Impact	Materials manufacturing	Materials transportation	Sidewalk construction	Sidewalk deconstruction	Total
Concrete sidewalk	PED (MJ eq./m^2)	383.0	197.2	9.5	22.5	612.2
	GWP (kg CO_2 eq./m^2)	56.0	12.4	0.7	1.6	70.6
Asphalt sidewalk	PED (MJ eq./m^2)	499.0	183.6	21.3	20.4	724.2
	GWP (kg CO_2 eq./m^2)	42.0	11.5	1.5	1.4	56.4
Granite sidewalk	PED (MJ eq./m^2)	816.2	282.8	12.0	26.8	1137.8
	GWP (kg CO_2 eq./m^2)	77.7	17.7	0.8	1.9	98.1

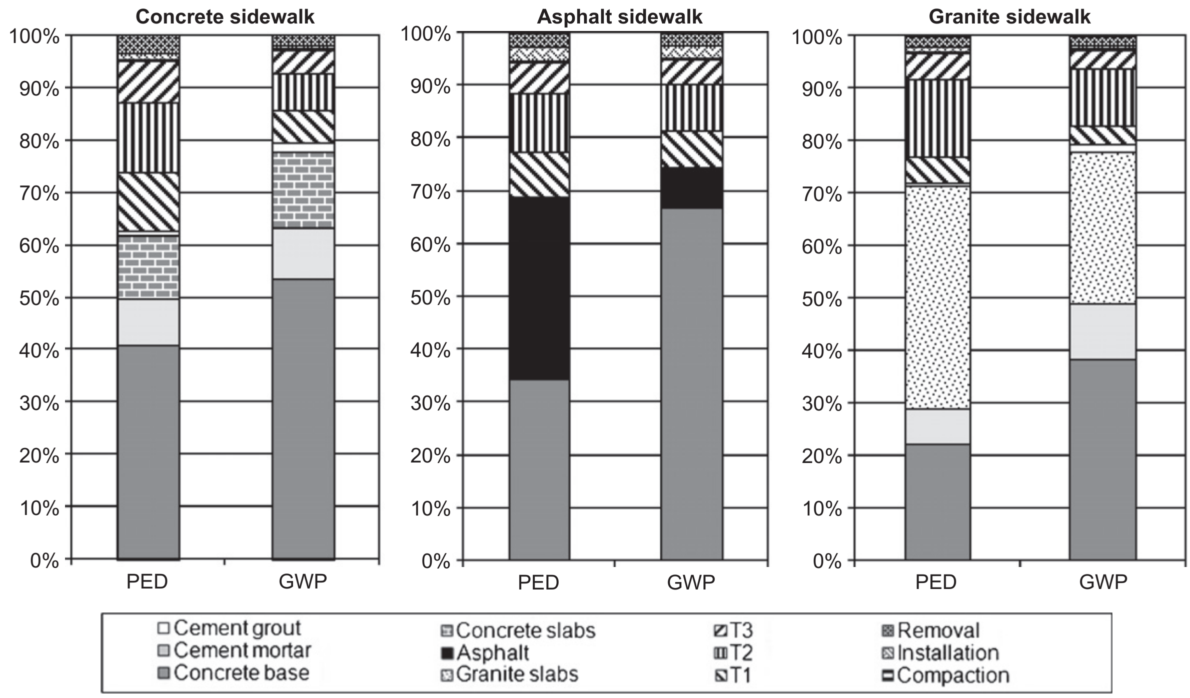


Fig. 3. Relative contributions to PED and GWP of the materials and sub-stages of the life cycles of the sidewalks (no M&R requirements are considered).

Table 3
Contributions to PED and GWP of the sidewalks' top layers and elements that contribute the most to their environmental burden.

Top layer	Impact contribution	Key element
Concrete slabs	Total	Portland cement (%)
PED (MJ-eq./m^2)	73.8	54
GWP (kg CO_2-eq./m^2)	10.0	79
Asphalt	Total	Bitumen (%)
PED (MJ-eq./m^2)	249.7	86
GWP (kg CO_2-eq./m^2)	4.4	44
Granite slabs	Total	Diesel and electricity (%)
PED (MJ-eq./m^2)	480.5	80
GWP (kg CO_2-eq./m^2)	28.3	78

considered in the environmental assessment. Impacts of electricity consumption are based on the Spanish power mix, where fossil fuels account for 57.8% of the primary energy sources used for producing electricity (Swiss Centre for Life Cycle Inventories, 2009). The rest of the electricity is produced by using nuclear power (22.2%), hydropower, wind and photovoltaic (18%) and cogeneration (2%) inputs that contribute to the PED of electricity but have a very low GWP.

As the concrete base is assumed to be the same in all sidewalk types, the environmental burdens of the sidewalk types are determined directly by the type of material applied as the top layer. Once the causes of the environmental impact contribution from the top layers are identified, the effect that the M&R schedule associated with their expected service lives may yield in the overall life-cycle PED and GWP of sidewalks can be better interpreted. To analyze this effect, we initially assume that the service life of a properly designed and constructed concrete or granite sidewalk could reach 45 years, being whereas an asphalt sidewalk could have a service life of 15 years on average. In the first case, no maintenance operations are required during the analysis period, whereas two M&R operations are required to restore the serviceability of the asphalt solution. Fig. 4 shows the evolution of the life cycle PED and GWP of the three types of sidewalks.

Once a sidewalk is constructed, the PED and GWP are determined by the relative inputs associated with the stages of materials production, materials transportation (T1 + T2) and sidewalk construction. The PED and GWP of sidewalks are considered to be constant over time until their top layer has to be replaced or the sidewalk is deconstructed. At these points, PED and GWP increase because of the inputs associated with maintenance operations (new top-layer production, transportation to site, replacement of the old layer, and transportation of related demolition wastes) or sidewalk deconstruction (removal and transportation of demolition wastes).

Under this scenario, the concrete sidewalk demonstrates an 8% and 28% lower GWP and a 46–56% lower PED than the asphalt and granite solutions. A concrete sidewalk is therefore the most environmentally friendly solution to reduce long-term impacts. However it is remarkable that the asphalt solution is the most environmentally sound option in terms of GWP until year 30, in spite of having been replaced once. In addition, the cumulative PED of an asphalt sidewalk is 5% lower than a granite conterpart at this point. If the serviceability of the sidewalks is shortened or extended from the expected duration, the relative M&R schedule would change, which would most likely affect the identification of the most environmentally friendly alternative. Environmental impacts are therefore significantly dependent on scenarios and assumptions concerning the service life and M&R schedule for pavements (Santero et al., 2011b); thus, the possible effect of the variability of their service lives on their life cycles and environmental burden should be carefully analyzed to create a more accurate picture of the difference in the PED and GWP footprints between sidewalk types.

Fig. 5 shows how the life-cycle PED and GWP of sidewalks accumulate over a period of 45 years, depending on their potential service lives and thereby on their M&R schedules.

The dotted lines indicate the PED and GWP values related to the case scenarios where the serviceability expectation for the sidewalks is shorter or longer than the assumed average functional lifetime of 20–45 years for concrete and granite sidewalks and 5–15 years for the asphalt sidewalk (indicated in solid lines). The continuous horizontal line and the data in the internal boxes are used as examples for the interpretation of the results. Three main conclusions can be drawn from the results:

- A sidewalk design with a long service life reduces the PED and GWP because of lower M&R requirements. A concrete sidewalk with a service life can have PED and GWP values that are reduced by 72% and 73% less than the same design with a shorter life. Long-life asphalt and granite sidewalks would see their PED and GWP reduced by 59% and 79% and by 80% and 84%. This result fits with the common assumption that longer service lives of pavements are always better for reducing long-term environmental impacts related to a reduction of M&R operations.
- When the service lives of sidewalks are assumed to be equivalent under certain exposure conditions, a concrete sidewalk becomes the environmentally preferable option for reducing long-term PED, but an asphalt sidewalk is the suitable choice for minimizing GWP. Concrete sidewalks account for 15–34% lower PED than asphalt sidewalks and 46–68% lower PED than granite designs when the shortest and longest potential service lives of the pavements are compared. However, concrete sidewalks account for GHG emissions that are 25–85% higher than those of asphalt sidewalks. As the type and amount of construction materials used constitute the largest input to life-cycle PED and GWP, they determine the

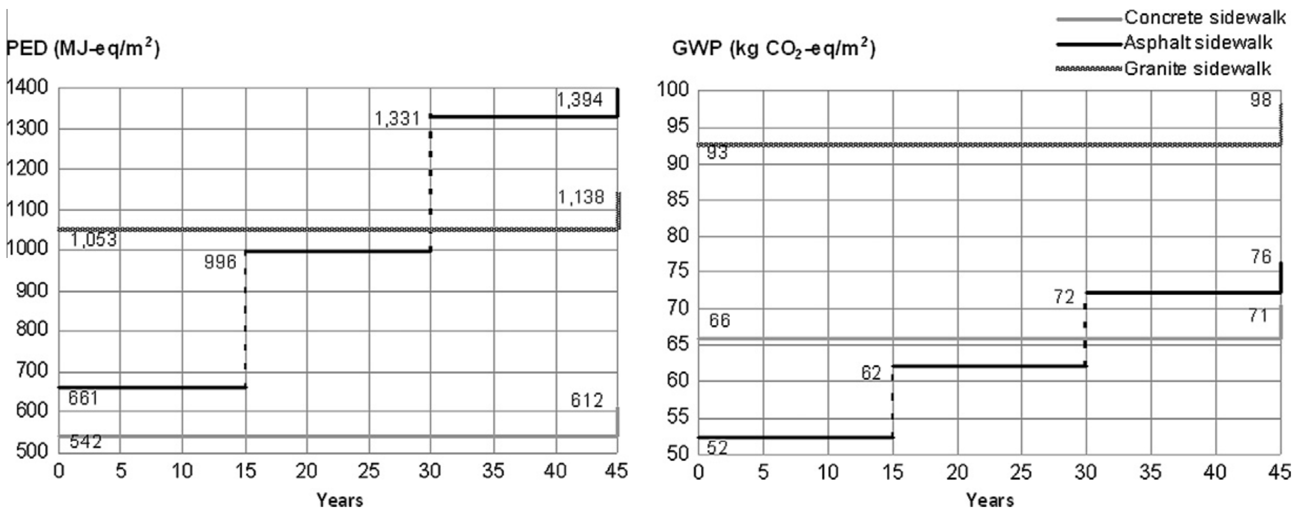


Fig. 4. Life-cycle PED and GWP of sidewalks based on an average service life of 45 years for concrete and granite sidewalks and 15 years for asphalt sidewalks.

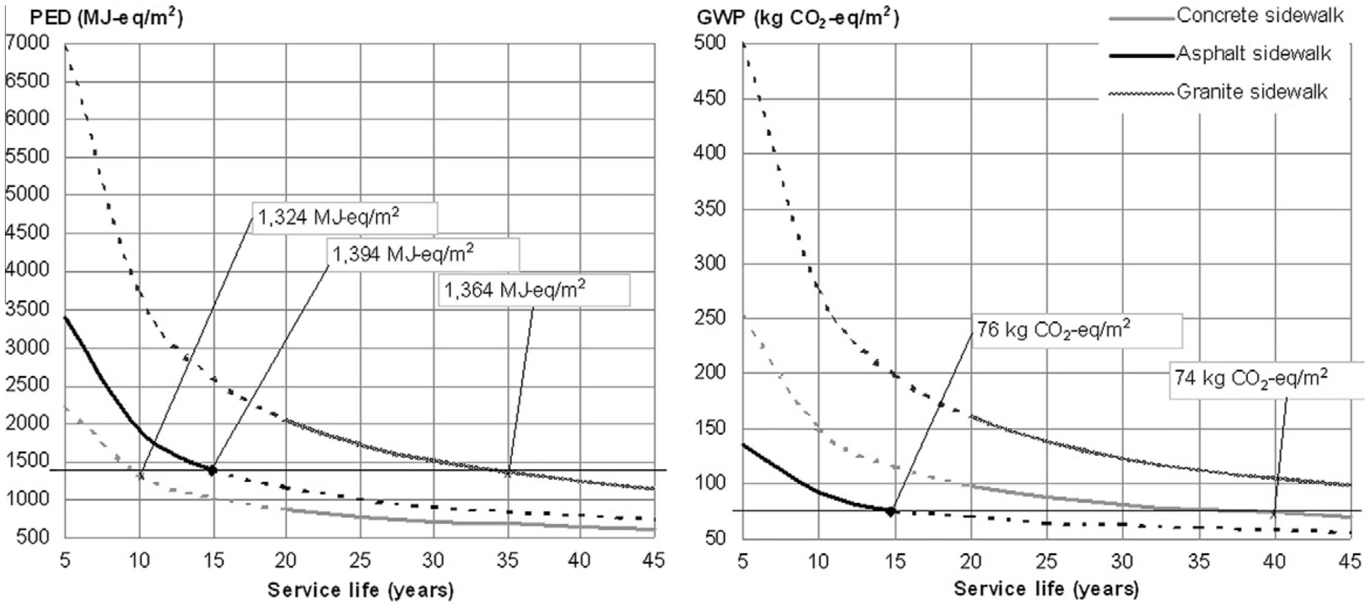


Fig. 5. Variation of the life-cycle PED and GWP of sidewalks versus potential service lives.

differences in the overall environmental burdens between sidewalks. Environmental gaps are narrower when sidewalks' service lives are longer because the amount of materials required to restore the serviceability of the sidewalks over time is lower.

- A long-life construction solution does not ensure that the life-cycle PED and GWP will be lower than those of another, shorter-lived design; these values depend on the environmental performance of the materials chosen for paving. When determining the environmental consequences of sidewalk designs, it is not appropriate to use the rule that a longer-life solution is better than a shorter-life design because M&R requirements are lower over time. For example, consider the life-cycle impact of an asphalt sidewalk that is assumed to have a service life of 15 years, as shown in Fig. 5. A granite sidewalk with a top layer that has a service life of 35 years has a PED only 2% less than that of the asphalt sidewalk. However, a concrete sidewalk with only 10 years of service life, which requires more M&R operations to restore its serviceability over the period of 45 years, would reduce the PED by 5%. The results for GWP are clearer. The GHG emissions of the asphalt sidewalk are 2.2% lower than those from a concrete sidewalk with 35 years of service life and 22% lower than those of a granite sidewalk with 45 years of service life. The service life of the concrete sidewalk has to be almost 40 years to reduce GWP by 2.6% relative to the GWP of the asphalt sidewalk. A service lifetime much longer than 45 years would be required for the granite sidewalk to become the best solution.

The results demonstrate that life-cycle environmental data and careful service-life planning should be integrated into decision-making to identify the long-term most environmentally friendly solution and best-practice environmental strategies. Decisions should not be based only on the environmental outcomes from one specific case scenario, as indicated in Fig. 4.

In the case studies, concrete or asphalt sidewalks are the environmentally optimal solution depending on the indicator that is used. PED is an indicator of energy efficiency where usually, a low PED means that the related fossil fuel consumption of the system is also low. PED can therefore be used to analyze the life-cycle energy efficiency of the systems and the share of energy coming from fossil or renewable resources that is embodied in them. GWP expresses however a potential to produce damage. GWP is a midpoint of a cause-effect chain. It can be understood as an intermediate position on the pathway to environmental damage (i.e., damage to the natural environment). When it is not possible to minimize both PED and GWP by promoting one specific design, we propose to focus attention on the GWP indicator because the objective of the analysis is to propose designs that avoid a cumulative contribution to environmental damage. However, it should be carefully considered that overall GHG emissions depend strongly on the type and amount of energy consumed throughout the life-cycle stages of the sidewalk, mainly manufacturing of materials. When electricity is consumed, the power mix considered during the environmental assessment has a direct effect on the GWP indicator. GWP from electricity consumption will be higher in regions or countries where large amounts of fossil fuels are used to produce electricity and vice versa. PED is not affected by the type of energy consumed, but by the amount.

4. Conclusions

Developing and implementing clean and energy-efficient production techniques and technologies is one step to minimizing the environmental burden of the construction materials in sidewalks, but it is also possible to reduce the burden by promoting the use of suitable materials. We find for example, that a top layer of concrete slabs has a lower PED contribution than asphalt and granite top layers, whereas an asphalt top contributes the least to GWP. Further, in looking at several case scenarios, we find construction with a long service life does not necessarily have a lower overall PED and GWP than another design with a shorter service life; the respective values depend directly on the environmental performance associated with the materials used. Based on our findings, we consider asphalt sidewalks to be the most environmentally suitable option to reduce long-term GWP in places or under exposure conditions where it is well known (through statistical or historical data) that the functional lifetime of pavements is usually less than 15 years, or it is predicted that the service lives of the construction designs could be equivalent. The PED will be higher for asphalt sidewalks than for concrete or granite sidewalks, but the reason for choosing asphalt is to minimize the long-term cumulative GHG emissions that have the potential for environmental damage. However, in places or under conditions where it can be assumed that a concrete sidewalk can last at least 40 years, it is the best solution to minimize both long-term PED and GWP. This conclusion should only be drawn if the asphalt sidewalk is not predicted to last more than 15 years, assuming this lifespan as its average service life.

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