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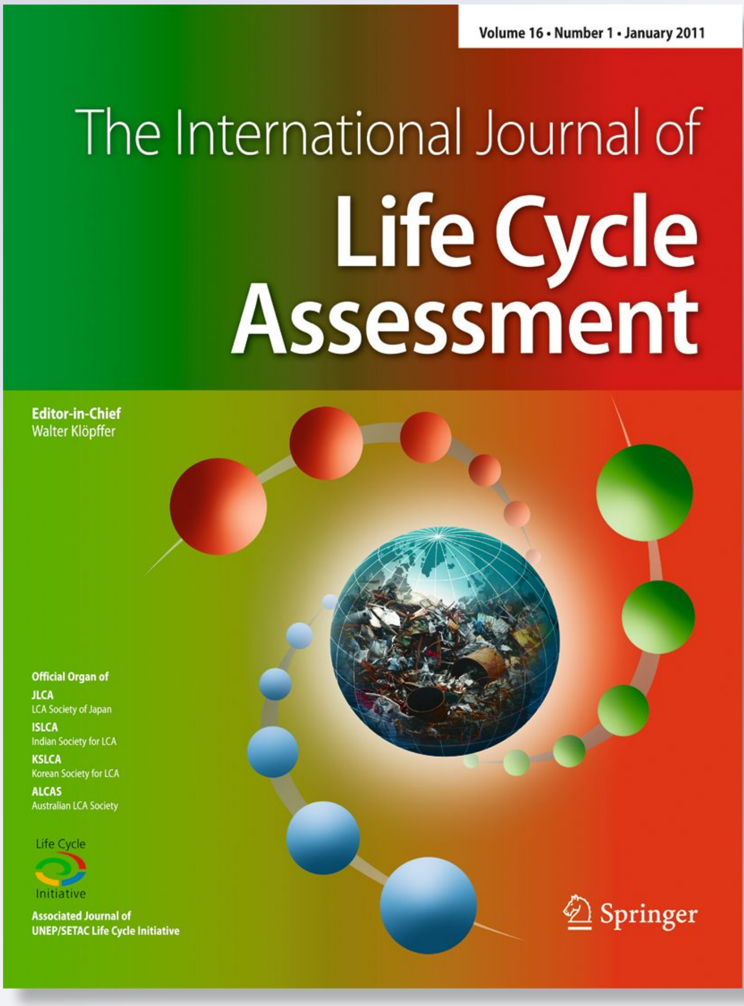

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BUILDINGS AND BUILDING MATERIALS

Life cycle assessment of granite application in sidewalks

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Abstract
Purpose Sidewalks are important built areas for promoting environmental sustainability in cities since they support walking as a zero emission form of transportation contributing to protect the environment and the health of individuals. However, sidewalk management is typically focused on assessing their suitability for users without applying any environmental criteria on the infrastructure design. The paper aims to quantify the environmental impact that sidewalks can contribute to the urban space if no environmental criteria are applied in sidewalk design.
Methods This study focuses on the environmental assessment of a very common sidewalk system found in cities to support pedestrian and light motorized traffic for over 45 years. The constructive solution consists of granite slabs (top layer) fixed on a mortar layer (3-cm thick) that is settled on a base of concrete (15-cm thick). The life cycle methodology was employed to conduct the environmental assessment of the system. The results are compared with the environmental outcomes of a sidewalk system that has the same function but is paved with concrete slabs to identify the environmentally optimal sidewalk design. The impact assessment method was CML Baseline 2001, and the inventory data were compiled from manufacturers associations, local authorities, and literature review.
Results and discussion Construction materials have the highest environmental impact (48–87%) in the sidewalk life cycle, where the granite top layer is the first contributor, although the amount of granite in the sidewalk system represents the 30% of the total weight of the construction materials used. A granite sidewalk has from 25% to 140% higher impact than a concrete one. The energy required to produce slabs is the key factor that characterizes the environmental impact of granite. Electricity and diesel consumption in stone cutting and moving represent over the 70% of the environmental burden of granite. The transportation of granite slabs is also relevant to the environmental impact. The use of imported granite could account for up to 76–177% of the total environmental impact of the sidewalk life cycle.
Conclusions Although granite is a natural material, using granite slabs as flooring material is not an environmentally suitable alternative over using concrete ones for paving sidewalks. The results have shown that if no environmental

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J.-M. F. Mendoza (✉) · J. Oliver-Solà · X. Gabarrell · J. Rieradevall
Sostenipra (ICTA-IRTA-Inèdit),
Institute of Environmental Science and Technology (ICTA),
School of Engineering (EE),
Universitat Autònoma de Barcelona (UAB),
Campus de la UAB, Bellaterra (Cerdanyola del Vallès),
08193 Barcelona, Catalonia, Spain
e-mail: joanmanuel.fernandez@uab.cat

J. Oliver-Solà · X. Gabarrell · J. Rieradevall
Inèdit Innovació SL, UAB Research Park,
Carretera de Cabrils km2 (IRTA),
08348 Cabrils, Barcelona, Catalonia, Spain

X. Gabarrell · J. Rieradevall
Department of Chemical Engineering,
School of Engineering (EE),
Universitat Autònoma de Barcelona (UAB),
Campus de la UAB, Bellaterra (Cerdanyola del Vallès),
08193 Barcelona, Catalonia, Spain

A. Josa
Department of Geotechnical Engineering and Geosciences,
School of Civil Engineering (ETSECCPB),
Technical University of Catalonia—Barcelona Tech (UPC),
C/ Jordi Girona 1-3, Building D2,
08034 Barcelona, Catalonia, Spain

A. Josa
Institute of Sustainability (IS.UPC),
Technical University of Catalonia-Barcelona Tech, (UPC),
Campus Nord, Building VX. Pl. Eusebi Güell, 6,
08034 Barcelona, Catalonia, Spain

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criteria are applied during sidewalk design and management, urban planners may be unconsciously contributing to an important environmental burden on the built environment. The ecodesign is a strategic opportunity to promote environmentally suitable urban infrastructures that contribute to promote urban sustainability in cities.

Recommendations Energy efficiency techniques, water management, and well-considered transportation management should be developed and implemented in the granite industry to minimize the environmental impact of using it for paving. Additionally, further research is needed to quantify the environmental performance of other construction materials used in sidewalk construction in order to identify the best environmental alternatives and design improvements by optimizing the use of materials to the sidewalks functions.

Keywords City · Granite · Concrete · LCA · Pavement · Sidewalks · Slabs · Sustainability

1 Introduction

1.1 Cities and the environment

According to United Nations projections (UNPD 2007), cities will house 60% of the world population by 2030, which is equivalent to the total global population of 1986. This means that urban areas are expanding, especially because cities have an important role in enhancing the dynamism, resilience, and overall competitiveness of national economies (Gertler 2004).

However, cities already consume 80% of the global energy output and contribute directly to more than 60% of greenhouse gas (GHG) emissions (UN-HABITAT 2010). As cities grow, the flow of energy and material through them increases (Decker et al. 2000). As such, energy consumption and GHG emissions by cities will likely increase by up to 35% between 2007 and 2030 (WEO 2009). Therefore, there is a growing concern about the relationship between the challenge of sustainability and expanding cities.

Urban design represents an important, yet undervaluated, opportunity to achieve sustainability and addressing climate change in cities (Marshall 2008). The built environment is responsible for large amounts of pollution worldwide (Hendrickson and Horvath 2000) due to the large amounts of energy, water, material resources, and emissions embedded in the building materials. Life cycle management of the built environment is a strategic opportunity to minimize the environmental burden of cities, but first, a comprehensive knowledge of the urban system is needed to move from general goals of the development of sustainable cities to the necessary clear guidance and targets for constructing sustainable urban infrastructures (Pauleit and Duhme 2000).

1.2 Urban planning

The application of environmental criteria during urban planning usually has a lower weight than criteria based on social and economic factors, such as, cost, aesthetics, and ergonomics (Oliver-Solà et al. 2009). From an environmental perspective, this results in land use practices that generate unsustainable urban sprawl (Balocco et al. 2004). Consequently, the adoption of environmental criteria is a prerequisite for developing environmentally friendly designs and promotes sustainable neighborhoods and cities.

In the last decade, sustainable neighborhood designs have become an important area of research (Oliver-Solà 2009; Engel-Yan et al. 2005). Open spaces, which are defined as “any unbuilt land within the boundary of a neighborhood that has the potential for providing environmental, social and/or economic benefits to communities” (Campbell 2001), are considered to be important spaces for contributing to urban sustainability. Nevertheless, the literature on the environmental assessment of these areas, specially those called “grayspaces” (or “civic spaces”), which are paved or hard landscaped areas with a civic function (Al-Hagla 2008), such as, sidewalks, urban squares, parks, and cycling paths, is mainly focused on studying their role in terms of sustainable mobility, comfort, leisure/recreation, health, and safety (i.e., WPPP 2002; PMP 2002; Emery et al. 2003; PMUB 2006; PBSME 2010), without studying their environmental impact contribution throughout their whole life cycle. Therefore, access to comprehensive environmental information is essential to facilitate the ecodesign of urban infrastructures that minimize the environmental burden of the built environment of cities.

1.3 Sidewalk paving

While most modern development planning use the road network as the key structural element, a sustainable design takes the circulation of people on foot and bike and the effectiveness of public transport as starting points (Barton et al. 1996). In this context, sidewalks are considered to be sustainable transport paths that involve benefits for the environment and the health of citizens. Sidewalks also represent better land use and involve equity investment because they can be used by most people (CEDEX 2009).

Sidewalks are defined as “an uninterrupted facility parallel to a carriageway that is a designated footpath with the main purpose of carrying pedestrian traffic and related activities” (Mateo-Babiano and Hitoshi 2005). Their management is essentially focused on the assessment of their suitability for pedestrians (Mateo-Babiano and Hitoshi 2005; Emery et al. 2003). Typically, no environmental criteria is considered during the infrastructure design, although sidewalks can represent approximately 5–7% of the total paved surface of urban settings (Oliver-Solà et al. 2009) and can significantly contribute to the environmental impact of the built environment of cities.

In sidewalk paving, concrete is the most used material, but asphalt and natural stone are also widely applied (PMP 2002). The use of concrete and asphalt has been well studied from a life cycle perspective. There is previous research on the assessment of the environmental impact of using these materials in road paving (i.e., Häkkinen and Mäkelä 1996; Josa et al. 2001; Zapata and Gambatese 2005; Stripple 2005; Rajendran and Gambatese 2007). Additionally, the environmental performance of using concrete in sidewalk paving has also been studied. Oliver-Solà et al. (2009) have analyzed different designs of concrete sidewalks that are suitable for different functionalities (pedestrian traffic in addition to non-motorized traffic such as bicycles and wheelchairs, motorized traffic, and access to underground services). The concrete sidewalks assessed are based on using interlocking blocks, continuous concrete layer or concrete slabs as top layer to fulfill one or a combination of functionalities. The sidewalk design that is environmentally optimal for each situation is determined by analyzing four combinations of functions. Results indicate that by optimizing the design of concrete sidewalks according to their required function(s), environmental impact can be reduced by 69–74%. Therefore, using environmental criteria in sidewalk construction can bring important environmental benefits.

Nevertheless, there is no information available about the environmental suitability of using natural stone in urban paving, although it is widely applied. Granite is the natural stone primarily used in external flooring due to its three fundamental characteristics: hardness, durability, and aesthetics (FDP 2005). Granite is often used as tiling (slabs) and blocks. The blocks are usually employed for areas where the mechanical load is greater, such as, curbs or areas for accessing parking lots (FDP 2005). Granite provides appropriated technical properties, can be easily formed into slabs without chemical treatment, and is easy to install on site. Due to its natural origin, granite is perceived as a natural product that may be of interest for mitigating the environmental impact of urban constructions. In this sense, the paper aims to assess if using granite slabs for sidewalk paving can contribute to reduce the life cycle environmental impacts of sidewalks.

2 Method

2.1 Objectives and scope

The objective is to determine the environmental performance of using granite slabs in sidewalk paving and whether using granite could help reduce the environmental burden of sidewalks paved with standard (prefabricated) concrete slabs. In this sense, we evaluate how the life cycle impacts of a sidewalk may change according to the construction material chosen for flooring (top layer).

To achieve this goal, a life cycle inventory of a typical sidewalk design based on granite slabs as top layer was compiled and its environmental impacts analyzed by means of a life cycle assessment. A sensitivity analysis of granite transportation management helped to establish a set of recommendations for improving the environmental profile of the material.

2.2 Functional unit

The functional unit provides a reference for the inputs and outputs associated with the system under study (ISO 14040 2006). The functional unit is 1 m^2 of sidewalk placed in a standard location in central Barcelona (Spain). It includes all pavement layers required for supporting pedestrians and light motorized traffic over a timeframe of 45 years, when the sidewalk would likely be deconstructed due to trenching or maintenance of underground services (telecommunications, power, gas and water supply, etc.). Figure 1 shows the structural profile of the constructive solution under study.

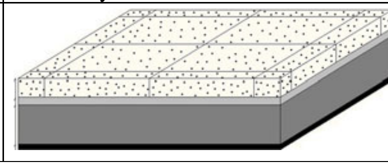
Although there are several design alternatives, the construction solution under study is structurally equivalent to the sidewalk system defined as S3 in Oliver-Solà et al. (2009) and has the standard dimensions that are commonly applied in sidewalk construction to fulfill the defined function. Both sidewalks designs consist of a concrete base layer of 15-cm thick with a typical compressive strength of 20–25 MPa. This is a technical condition required to support light motorized traffic. Granite slabs (top layer) are fixed on a 3-cm mortar layer. But a 2-cm mortar layer is required when concrete slabs are used for flooring. The amount of mortar required is related to the dimensions of the slabs that are selected as top layer. Granite slabs used to support the sidewalk function typically have dimensions of 40×40×7 cm, while concrete slabs are 20×20×4 cm. Sidewalks are named after their top layer.

2.3 Description of the granite sidewalk under study

The life cycle stages that are assessed include material production, sidewalk construction, sidewalk deconstruction, and material transportation. The system boundaries under study are described in Fig. 2.

Materials production All the element and energy inputs required for the production of the construction materials are accounted from cradle to gate.

Fig. 1 Structural section of the sidewalk system under study

Layers	Layout for $1m^2$ of sidewalk	Sidewalk function
Granite slabs (7cm) Mortar (3cm) Concrete (15cm) Subgrade		Pedestrian traffic + Light motorized traffic Supported over 45 years

- Granite slabs (a). Slabs production consists of two main substages: granite quarrying and processing. The basic and most common production process for granite slabs is shown in Fig. 3.

  In quarrying, heavy machinery is used to remove a granite bench from the geologic deposit. After drilling boreholes along the perimeter of the bench, it is removed by mostly using diamond wire saws, but hydraulic splitters and explosive charges are also applied. Once the bench is removed, it is transferred to temporal storage or directly shipped to the processing facility by using heavy equipment, such as, cranes and trucks.

  In processing, granite blocks are cut into variable thickness panels that are subjected to a surface finishing and shaping process to obtain slabs of desired size, shape, and aesthetics. Diamond wire saws and circular blade saws equipped with diamond edges are used to cut the blocks and panels. Finally, the slabs are packaged using wooden pallets and aluminum strips.
- Concrete and mortar (b). The production begins with the extraction of raw materials, which are basically aggregates used in cement manufacturing. Mortar is produced by mixing cement, fine aggregate (sand), water, and possible additives. For concrete, a coarse aggregate must be added to the mixture as well.

  The cement type considered is CEM II/A-L 32.5R Europe, appropriate for sidewalk applications.

Sidewalk construction Soil is compacted using hammers of varying sizes depending on the magnitude of the work. Subsequently, a uniform base of concrete is placed on top of the subgrade. The concrete is poured from a mixer truck, spread manually, then compacted with vibration and smoothed by ruler. A layer of mortar is put over the concrete, and the granite slabs are manually placed on it.

Sidewalk deconstruction The sidewalk is supposed to be removed after 45 years due to trenching or maintenance of underground service networks (electricity, gas, water, and telecommunications). Backhoes equipped with pneumatic hammers are required for deconstruction.

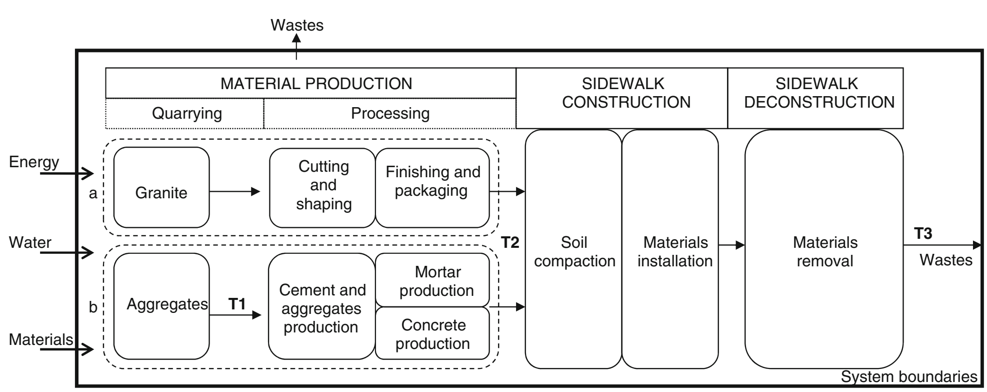
Materials transportation Transport needs were estimated from a local market perspective. Transportation of materials was divided into three substages (see Fig. 2): the transport of concrete and mortar constituents from manufacturing plants to the material production plant (T1); materials transportation from production plant to the sidewalk placement (T2); and transport of construction wastes when the sidewalk is deconstructed (T3).

2.4 Source and data quality

To compile the input/output data related to granite slabs production (see Fig. 3; Table 1), different environmental inventories available were analyzed and compared to each other. Subsequently, a life cycle inventory (LCI) of granite quarrying and processing prepared by the University of Tennessee for the Natural Stone Council of USA (NSC 2009) was chosen to assess the environmental impact of granite slabs production.

Although different quarrying and processing techniques can be applied in the granite industry, the production of granite slabs is fairly standardized worldwide. In this sense, there are no significant variations when processes of quarrying and processing between industrial facilities with

Fig. 2 System boundaries and the process chain under study



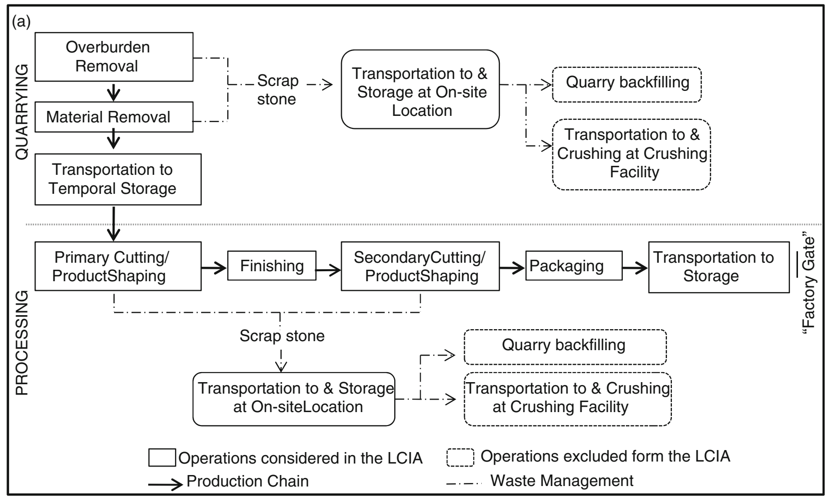


Fig. 3 Flow diagram of granite slabs production. Adapted from NSC (2009)

similar size and production volume are compared. The dataset of the NSC (2009) refers to the quarrying and processing of a large volume of granite from several companies located throughout the USA and Canada. The data reflect a diversity of operations with respect to size and location of quarries and facilities and is updated in 2009. Based on the high quality of the data, it is considered that this LCI can be used globally for studying the environmental performance of the production of granite slabs.

Regarding the inputs of concrete and mortar to the system and the assumptions of materials and wastes transportation distances, data were collected from Oliver-Solà et al. (2009). Transportation of the granite slabs to the sidewalk placement (T2) was established by assuming that the slabs could travel directly from local quarries or nearby facilities that are located 100 km from the city center of Barcelona (Spain). Finally, the energy consumption by machinery required in sidewalk construction and deconstruction was defined through consultation to national statistics sources (ITeC 2010).

2.5 Methodology

The life cycle assessment (LCA) methodology (ISO 14040 2006) was applied to assess all environmental impacts associated with the sidewalk system by accounting and evaluating resource consumption and emissions associated to the corresponding functional unit.

Impact assessment Life cycle impact assessment (LCIA) methods aim to connect, as far as possible, each LCI result (elementary flow or other intervention) to the corresponding environmental impacts (Jolliet et al. 2003). Environmental impact assessment is based on the CML baseline 2001 method (Guinèe et al. 2001). The midpoint impact categories that were considered included: abiotic depletion potential (ADP [kilogram Sb equivalent]), acidification potential (AP [kilogram SO_2 equivalent]), eutrophication potential (EP [kilogram PO_4^{3-} equivalent]), global warming potential –100 years (GWP [kg CO_2 equivalent]), human toxicity potential (HTP [kilogram 1.4-DB equivalent]), ozone depletion potential (ODP [kilogram CFC-11 equivalent]) and photochemical ozone creation potential (POCP [kilogram C_2H_4 equivalent]). The software used for environmental assessment was GaBi 4.3 (PE International 2008) as well as the ecoinvent v1.2 (2006) database. Also, the EcoConcrete LCA tool (CEMBUREAU, BIBM, EFCA, ERMCO, EUROFER, UEPG 2003) was applied for quantifying the impact of concrete and mortar and the relative contribution of their constituents. This tool was promoted by the European Union (EU) Joint Project Group on the LCA of concrete and has access to detailed life cycle inventory data provided by a European concrete producer. Therefore, data are based on the standard production of concrete in Europe and considered to be high quality. Table 1 shows the LCI and ecoinvent processes selected for the LCIA of the granite sidewalk.

Although the stage of use of the sidewalk could contribute to local environmental impacts, such as, urban heat island or the loss of life by sealing or leaching the soil because these factors are not considered in CML baseline 2001, this life cycle stage was not included in the environmental assessment. Moreover, being aware of the importance of maintenance operations in contributing to life cycle impacts, it is assumed that sidewalks will remain undisturbed for 45 years. The assumption is based on the ratio of sidewalk renewal in the city of Barcelona (45 years) due to trenching or maintenance of underground services. Therefore, it is considered that the sidewalks can fulfill their function during this timeframe without replacements of their pavement layers.

Table 1 Life cycle inventory for 1 m^2 of sidewalk

LC stages	Substages	Data per functional unit			Ecoinvent processes
Material production			Natural Stone Council (2009)		
	Granite slabs	Resources consumed	Quarrying	Processing	
		Electricity, MJ	39.5	39.5	ES: electricity, medium voltage, at grid
		Natural Gas, MJ	6.9E-05	3.0E-02	RER: heat, natural gas, at boiler modulating <100 kW
		Propane, MJ	0.2	9.9	RER: propane at refinery
		Diesel, MJ	86.5	23.2	GLO: diesel burned in building machinery
		Gasoline, MJ	6.2	13.8	ELCD: gasoline (regular) at refinery
		Acetylene, MJ	2.1E-02	–	CH: acetylene, at regional storehouse
		Groundwater, kg	37.4	5,792.8	Created from ecoinvent database
		Surface water, kg	112.1	934.3	
		Public supply water, kg	1.0	89.7	RER: tap water, at user
		Ammonium nitrate, kg	4.0E-03	–	RER: ammonium nitrate, at regional storehouse
		Light fuel oil, kg	6.4E-04	–	RER: light fuel oil, at regional storehouse
		PENT, kg	7.9E-03	–	RER: penta-erythritol, at plant
		Polyurethane, kg	1.2E-03	1.7E-02	RER: polyurethane, flexible foam, at plant
		High carbon steel, kg	5.4E-03	–	RER: steel, converter, unalloyed, at plant
		Industrial steel, kg	3.0E-03	–	RER: reinforcing steel, at plant
		Mild steel, kg	5.7E-02	–	RER: steel, low-alloyed, at plant
		Stainless steel, kg	4.0E-04	5.4E-03	RER: steel, converter, chromium steel 18/8, at plant
		Aluminum, kg	–	0.3	RER: aluminum, secondary, from old scrap, at plant
		Wood pallet, kg	–	0.8	Extracted from Gasol et al. (2008)
		Granite stone, kg	518.0	314.5	–
			Oliver-Solà et al. (2009)		
	Mortar	Cement, kg	9.9		EcoConcrete LCA Tool
		Fine aggregate, kg	60		
	Concrete	Cement, kg	45		
		Fine aggregate, kg	150		
		Coarse aggregate, kg	150		
		Tap water, kg	19.7		
		Additives, kg	0.7		
Material transportation			Assumptions		
	T1	Cement, km	75		RER: transport, lorry 28 t
		Aggregates, km	40		
		Additives, km	100		
	T2	Granite slabs, km	100		RER: transport, lorry 16 t
		Concrete and mortar, km	30		
	T3	Concrete, mortar, granite, km	30		RER: transport, lorry 28 t
Sidewalk construction			ITeC (2010)		
	Compaction	Diesel (rammer), MJ	12.2		GLO: diesel burned in building machinery
	Installation	Electricity (mixer for grout), MJ	0.3		GLO: diesel burned in diesel–electric generating set
Sidewalk deconstruction			ITeC (2010)		
	Removal	Diesel (backhoe), MJ	38.0		GLO: diesel burned in building machinery

The environmental impacts of propane, gasoline, and acetylene combustion during granite production (see Table 1) were calculated using data from official reports on the combustion of these products (GRI 1999, U.S. EIA 1998 and CR 2009, respectively).

Waste management The environmental assessment of the granite scraps generated during the material production stage (see Figs. 2 and 3) was excluded from the system boundaries. The yield of granite slabs production is about 22%. In other words, for every 1 kg of granite produced, 3.5 kg of granite scraps are generated, primarily due to the stone breaking when it is handled. Nevertheless, the scrap is generally used as quarry backfilling matter or is subjected to a grinding process for generating aggregate that is reclaimable in construction. As such, granite scraps become an industrial co-product with economical value. However, the impacts of transforming scraps into co-products have not been allocated to the production stage of granite slabs due to two main reasons:

- Granite scraps and subsequent aggregate generation is not a goal of the industrial production of slabs. But this is an inevitable consequence due to the current state of technology applied in the granite industry.
- A large volume of scraps is generated per unit of finished product but is not reasonable to allocate inputs and outputs by underlying physical relationships between granite slabs and aggregates. On the other hand, aggregates generated per unit of finished product represent less than the 5% of the final price of granite slabs. Therefore, aggregates have no economic benefit to the industry. In this sense, it is considered that inputs and outputs of scrap management correspond to the production of aggregates as new products and impacts should not be allocated to the production of granite slabs.

Only, transportation of scraps to on-site storage is assessed. Moreover, due to uncertainties concerning the waste treatment processes that will be employed once the sidewalk is deconstructed after 45 years, impacts of construction waste management were excluded from the LCIA. This is consistent with system boundaries defined by Oliver-Solà et al. (2009) for performing under the same conditions the comparative assessment between the sidewalk solutions. At the same time, to incorporate construction wastes management in the LCIA of systems would affect the absolute values, but not the corresponding relative contribution between systems due to treatment of construction wastes is similar (crushing and/or disposal to landfill). Only, inputs and outputs of the deconstruction stage and waste transportation to final disposal have been addressed.

3 Results

3.1 Life cycle inventory data

The resources and processes required throughout the life cycle of the sidewalk system defined in Figs. 1, 2, and 3 are shown in Table 1.

3.2 Life cycle impact assessment

3.2.1 Impact assessment of the granite sidewalk

The environmental life cycle impacts for 1 m^2 of sidewalk are shown in Table 2. The materials production stage is the largest contributor to the environmental impact of all the categories analyzed. It represents from 48% to 87% of the total environmental burden of the sidewalk life cycle, depending on the impact category analyzed. The highest difference in the relative contribution to the impact is in the ADP and GWP categories, where the input of construction materials is a factor of 6.4 and 3.5 greater than the rest of life cycle stages put together.

The material transportation stage is also relevant in contributing to total impact. It contributes up to 30% in the EP, ODP, and POCP categories while the stages of sidewalk construction and deconstruction together contribute less than the 10% of the impact of all categories.

3.2.2 Impact assessment of the materials and processes

When the relative contribution to impact is analyzed according to the type of construction materials that constitute the sidewalk (Fig. 4), it is found that the granite top layer is the main contributor, with the exception of ADP and GWP categories. In this case, the concrete base accounts for 274% and 69% higher input than granite top layer. Mortar is the lowest contributor to environmental impact except in ADP where contributes by a factor of 1.5 higher than the granite top layer.

Regarding the environmental impact of the material transportation substages, transport to the installation site (T2) has the highest input. It contributes over 60% of the total impact of the transportation stage, where transporting the granite slabs contributes 57% of the total T2 impact due to the greater distance travelled.

In the sidewalk construction stage, the installation of materials has very little impact due to the fact that the materials are, basically, manually installed. However, in soil compaction and sidewalk removal, diesel-powered tampers and backhoes are required which determine the contribution to impact of these stages.

Being aware of the importance of construction materials in contributing to the life cycle impacts of the sidewalk,

Table 2 Characterization results for the sidewalk life cycle

Impacts	Material production	Material transportation	Sidewalk construction	Sidewalk deconstruction	Total
ADP	1.1E+00	1.4E-01	7.3E-03	2.3E-02	1.3E+00
AP	4.3E-01	1.3E-01	1.5E-02	3.4E-02	6.1E-01
EP	5.7E-02	3.0E-02	2.7E-03	7.0E-03	9.7E-02
GWP	8.5E+01	2.0E+01	1.1E+00	3.5E+00	1.1E+02
HTP	7.7E+00	3.1E+00	8.6E-02	2.7E-01	1.1E+01
ODP	4.3E-06	2.8E-06	1.3E-07	4.3E-07	7.7E-06
POCP	3.0E-02	2.7E-02	1.4E-03	4.0E-03	6.3E-02

Table 3 indicates the industrial inputs that contribute the highest to their environmental burden.

With regard to the stages of materials transportation and sidewalk construction and deconstruction, the diesel consumed by trucks and construction machinery is responsible for almost 100% of the environmental impact associated with them. Therefore, the life cycle impact of the sidewalk is mainly associated with the consumption of three elements: cement, electricity, and diesel. However, the impact of cement highly depends also on the energy consumed during its production stage. But it has been mentioned in the "Discussion" section.

Impact assessment of granite slabs To better understand the origin of the high environmental burden of granite slabs, Table 4 indicates impacts of granite quarrying and processing into slabs and Fig. 5 the relative contribution by the resources consumed during the production stage.

According to the LCI data (see Table 1), the 60% of the total energy required in slabs production is consumed in stone quarrying, mainly due to the input of diesel that represent the 79% of the total diesel consumed in the production stage. Basically for that reason, granite quarrying has a higher impact than processing.

Energy consumption accounts for 72% to 96% of the total impact of slabs production, while water and material consumption combined only exceed 10% of contribution in HTP (28%). Diesel is the primary energy source consumed (50%) in the production stage and the first contributor in EP, ODP, and POCP categories. Electricity is the second energy source consumed (36%) but is the first contributor in the rest of impact categories.

Auxiliary materials are also consumed primarily during stone quarrying. The highest contribution to impact is in HTP (22%) category, where the steel consumption represents 14%. The stainless steel that is used in the saws for cutting is the main contributor to the HTP impact due to its chromium content.

Finally, a large amount of water is required in stone cutting. However, the total contribution of water consumption to the impact is lower than 6%, which is the maximum value defined by the input to GWP. The water pumping process is the responsible for the highest emissions of greenhouse gases.

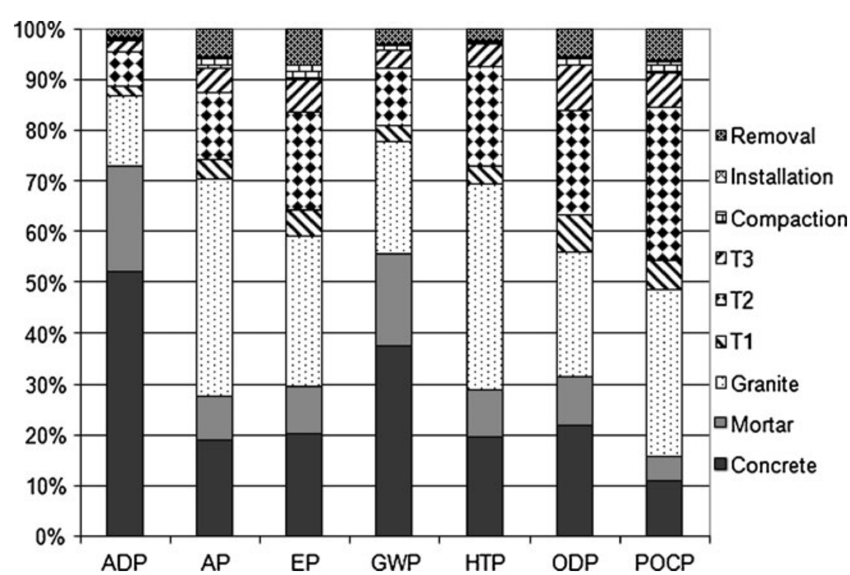


Fig. 4 The relative impact contribution of each substage of the sidewalk life cycle

Table 3 Industrial flows that account the highest input to the environmental impact of the construction materials

Impacts	Concrete	Mortar	Granite	
	Cement (%)	Cement (%)	Electricity (%)	Diesel (%)
ADP	72	87	43	38
AP	91	95	55	38
EP	93	95	21	71
GWP	97	98	48	41
HTP	94	96	53	17
ODP	74	79	18	67
POCP	94	98	37	57

3.2.3 Comparative environmental assessment: environmental suitability of using granite or concrete slabs as flooring material in sidewalk paving

To determine the environmental performance of using granite slabs compared to concrete slabs as flooring material, LCIA results (see Table 2) are compared to the environmental outcomes obtained from the life cycle assessment of the S3 sidewalk system from Oliver-Solà et al. (2009), which was described in previously sections.

Comparison of the LCIA results (Table 5) shows that the granite sidewalk has a worse environmental performance than the concrete one. Using granite slabs for flooring generates an increase of 50% to over 100% in the total environmental impact of the sidewalk system, depending on which impact category is analyzed.

Focusing on the contribution to GWP, due to its current political and social concern in terms of climate change, using granite slabs produce 35 kg/m^2 more CO_2 emissions than using concrete slabs for sidewalk paving. However, the main differences in the relative contribution to impact between the sidewalk systems is in the AP, HTP, and POCP categories. The impact is by than a factor of 2 higher in the granite sidewalk.

Table 4 The environmental impact contribution of granite quarrying and slabs processing

Impacts	Granite slabs production	
	Quarrying	Processing
ADP	9.5E-02	8.1E-02
AP	1.5E-01	1.1E-01
EP	1.9E-02	9.0E-03
GWP	1.4E+01	1.0E+01
HTP	2.1E+00	2.4E+00
ODP	1.2E-06	7.0E-07
POCP	1.3E-02	7.3E-03

3.2.4 Granite transport management

The results of the LCIA of the sidewalk system (see Table 2) showed that material transportation is the second highest impact stage, and the materials transportation to the site (T2) is the primary contributor to the total impact. Construction materials have been supposed to come from local quarries located near the urban areas where the slabs would be installed. However, granite used in construction often comes from regional or global markets. The Observatory of the Natural Stone Market in Spain (OMPN 2009) shows that the major importing/exporting countries of finished granite in the EU are Portugal, Spain, France, Italy, Poland, Germany, UK, and Turkey, while China, India, and Brazil are the non-EU countries that export large quantities of granite to the EU.

To determine how life cycle environmental impacts change when imported granite is used for sidewalk paving (Fig. 6), two importation scenarios were considered.

- Regional market: is assumed that finished granite is sold between two EU countries. Imported granite travels a total of 1,000 km by truck (lorry of 28 tons) from the industrial facility to storage.
- Global market: granite travels from China to the EU. It travels along 9,000 km by ship (transoceanic freight ship) and is then moved 1,000 km by truck (lorry of 28 tons) to storage.

It is assumed that the production stage and the LCI data are the same as shown in Fig. 3 and Table 1 and that only the distances and the type of vehicles used during material transportation to site (T2) varied.

Results show that the environmental impacts associated with using imported granite in sidewalk paving are significant. The use of granite coming from regional markets contribute to increase from 20% to 76% the life cycle environmental impact of the sidewalk while using granite from global markets results in an impact that is from 49% to 177% higher than using granite obtained at local quarries and facilities.

It is interesting to note that material transportation over 1,000 km by truck is approximately from a factor of 1.6 to 3.4 environmentally worse than transportation over 9,000 km by ship. It is related to the fuel consumption by different means of transport. In this sense, if no long additional transportation by land was necessary (locations close to sea), using imported granite from global markets would have had a better environmental profile than using granite from regionals markets. However, almost always a large transportation of materials by land is required due to the varied location of material stores. Therefore, the use of local materials is still the most environmentally friendly choice for minimizing the impact of materials transportation.

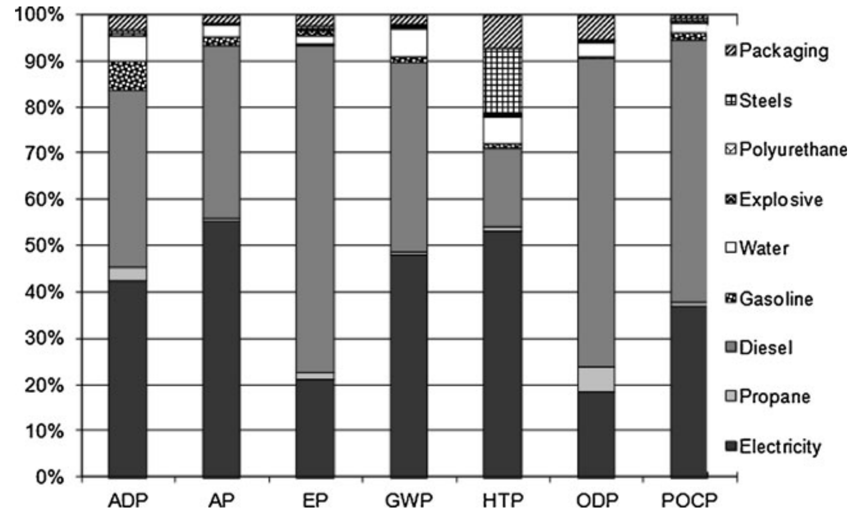


Fig. 5 Environmental impact contribution by type of resources consumed during granite slabs production. The contributions of natural gas and acetylene consumption are excluded due to its low input

4 Discussion

Materials used in sidewalk construction largely determine the environmental performance of the infrastructure. The contribution of the granite top layer to the impact is a factor 1 to 2.1 higher than the contribution of concrete and mortar together, even though the amount of granite represents almost 30% of the total weight of the materials that comprise the constructive solution. The key factor for the impact of granite is the amount of energy required during slabs production. Diesel consumption and, to a lesser extent, gasoline and acethylene are associated with the intensive use of heavy machinery for removing and transfer granite benches (4–7 m^3) and blocks to storage sites (quarries) and moving the slabs inside the industrial facilities. This process is typically conducted slow and delicately to preserve the quality of the stone and prevent breakage. The contribution to impact by diesel is associated with the pollutant emissions generated during its combustion in the trucks and craines used. The electricity consumption, along with the consumption of natural gas and propane, is mostly attribute to the stone-cutting and finishing process. The standard classification of natural stones for construction UNE-EN 12670 (2003) states that granite is a natural compact stone that consists of a mass of minerals, such as, quartz and feldspar, that has a hardness between 5 and 7 on the Mohs scale. The hardness and abrasiveness (siliceus stone) of granite requires the use of heavy equipment for cutting it. The heavy equipment consist mainly of electric-powered saws. Cutting is therefore an energy-intensive process. Impacts of the electricity consumption are referred to the Spanish power mix, where fossil fuels (mainly hard coal but also natural gas, oil, and lignite) represent 54% of the inputs required for producing electricity. These accounts for over 82% of the impacts related to the power mix generation, being in ADP, AP, GWP, and HTP categories where their input is the highest (including also POCP). Data about the type of energy inputs and the impacts of power mix generation were analyzed through consultation of the ecoinvent database.

Water consumption during slab production is also associated with the abrasiveness of granite. Sufficiently elevated temperature can cause major machine and material damage, therefore a continuous stream of water over the wire is required to dissipate the heat generated by the cutting

Table 5 The environmental impact of using granite slabs instead of concrete slabs for sidewalk paving.

Impacts	Concrete sidewalk	Granite sidewalk	Impact increment (%)
ADP	1.0E+00	1.3E+00	25
AP	3.0E-01	6.1E-01	104
EP	5.5E-02	9.7E-02	76
GWP	7.4E+01	1.1E+02	47
HTP	4.7E+00	1.1E+01	139
ODP	4.5E-06	7.7E-06	71
POCP	2.8E-02	6.3E-02	123

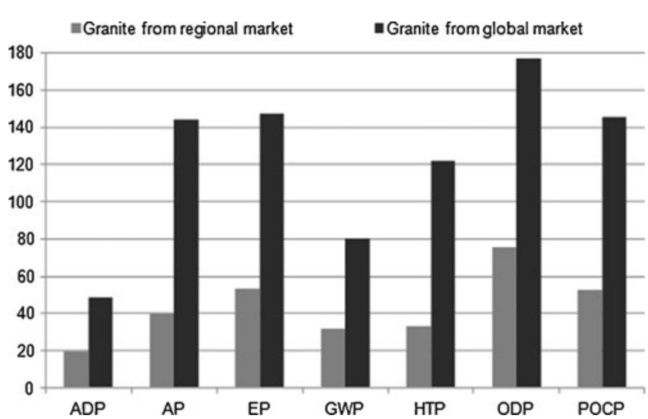


Fig. 6 Increase on the life-cycle environmental impacts when imported granite is used for sidewalk paving

processes. This explains the large amount of water that is consumed, although its contribution to the total impact seems irrelevant due to the high environmental burden associated with the energy consumption.

Nevertheless, it is remarkable that the concrete base layer is also important in contributing to the global impact of the sidewalk. It represents 52% of the total life cycle impact in the ADP category, and it is the primary contributor to GWP (48%) for the impact of construction materials. Cement is the highest impact constituent of concrete and mortar, whereas clinker is the cement component that contributes the most to the final impact of it. The fuel combustion during clinker production, the chemical reactions that occur in the clinker kiln, and the energy consumed throughout the whole production process of clinker and cement determine the impact of it (Josa et al. 2004). The higher contribution of concrete to ADP is associated with the type and amount of elements and fossil fuels required during production. In the manufacturing of cement, different elements that have a scarcity ratio assigned, such as, bauxite and limestone, are consumed. However, other elements required, such as, sand, clay, or gravel, do not have a specific scarcity ratio because they are considered resources that are replenished by geologic forces in a period lower than 500 years (van Oers et al. 2002). Granite is included in this latter group. For that reason, contribution to ADP is higher in the case of concrete.

These findings allow to establish that the natural features of granite stone highly influence the environmental impact of the production of slabs, whereas diesel and electricity consumption largely determine the environmental profile of the material. The geometry of the granite slabs is significantly relevant for the different inputs and outputs. Therefore, to adjust the size of the slabs by trying to reduce the number of cuts required would contribute to reduce the energy and water inputs and also the environmental impacts generated.

Regarding the impact of the materials transportation stage, it depends on the distances that are traveled by the materials, the amount of materials that have to be moved, and the type of vehicle as well as the fuel used for transportation. In this case study, the contribution of transportation is especially high for the EP (31%), ODP (37%), and POCP (43%) categories in which, as shown in the case of granite contribution to them, the impacts are associated with the diesel consumption of the trucks.

The type, technical requirements, and the amount of construction materials used in sidewalk construction depend on the sidewalk function to be fulfilled. This case study uses the fact (based on construction designs) that a granite top layer or a concrete one can be applied for fulfill the sidewalk function. However, the environmental performance of a sidewalk paved with granite slabs is significantly worse, by a factor of 1.3 to 2.4, than using concrete slabs for the same purpose.

Therefore, the type of top layer chosen for paving highly determines the different contribution to impact between sidewalks. But the difference can still be higher if materials coming from non-local markets are used. In this sense, the granite used in the sidewalk construction is very often imported from regional or global markets, especially China. As such, the life cycle impact of the sidewalk can increase significantly. The study has shown that using imported granite for sidewalk paving may result in an increase in the environmental impact of the sidewalk up to 170%, depending on the importation scenario as well as the impact category analyzed.

5 Conclusions and recommendations

Sidewalks are considered to be sustainable transportation paths that can provide important benefits for the environment and health of citizens by promoting walking as a zero emission form of transportation. Sidewalks are one of the key urban elements that are often considered in modern sustainable development planning. However, they are typically designed to be suitable during the use stage. The criteria applied during sidewealk design is mainly focused on social, technical, and economic factors.

This study has shown that if no environmental criteria are applied during sidewalk design and management, urban planners may be unconsciously contributing to an important environmental burden in cities. Therefore, the ecodesign of sidewalks is a strategic opportunity for developing environmentally friendly infrastructures and promoting the sustainability of the built environment of cities.

Construction materials have the greatest environmental burden on the sidewalk system assessed. The materials chosen for flooring largely determines the environmental life cycle impact of the infrastructure. Choosing granite slabs as flooring material cause the total environmental impact of the sidewalk system to increase up from 25% to almost 140% compared to using concrete slabs to fulfill sidewalk functionality.

The large amount of energy required during granite quarrying and processing is the factor that characterizes the environmental impact of granite slabs. In light of these results, we conclude that using granite slabs as flooring material is not an environmentally suitable alternative over using concrete ones for constructing sidewalks for pedestrian and light motorized traffic. Energy efficiency techniques and technologies should be developed and implemented in the granite industry to reduce the environmental impact of production. Water management should also be prioritized at quarries and processing facilities for both economic and environmental reasons. To produce 1 m^2 of granite (7-cm thick), approximately 7 tons of water is required, where about 99% comes from groundwater and surface water. Therefore, actions to reduce water consumption are relevant, especially in locations where water scarcity is a problem.

Also, complementary actions such as to avoid oversizing the thickness of the concrete base or altering the construction would contribute to reduce the overall impact of the system, while fulfilling the sidewalk function. In this sense, replacing the base of concrete by installing a compacted hardcore base with a flexible jointing could greatly reduce the environmental impact of bedding. However, technical tests should be made to determine whether a compacted hardcore base can support the sidewalk function for 45 years without being replaced or under which conditions it can be achieved.

Sidewalks should be designed and constructed prioritizing environmentally improved and suitable materials. To determine which materials are environmentally suitable for paving, further research is required to assess the environmental performance of other construction materials that are commonly used in sidewalk construction, such as, asphalt and ceramics. Also, research on the effects of adjusting the design and optimizing the use of construction materials to the specific sidewalk function(s) is required to characterize environmental alternatives. Additionally, the promotion of using materials from local markets should be prioritized to minimize the environmental impact associated with transportation, especially from those materials that are normally imported, such as granite. The use of high-quality and detailed average data about the distances travelled by construction materials is considered relevant for developing improvement strategies. At the same time, this issue could be analyzed and integrated by companies as part of a policy of ethical trading. Well-considered transportation management can be advantageous to a quarry, processing facility, and supplier, since it promotes shipment efficiency while minimizing negative impacts to the environment and reducing costs and risks.

The promotion of sustainable mobility in cities is one of the key strategies employed by governments to counteract climate change and health problems due to air pollution. Therefore, sidewalks, cycling paths, city squares, and other open spaces have an increasingly important role in new urban development or refurbishing plans. However, sustainable transportation also requires sustainable infrastructures that contribute to minimize the environmental impact of the built environment of cities. Therefore, the ecodesign and life cycle management of urban mobility infrastructures should be employed to design environmentally friendly urban solutions that contribute to promote urban sustainability in cities.

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