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Environmental optimization of concrete sidewalks in urban areas

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Abstract

Background, aim, and scope New neighborhoods and cities are built in both developing and developed countries worldwide. Given this urbanization context and current global environmental threats, the concept of sustainability will, in the long term, succeed or fail in cities. To succeed, we need to provide life-cycle-based data aimed at improving the environmental performance of new urban developments and redevelopments. This study discusses the installation criteria for three specific types of sidewalk; these criteria are currently based exclusively on economic and social factors, leading to design uniformity. This study also provides a comparative life cycle assessment (LCA) of these three types of concrete sidewalks and identifies potential redesign solutions. If sidewalk design were adapted to specific usability requirements, the environmental impact factors associated with sidewalks, and therefore cities, would be significantly optimized and reduced.

Materials and methods Although a wide range of materials and constructive solutions are available for sidewalk paving, this study focuses on three very common concrete-based systems with different functionalities in terms of traffic, surface characteristics, and maintenance (i.e., interlocking blocks, continuous concrete layer, and slabs set on a 10-, 12-, and 15-cm-thick concrete base). These systems are analyzed from a life cycle perspective. The impact assessment method used was CML 2 Baseline 2000; input data were provided by the City of Barcelona and other local municipal councils in Catalonia, Spain as well as by local producers.

Results In terms of main findings, this study provides a comprehensive description and inventory of the sidewalk systems under study. According to the LCA, the slab system has the highest environmental impacts; this happens to be the most widely used sidewalk type in the area studied, mainly due to aesthetic concerns and the imperatives of maintaining underground urban services. Regardless of the thickness of the concrete base, the slab system has the highest impact in all categories compared with the other two sidewalk types. However, when the slabs are set on 10 cm of concrete, performance approaches that of the continuous concrete system (with the difference ranging from 3.4% to 6.3%, depending on the impact category); this system is very convenient when maintenance work on underground urban services is required. The interlocking block system, which has the lowest structural capacity, reduces environmental impacts in all categories by 73.8% compared with the highest impact system (i.e., slabs plus a 15-cm concrete base). However, the interlocking block system is limited to areas in which vehicular traffic is prohibited. Nevertheless, there is a high potential for environmental impact reductions when this system is used in places where high structural capacity is not required.

The highest environmental impacts of the various sidewalk types are associated with the use of cement

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(accounting for approximately 24% to nearly 77% of the total impact, depending on the impact category and the sidewalk system used); other impacts have origin in site-to-site transportation of materials, installation, and removal of slabs and continuous concrete layers.

Aggregates, which are the materials used in larger quantities in concrete, have a negligible effect on the environmental impact (less than 10% in the categories where its effect is most pronounced). In contrast, the contribution of admixtures, which are used in much smaller quantities, exceeds 10% in the abiotic depletion category.

Discussion The redesign of sidewalks using environmental criteria and adjusting the sidewalk types to functions fulfilled can bring important benefits. Using a linear regression of the characterization results based on the weight of cement in each system, Pearson's coefficient of regression is greater than 0.99 for all impact categories. Therefore, the content of cement is a key factor in determining the environmental impacts of each sidewalk type.

Conclusions In certain high-traffic areas, e.g., when a sidewalk is located between a roadway and a parking garage entrance or when a sidewalk must to be dug up frequently to access underground service networks (in a process known as 'trenching"), the sidewalk must be reinforced and surface damage must be concealed. In such cases, the environmental impacts may be justified. However, sidewalks have multiple uses, and in many cases, their structural requirements are not excessively rigorous. Therefore, the systematic application of the slab system exacerbates urban environmental impacts. Restricting the use of concrete sidewalks with high structural capacity to street sections that actually require them could reduce environmental impacts by up to 73.8% in pedestrian-only areas.

Recommendations and perspectives In light of these findings, attention should be paid to the appropriate selection of sidewalks in urban developments and redevelopments based on street function. In addition, the use of materials containing cement should be optimized, local suppliers should be selected, and sidewalks should be designed to facilitate dismantling and reutilization of their components, especially when frequent access to underground networks is required.

Keywords Blocks · Cement · Cities · Civil engineering · Ecodesign · LCA · Pavement · Public space · Slabs

1 Background, aim, and scope

1.1 Towards sustainable urban settlements

Understanding the metabolism of urban settlements and the characteristics of their material and energy flows is essential to understanding the many subtle interrelated factors present in cities (Bettini 1996). Based on this knowledge, the most pressing urban environmental problems, which are related to increases in inputs and management of the residual outputs, can be identified and strategies to improve urban sustainability can be developed.

Following the United Nations Conference on Environment and Development in Rio de Janeiro in 1992, Local Agenda 21 (LA21), as a global framework, has been widely used to describe the necessity to ensure a sustainable urban development. The tools included in this municipal environmental planning process, such as environmental diagnoses and environmental indicators, are used to identify socio-environmental issues and propose improvements. Environmental indicators are used to monitor socio-environmental trends and to evaluate the efficiency of proposed initiatives, as well as to set goals and to guide the decision-making process.

Using the LA21 content, environmental data are used to optimize the process of urban planning. However, life-cycle-related urban environmental data (including sidewalk data) are still in short supply (relevant examples are provided in Intron 1995). To manage global environmental threats, "life cycle thinking" is needed to improve the urban design process. Therefore, access to information is crucial to the decision-making process.

Research in the area of sustainable urban infrastructure reflects the need to design and manage engineering systems in light of both environmental and socioeconomic considerations (Sahely et al. 2005). Concerning the environmental analysis, in the 1990s, several studies used life cycle assessment (LCA) to compare among infrastructures made of different materials. A case study from that period was the Zaltbommel road bridge (Kortman and Lim 1992). This case used LCA to compare the environmental impact of two alternative bridges, made of concrete and steel, respectively. The goals of the study were to help develop a meaningful LCA system and to improve the awareness of the Public Works Department in The Netherlands. Another study from that period was conducted by the Technical Research Centre of Finland (VTT) (Häkkinen and Mäkelä 1996) and compared the environmental impact of concrete and asphalt pavements for a specific application in Nordic motorways.

1.2 Concrete sidewalks

Although much attention on mitigating climate change has focused on alternative fuels, vehicles, and electricity generation, better urban design represents an important yet undervalued opportunity. Fortunately, such decisions are well within the reach of local governments and leaders and can reduce long-term carbon emissions (Marshall 2008).

Within the framework of Kyoto Protocol and other global initiatives to reduce human impact on the environment, cities are a cornerstone in the implementation of strategies for resource conservation and efficiency on its use, establishing an intrinsic union between the concepts "city" and "sustainability" (Harper and Graedel 2004). It is in this context that the study of sidewalks is especially interesting, particularly because they represent a significant share of the urban landscape. For instance, in Barcelona (Spain), they account for 6 km^2 (2006), or 7.2% of the total developed area. Similar values are also found in Sacramento (USA) where 5% of the developed areas are covered by sidewalks (Akbari et al. 2003.). By sidewalk, we understand a pedestrian path, usually paved, running along the side of a street.

All the sidewalk systems analyzed in this study are commonly used worldwide. Data for the study were obtained from public officials and developers that operate in Barcelona (Catalonia/Spain) and other nearby towns. However, the selected sites are comparable to locations in other European cities and regions.

The administrative criteria for installing specific types of sidewalk are usually determined by economic and social factors such as price, aesthetics, and ergonomics; environmental factors are not usually taken into account. A wide range of sidewalk materials and systems are used, e.g., asphalt, stone slabs, wooden bricks (in flat and dry areas, compacted earth may be used, with no other materials than top layer). However, this study focuses on concrete sidewalks, which are very common in many urban areas. In the case of Barcelona, a compact and densely populated city, concrete sidewalks account for 97% of the total sidewalk area, which in turn accounts for more than 45% of the total paved public area. In all likelihood, these statistics could be similar in other cities.

Paving with concrete is usually viewed as an environmentally and economically sustainable choice, primarily due to concrete's durability and low maintenance requirements (ACPA 2007). High durability ensures that the desirable performance characteristics and environmental advantages of concrete paving remain essentially intact for several decades. In the case of sidewalks, however, durability may be reduced due to the need to access underground distribution networks by trenching, which entails demolishing (and then reconstructing) the paved area.

Literature on paving has focused primarily on road paving. During and after the first oil crisis in the 1970s, many comparative studies were carried out on paving alternatives that consumed less energy or oil (for related discussion, see Asphalt Institute 1975; Wester 1980; Cembureau 1980; RGRA 1981; Fernández 1981). Other authors have analyzed design alternatives and issues relating to road paving maintenance and repairs (see Thenoux et al. 2007; Chiu et al. 2008 for recent papers on energy consumption and LCAs of pavement rehabilitation).

However, scientific literature on sidewalks has focused exclusively on economic issues (e.g., price), social issues (e.g., usability, ergonomics, wheelchair users' vibration exposure), and local environmental issues (e.g., soil sealing and the heat island effect; Asaeda and Ca 2000; Tan and Fwa 1992). Few studies have been conducted covering a wide range of global and regional environmental impacts from a life cycle perspective.

It should be assumed that all of the sidewalks analyzed in this study are located next to roadways and are suitable for pedestrian use. However, many urban sidewalks also have non-pedestrian uses, which may include accommodating street cleaning equipment or vehicles entering parking garages. Therefore, different sidewalk sections have different functions and, thus, different structural requirements.

In addition, certain aesthetic requirements may affect sidewalk installation, e.g., if urban services (water, energy, and telecommunications networks) are underground. When these networks are repaired or replaced by trenching, the pavement must be reconstructed; this process leaves "scars" that are often concealed with slabs. However, installing these networks beneath sidewalks is more convenient than installing them beneath the roadway where trenching would disrupt traffic flows and repaving would be more costly. In other words, the sidewalk life cycle is affected by the frequency of trenching operations, in addition to the durability of various component materials and structural sections.

In the case of Barcelona, approximately 13 ha of sidewalk is dug up every year to install or repair underground networks (Torrero JM, ACEFAT, Barcelona City Council, Director of the Department of Civil Works Management and Coordination, June 2008, personal communication). This surface is equivalent to 2.2% of the total sidewalk area containing concrete-based materials (approximately 5,850,000 m^2), distributed as follows: 91.6% concrete slabs and 8.4% continuous concrete layer (Llauradó JM, Barcelona City Council, Department of urban planning, May 2008, personal communication).

2 Goal and scope

2.1 Objectives

All of the sidewalk systems analyzed in this study are suitable for pedestrian use, in addition to non-motorized traffic such as bicycles and wheelchairs. However, different sidewalk systems have different functionalities and are not structurally equivalent, as shown in Fig. 1. This study therefore does not aim to compare these systems directly but rather attempts to quantify the potential environmental

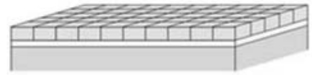
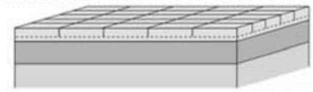
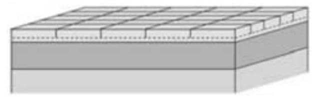
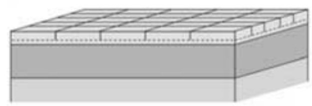
Systems		Layers	Layout for 1m² of sidewalk	FU_1	FU_2	FU_3	FU_4
B		Blocks, 6cm; Sand bed, 3cm; Subgrade		x	x		
C		Concrete, 15cm; Subgrade		x		x	
	1	Slabs, 4cm; Mortar, 2cm; Concrete, 10cm; Subgrade		x	x		
S	2	Slabs, 4cm; Mortar, 2cm; Concrete, 12cm; Subgrade		x	x		
	3	Slabs, 4cm; Mortar, 2cm; Concrete, 15cm; Subgrade		x	x	x	x

Fig. 1 Structural section of systems B, C, and S1-3 and technically suitable sidewalks according to its function

impacts of three most usually installed types of concrete-based sidewalks in the case of Barcelona and nearby cities and that are also commonly used in many countries with subsequent variations and adaptations; to identify which type is environmentally preferable based on certain functionality; to compile an inventory of materials and processes; and to assess the potential environmental savings to be gained in matching each type of sidewalk use to the specific functionality that it fulfills. Additionally, the results obtained should provide guidelines for the redesign of these sidewalks integrating environmental criteria.

2.2 Functional unit

The functional unit provides a benchmark for inputs and outputs (ISO 2006). The functional unit is 1 m^2 of sidewalk, including all pavement layers extending from the compacted soil (subgrade) to the surface (top layer), over a timeframe of 45 years. Given that sidewalks in urban contexts may have one or more of three different functions (including all three at the same time), four combinations of functions have been defined to determine which sidewalk type is environmentally optimal for each situation. The four combinations of sidewalk functions are as follows:

- FU_1: Pedestrian traffic only;
- FU_2: Underground services+pedestrian traffic;
- FU_3: Motorized traffic+pedestrian traffic;
- FU_4: Motorized traffic+underground services+pedestrian traffic.

Curbs are not included in the analysis because they are assumed to be the same for all four combinations of sidewalk functions and are frequently outside the maintenance area, i.e., they are not affected by trenching.

According to developer-supplied data, a properly designed and constructed sidewalk consisting of a continuous layer of concrete or concrete slabs has a lifespan of 25–50 years; it may be less than 20 years if, for instance, low-strength concrete is used. Due to the high degree of uncertainty associated with the average lifespan, another benchmark must be used to define the timeframe for the functional unit. According to data provided by the City of Barcelona, an area equivalent to the entire sidewalk surface (including inner and outer, residential and non-residential urban areas) is reconstructed every 45 years due to trenching or maintenance. Since 45 years falls within the component materials' potential lifespan, we will use it to represent the average lifespan of a sidewalk. At the same time, by using this 45-year average, the effect of trenching during the time of use can be disregarded.

2.3 Description of the sidewalk systems under study

This section describes in detail the structural features of the various sidewalk systems (Fig. 1), which are named after their top layer. We also discuss optimal functionality-based solutions and describe the system boundaries and process chain under study.

Interlocking blocks In the case of small surface areas, the subgrade is compacted using machinery such as tampers operated by a single worker. However, in exceptional circumstances when large areas must be paved, heavy equipment, such as vibrating rollers, is used. On top of the subgrade, a 3-cm layer of sand is used as a base for the concrete blocks, which typically have a compressive strength of 30 MPa. Fine aggregates (maximum size <1 mm) are poured into the joints and the blocks are compacted with a plate compactor to fit them together; this system provides for a measure of flexibility. The interlocking concrete blocks analyzed in this study measure 20× 10× 6 cm, and their composition is completely homogeneous. This paving system is occasionally used for plazas or pedestrian areas, but rarely for sidewalks.

Continuous concrete layer As with the block system, in small surface areas (such as sidewalks), the subgrade is compacted using tampers. Concrete with a typical compressive strength of 20–25 MPa is poured from the mixer truck and spread, compacted, and finished manually. Since the top layer of the sidewalk is made of concrete, finishing (e.g., texture, evenness) is particularly important. In this study, the top layer is 15 cm thick and highly durable (concrete producers guarantee a service life of more than 30 years).

Slabs As with the two previous systems, the subgrade must be compacted. A concrete layer with a thickness of 10, 12, or 15 cm with a typical compressive strength of 20–25 MPa is cast on top of the compacted soil (subgrade). The concrete is poured from the mixer truck and spread manually. The standard thickness of the concrete layer increased from 10 cm in the 1980s to 12 cm in the 1990s; a 15-cm layer is used in parking garage entrances to ensure appropriate structural performance. In keeping with this process of progressive structural reinforcement, the new trend is the standard use of a 15-cm layer.

On top of the concrete, there is a 2-cm layer of dry mortar on which the concrete slabs are laid, tapped down with a mallet, and finished with a grout that seeps through the slab joints into the mortar. The slabs typically measure 20× 20× 4 cm. They have a double-layer structure; the upper layer has a higher compressive strength (approximately 30 MPa) and better finishing, with a combination of cement and fine and coarse aggregates.

The slab system is the most commonly used in Barcelona (and in some other nearby cities); under municipal regulations, it must be used in any new development or redevelopment for maintenance and aesthetic reasons.

Slab and continuous concrete sidewalks are deconstructed with pneumatic hammers installed on backhoe loaders; block sidewalks can be deconstructed manually, since the blocks are not permanently attached to each other.

Various factors are used to determine which of the sidewalk systems described in Fig. 1 will be chosen. All of the systems analyzed are suitable for the FU_1 pedestrian-only function; however, when underground services are installed (FU_2), continuous concrete sidewalk is no longer suitable (this is an aesthetic concern since there are no technical problems associated with trenching). Accommodating vehicle traffic on sidewalks (FU_3) reduces the number of suitable systems to two (C and S3), while S3 is the only system that can accommodate a combination of vehicles and underground networks (FU_4).

Taking into account the criteria described in Fig. 1, municipalities often prefer to standardize their sidewalks (also for aesthetic reasons); in so doing, they ensure that all sidewalks are prepared for the multifunction scenario (S3).

The hypothesis of this study is that when design is tailored to usability requirements, the environmental impacts associated with pedestrian comfort/convenience and other related sidewalk functions (e.g., accessing underground networks or parking garages) can be significantly reduced in some cases. In other words, “one-size-fits-all” solutions are unsuitable in many cases and carry a higher environmental cost than “tailor-made” solutions do.

The main sidewalk construction/deconstruction stages are as follows: raw material extraction, material production/processing, soil compaction, sidewalk installation, sidewalk maintenance/removal, and materials transportation (raw materials, other components, and final disposal; Fig. 2). Due to the durability of sidewalk materials and uncertainties concerning disposal at the end of their life cycle, only transportation is considered in the final stage; waste treatment processes are not considered.

2.4 Data quality

The foreground system is composed of the materials (type and weight), processes, and transportation distances of the various infrastructural elements that compose the sidewalk systems under study based on the technical standards prescribed by municipalities in 2008 and the material composition data provided by local producers.

Input/output data for the concrete were compiled using the EcoConcrete LCA tool (CEMBUREAU, BIBM, EFCA, ERMCO, EUROFER, UEPG 2003), a customized peer-reviewed MS Excel-based software program promoted by the EU Joint Project Group on the LCA of concrete, which has access to detailed inventory data provided by European concrete producers. In addition, the Ecoinvent 1.2 database (Ecoinvent 2006) was used for the sand-related processes (DE: silica sand, at plant; Kellenberger et al. 2004), emissions from transporting materials to the site (RER: transport, lorry 16t), transportation of concrete constituents and disposal (CH: transportation, lorry 28t; Spielmann et al. 2004), and diesel combustion in a diesel–electric generating set (GLO: diesel, burned in diesel–electric generating set; Dones 2003).

The cement type used in the analysis was CEM II/A-L 32.5R Europe, which is the most appropriate for sidewalk applications in the EcoConcrete inventory. However, we are well aware that if CEM I or CEM III cement were used, the results would vary significantly, not only in terms of environmental impacts but also in terms of performance.

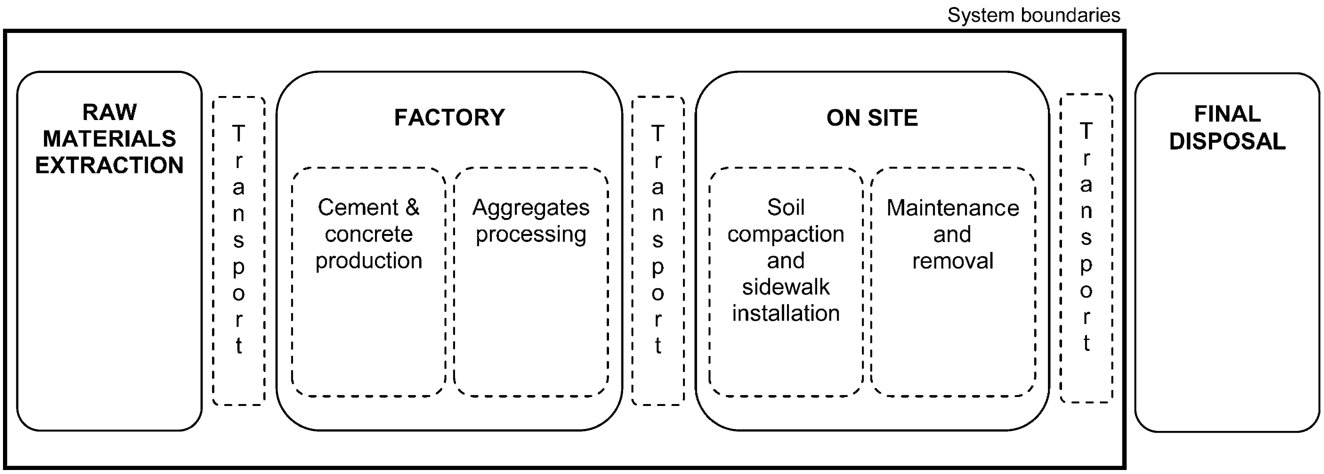


Fig. 2 System boundaries and process chain under study

The results would be significantly affected by inventory uncertainties and differences between technologies if different types of materials were compared (e.g., asphalt, natural stone). But the fact that all of the sidewalk systems studied use Portland-based cement materials increases the reliability of the comparison. In addition, the durability of materials and the safety criteria in civil engineering works makes of it a conservative sector where technological changes take place slowly. As a result, inventories are considered valid for longer periods compared with other sectors.

2.5 Methodology

The LCA methodology is used to assess all environmental impacts associated with a product, process or activity by calculating and evaluating resource consumption and emissions (ISO 2006). Civil engineering and the built environment are high-potential fields for LCA, and research in these areas may provide useful information for the ecodesign of cities in the future.

Of the various steps in the life cycle impact assessment (LCIA) methodology (ISO 2000), only classification and characterization have been used in this study. In the classification step, each environmental burden is linked to one or more impact categories; in the characterization step, the contribution of each burden to each impact category is calculated by multiplying each burden by a characterization factor. The classification and characterization method used was CML 2 Baseline 2000 (Guinée et al. 2001). The selected midpoint impact categories and their units are as follows: abiotic depletion potential (ADP, kg Sb eq.), acidification potential (AP, kg SO_2 eq.), eutrophication potential (EP, kg PO_4^{3-} eq.), global warming potential (GWP, kg CO_2 eq.), human toxicity potential (HTP, kg 1.4-DB eq.), ozone layer depletion potential (ODP, kg CFC-11 eq.), and photochemical ozone creation potential (POCP, kg C_2H_4 eq.).

Other local impacts such as contribution to urban heat island, negative impact to soil by sealing or leaching, potential loss of biodiversity living in cities, and others are neither considered by CML 2 Baseline 2000 nor properly agreed and have not been included in the analysis.

3 Results

3.1 Inventory data

The transportation distances for goods and waste materials are estimates for a standard location in central Barcelona. Since most producers and waste treatment facilities are located on the outskirts of the city, the estimated travel distance is 30 km. Concrete components are transported by truck to the production plants; according to the production companies, the average distances are 75 km for cement, 40 km for aggregates, and 100 km for admixtures. Table 1 indicates the materials and energy content for 1 m^2 of the various systems.

3.2 Impact assessment of systems

The life cycle impacts for 1 m^2 of the various systems are presented in absolute values in Table 2 and are disaggregated in the following section (Fig. 3).

The highest impact sidewalk system, slabs, is the most widely used in the area of study mainly due to aesthetic and maintenance concerns.

Independent of the thickness of the concrete base, the slab system has the highest impacts in all categories. However, the slab system plus 10 cm of concrete performs similarly to the continuous concrete system, with differences between them being less than 6.5% in all impact categories.

Table 1 Materials contained in 1 m^2 of the various systems

	Layer	LC phase	Data per functional unit			
System B	Subgrade	Compaction	12.17 MJ (gasoil)			
	Sand	Material	30 kg sand			
		Transport	To site (16-tonne truck): 30 km sand			
	Block	Material	15 kg cement			
			129 kg aggregate			
			8.21 kg tap water			
			0.225 kg admixture			
		Transport	Concrete components (lorry 28t): 75 km cement, 40 km aggregates, 100 km admixture			
			To site (lorry 16t): 30 km blocks			
			To disposal (lorry 28t): 30 km blocks			
		Installation	2.43 MJ (gasoil) (plate compactor)			
		Removal	0 MJ (manual)			
System C	Subgrade	Compaction	12.17 MJ (gasoil)			
	Concrete	Material	45 kg cement			
			150 kg fine aggregate			
			150 kg coarse aggregate			
			19.66 kg tap water			
			0.675 kg admixture			
			Components (lorry 28t): 75 km cement, 40 km aggregates, 100 km admixture			
		Transport	To site (lorry 16t): 30 km concrete			
			To disposal (lorry 28t): 30 km concrete			
		Installation	0 MJ (concrete mixer is included in transport)			
		Removal	34.43 MJ (gasoil)			
System S	Subgrade	Compaction	12.17 MJ (gasoil)			
	Concrete	Material		S1	S2	S3
			Cement	30 kg	36 kg	45 kg
			Fine aggregate	100 kg	120 kg	150 kg
			Coarse aggregate	100 kg	120 kg	150 kg
			Tap water	13.11 kg	15.73 kg	19.66 kg
			Admixture	0.45 kg	0.54 kg	0.67 kg
	Mortar	Material	6.6 kg cement			
			40 kg fine aggregate			
	Slab	Material	11 kg cement			
			85 kg aggregate			
			5.47 kg tap water			
			0.165 kg admixture			
	Common Processes	Transport	Concrete components (lorry 28t): 75 km cement, 40 km aggregates, 100 km admixture			
			To site (lorry 16t): 30 km concrete, mortar and slabs			
			To disposal (lorry 28t): 30 km concrete, mortar and slabs			
		Installation	0.34 MJ (electricity) (mixer for grout)			
		Removal	34.43 MJ (gasoil)			

The interlocking block system has the lowest environmental impacts by far, with impacts reduced by approximately 70% in all impact categories compared to the highest impact type (S3). In light of this finding, block sidewalks may be the best choice in urban environments. However, they are not suitable for occasional vehicle circulation (as shown in Fig. 1) and may have functional and maintenance problems, depending on the use conditions.

Table 2 Characterization results for each sidewalk

	Blocks	Concrete	Slabs 1	Slabs 2	Slabs 3
ADP (kg Sb eq.)	2.65E−01	7.39E−01	7.74E−01	8.69E−01	1.01E+00
AP (kg SO_2 eq.)	8.62E−02	2.28E−01	2.43E−01	2.66E−01	3.00E−01
EP (kg PO_4^{3-} eq.)	1.60E−02	4.16E−02	4.43E−02	4.85E−02	5.47E−02
GWP (kg CO_2 eq.)	1.97E+01	5.33E+01	5.79E+01	6.45E+01	7.43E+01
HTP (kg 1.4-DB eq.)	1.32E+00	3.33E+00	3.63E+00	4.04E+00	4.65E+00
ODP (kg CFC-11 eq.)	1.40E−06	3.32E−06	3.55E−06	3.93E−06	4.49E−06
POCP (kg C_2H_4 eq.)	8.78E-03	2.14E−02	2.27E−02	2.49E−02	2.81E−02

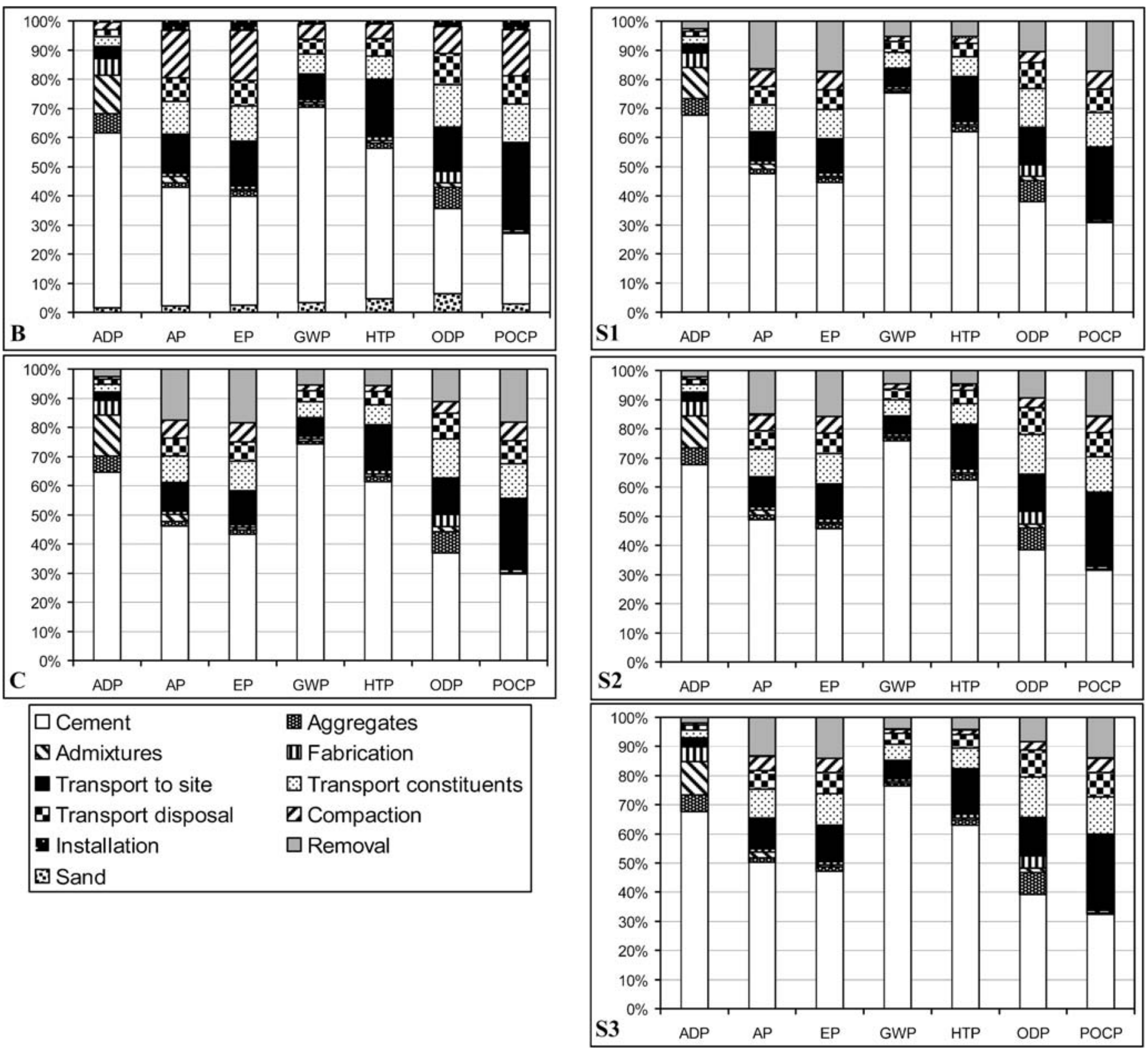


Fig. 3 Contribution to each impact category of the various materials and processes involved in each system (water is not included due to its low contribution). *From top to bottom in the left column* B and C and in the *right column* S1, S2 and S3

Table 3 shows that based on characterization results and functional limitations, the best environmental choice in areas without vehicular traffic (FU_1 and FU_2) would be blocks; in areas with vehicular traffic but without underground networks (FU_3), the best environmental choice would be a continuous concrete layer, and in areas with both requirements (FU_4), the best environmental choice would be slabs plus 15 cm of concrete base. Although the latter is the highest impact system, it is the only suitable choice in technical and aesthetic terms.

3.3 Impact assessment of materials and processes

When the results are disaggregated by material type (see Fig. 3), it becomes clear that the highest impact material is cement (contributing from approximately 24% to nearly 77% of the total impact, depending on the impact category and system). Cement has the highest and the lowest contribution in the GWP and POCP categories, respectively.

The slab and continuous concrete layer systems perform similarly in relative terms. In these systems, cement content and transportation are the highest impact processes, followed by materials removal. In the block system, the most relevant processes are also cement content and transportation, although the relative distribution varies slightly as the relative contribution of transportation increases with respect to that of cement; compaction also appears to be environmentally relevant.

Machinery use is less extensive in the block system than in the other systems, primarily because materials can be removed manually. However, this is not reflected in Fig. 3 because the relative contribution of compaction in the block system is high.

Aggregate is used in larger quantities but contributes little to the impact (less than 10% in ADP and ODP where it contributes the most). This means that efforts to use recycled aggregates would have a negligible effect on reducing the environmental impact of sidewalks. On the other hand, admixtures which are used in very low quantities contribute more than 10% in ADP, probably due to the raw materials used to produce the chemicals in the admixtures.

Table 3 Environmentally optimal sidewalk and impact reduction with respect to S3

	Environmentally optimal sidewalk	Impact reduction with respect to Slabs 3 (%)
FU_1: Pedestrian traffic only	Blocks	68.7–73.8
FU_2: Underground services+ pedestrian traffic	Blocks	68.7–73.8
FU_3: Motorized traffic+ pedestrian traffic	Concrete	26.0–26.9
FU_4: Motorized traffic+ underground services+ pedestrian traffic	Slabs 3	0

The impact of transportation is also relatively high, especially in the POCP impact category for all sidewalk types and in ODP for interlocking block sidewalks where the impact is higher for transportation than for cement. The transportation factor with the largest contribution is the transportation of elements and materials from factory to site.

Finally, the removal or demolition stage is relevant in the case of the slab and continuous concrete layer systems (especially in the AP, EP, and POCP impact categories) since the machinery used (pneumatic hammers installed on backhoe loaders) consumes large amounts of energy. In slab systems, the environmental cost of demolishing paved sidewalks ranges from a minimum of 1.9% in subsystem S3 to a maximum of 17.3% in subsystem S1, depending on the impact category. In the continuous concrete layer system, demolition's contribution to emissions ranges from 2.6% to 18.4% in ADP and EP, respectively.

4 Discussion

Apart from the global and regional environmental impacts, other local impact categories, such as urban heat island contribution or soil sealing and leaching, could have also been suitable for analyzing environmental impacts of sidewalks. However, given that all the studied systems use the same type (but different quantities) of materials, local impacts are expected to be similar among them.

As previously described, the environmental impact associated to each sidewalk can be reduced up to 68.7–73.8% in the block system with respect to the slabs with a 15-cm concrete base. So, the redesign of sidewalks using environmental criteria and adjusting the sidewalk types to functions fulfilled can bring important benefits. Regarding the sidewalk functions, this means that when different functions are combined in the same street section (e.g., FU_2 and FU_4), different sidewalk systems should be combined depending on the functions of each individual section. Moreover, combining various sidewalk alternatives with different surface appearances in the same urban area may present difficulties.

Esthetic requirements for sidewalks may also entail relevant differences on environmental impact. For instance, use slab sidewalk with 15-cm concrete base rather than a continuous concrete layer in order to obtain a better finishing and concealment of trench marks increases the environmental impact by 26.0–26.9% with no gain in technical functionality.

Concerning the values for the GWP category obtained for the concrete sidewalks in this study, similar values were presented by Flower and Sanjayan (2007) who found that

Portland cement accounted for 74–81% of total CO_2 emissions in commercially produced concrete mixes. Cement is used in many different system components (e.g., slabs, concrete bricks, mortar, and concrete; see Table 1), while clinker is the cement component that contributes the most to the total final impact (as a result of the chemical reactions in the clinker kiln, the fuel combustion during clinker production and the energy consumed throughout the whole production process; Josa et al. 2004); clinker is also one of the main sources of distortion in the LCIA of the cement inventories (Josa et al. 2007).

Based on a linear regression of the characterization results in Table 2 with the weight of cement in each system, Pearson's coefficient of regression is greater than 0.99 in all impact categories. Therefore, cement content is a key factor in determining the environmental impact of each sidewalk.

The results obtained concerning the processes with a higher contribution to the final impact associated with the slabs and continuous concrete systems (cement content and transportation) are supported by Schuurmans et al. (2005) who defend that cement content and truck transportation are the main contributing factors as regards concrete's environmental impacts.

In connection with cement content, data were obtained from real doses in each sidewalk system. However, for transport from factory to site, average distances had to be estimated. Moreover, if the distances were increased or decreased, it would affect all the analyzed systems in a similar way. This draws the conclusion that although the absolute impact values could be influenced by different assumptions in the distances, the relative results obtained in this paper are accurate and can be generalized.

5 Conclusions

During the fieldwork, we observed a trend toward uniformity of sidewalk types aimed at facilitating installation and maintenance and ensuring the consistent appearance of all city sidewalks, with no consideration for environmental concerns. However, "one-size-fits-all" solutions entail a significant increase (68.7–73.8% for FU_1 and FU_2 and 26.0–26.9% for FU_3) in the environmental impacts associated with sidewalks. For this reason, the technical functionality criteria are especially important.

The use of block sidewalk should be prioritized in all sections that do not require structural reinforcement, i.e., because vehicles are not driven on the sidewalks. Efforts should be focused on prohibiting automobiles in pedestrian areas, or at least minimizing their use, since this factor is the main contributor to environmental impacts.

Based on our findings, the main contributor to environmental impacts for the various sidewalk types is cement use (GWP is the impact category in which cement contributes the most: B, 67.09%; C, 74.38%; S1, 75.25%; S2, 75.78%; S3, 76.40%; POCP is the category in which cement contributes the least: B, 24.08%; C, 29.71%; S1, 30.68%; S2, 31.44%; S3, 32.36%). Based on previous studies, we know that clinker is the main contributor to cement impact. In light of these results, techniques should be developed and implemented to reduce environmental impacts at the clinker manufacturing stage and, if possible, to use other types of cement with more additions and less clinker.

Other materials, such as aggregates, are used in large quantities but are low-impact. For this reason, strategies like using recycled aggregates would have a negligible effect on reducing the overall environmental impact. However, there is no reason not to recycle aggregates if rubble or materials from other construction sites are available.

6 Recommendations and perspectives

As regards ecodesign and green public procurement, it is essential that sidewalks are adapted to their required function(s), thereby avoiding the current oversizing of many sidewalk sections and reducing the environmental impacts within the public space. Secondly, the use of certain materials, especially those containing cement, should be optimized. Thirdly, local suppliers should be used wherever possible. Although the final users may have little knowledge of the background processes as regards materials and sources, transportation distance is easily determined. Since source-to-site transportation is the most environmentally relevant transportation factor, supplier proximity should also be taken into consideration. Finally, sidewalks should be designed to facilitate dismantling and reutilization, especially when access to underground networks is required.

As regards the latter point, future studies should consider the possibility of expanding sidewalk systems to include underground service galleries. This would facilitate underground network access and repairs and yield substantial social gains. However, the environmental gains would not be quite so apparent due to the large quantities of concrete that could be required to build the galleries; this topic warrants a deeper life cycle analysis.

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