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Use of environmental product declarations (EPDs) of pavement materials in the United States of America (U.S.A.) to ensure environmental impact reductions

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A B S T R A C T

Recent green public procurement (GPP) initiatives in the U.S.A. rely on the use of the construction materials EPDs. EPD programs, however, were initiated by the material manufacturers, motivated by their interest to use EPDs as communication tools, improve production efficiency, and extend outreach. The goal of GPP initiatives is to produce the environmental improvements, however, it is unclear if the current EPD programs and GPP mechanisms can reliably support that goal. This study investigates the use of EPDs in GPP to ensure the environmental improvement of materials (use of EPDs as a procurement aid) and pavements (use of EPDs as a data source). The objective of this study was to identify prerequisites, challenges, implementation frameworks that include stakeholders and ensure environmental benefits with EPDs. A review of to-date EPD programs for pavement materials, communication with stakeholders, and analysis of pavement life cycle assessment (LCA) were performed. The use of EPDs that ensures environmental improvements of materials is contingent on EPD consistency and PCR prescriptiveness. EPDs can be suitable as data sources in pavement LCA due to their availability, transparency, and because they facilitate collaboration and improvements throughout the supply chain. However, it is noteworthy that if EPDs are used in that capacity, harmonization of all relevant PCRs and the establishment of aligned pavement LCA framework are necessary for reliable environmental improvements. The availability of public background data can support both EPD development and GPP efforts, by providing transparency, inclusivity, and low costs of LCA. Greater automation, systems for data transfer and management, and increased stakeholder collaboration can also support GPP in a way that ensures environmental improvements of pavement materials and infrastructure.

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1. Introduction

Inclusion of environmental consideration into public procurement, also known as GPP, is gaining popularity worldwide (Akenroye et al., 2013; Bohari et al., 2017; Adham and Siwar 2012; Sanchez et al., 2013; Sparks 2018; Zhu et al., 2013). GPP is a practice of selection of products and services with lower life-cycle environmental impacts compared to the typically procured counterparts (European Comission, 2008). As such, GPP can incentivize improvement of environmental performance and increase the knowledge of sustainable production and consumption (Chiappinelli and Zipperer, 2017). In Europe, sectors of information technology equipment, road vehicles, and buildings have the legislation related to GPP (Antón and Díaz, 2014). In the domain of pavement infrastructure, recent GPP efforts indicate that environmental impacts are becoming an important consideration. In the Netherlands, environmental impacts based on pavement LCA are used as a basis to reduce bidding prices (Ministerie van Verkeer and Waterstaat, 2015). A pilot project in Belgium used 11 social and environmental indicators for bidding price reduction, however, the pilot did not include pavement LCA (Maeck and Redant, 2018). In the U.S.A., the State of California legislated ‘Buy Clean’ act, which requires EPDs for select building materials purchased on public

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projects beginning from 2020 (California Legislative Organization, 2017). Collected EPDs will be used to develop material-specific maximum global warming potential (GWP) values as benchmarks. From 2021, procured materials should demonstrate environmental impacts below the benchmark, while the use of pavement LCAs in bidding is planned for the future. The city of Portland, Oregon requires EPDs for concrete purchased on city construction projects starting from January 2020, with plans to create benchmarks like those in California by April 2021 (OCAPA and Oregon DEQ, 2016). Similar undertakings have been considered in Washington State and Minnesota (Carbon Leadership Forum, 2019; Minnesota Legislature, 2019a, 2019b), while the accompanying technical and administrative implementation frameworks are currently in development.

The motivation to achieve environmental improvements and emission reductions is underpinning GPP efforts. Emerging GPP initiatives in the U.S.A. rely heavily on the use of EPDs, creating urgency for industry and State agencies. In the building sector, the production of EPDs was incentivized through green building systems (Gelowitz and McArthur, 2016, 2017; Braune et al., 2007). However, in the domain of infrastructure, production of EPDs was mainly a bottom-up effort, initiated by material producers (Mukherjee and Dylla, 2017). The GPP legislation was initiated after most of the relevant EPD programs were developed. It is, therefore, worthwhile to investigate the fit of the existing EPD programs in GPP in a manner that is likely to produce desired environmental improvements.

To that end, the objective of this study is to investigate prerequisites, barriers, and path forward to the use of EPDs ensures environmental footprint reductions and that includes stakeholders in the environmental pursuits. Three roles of EPDs are analyzed: as a: 1) communication tool—current use of EPDs, 2) material procurement aid—aligned with legislation in California and Portland, Oregon, and 3) data source in LCA analysis with a broader scope—aligned with intended future development in California. Section 2 outlines the relevant background on EPDs, current implementation opportunities and challenges.

2. Background

2.1. EPDs and their use

Environmental labels communicate the environmental performance of products. International Organization for Standardization (ISO) standards defines type I, II, and III labels. Type I labels are awarded if the product satisfies multicriteria environmental performance and are third-party verified (ISO, 1999). Type II labels are self-declared claims on one indicator of choice, such as recycled content or energy consumption (ISO, 1999). Type III labels or EPDs report multiple environmental impacts reflective of a supply chain, calculated using LCA method per predefined rules known as PCRs (ISO, 2006). EPDs are third-party verified (ISO, 2006). Because of their underlying technical framework and verification, EPDs are commonly considered as the most comprehensive of the three label types (Simonen and Haselbach, 2012). PCRs provide specific guidelines for EPD development set forth by a program operator through the consensus of the key stakeholders. In recent years, multiple industries worldwide developed PCRs and EPDs for their products. Examples include products from food, chemical, horticultural, building industries, metals, detergents, materials, furniture, packaging, electronics, and others (Subramanian et al., 2012; Gelowitz and McArthur, 2017; Strazza et al., 2016; Santero and Hendry, 2016). EPDs can potentially be used in several capacities: as a communication tool, procurement aid, and as a data source, elaborated as follows.

EPDs provide a convenient and standardized means of communicating product-specific LCA results to users who may not possess LCA knowledge (Bergman and Taylor, 2011). Strömberg (2017) claimed that the key advantages of EPD's are the efficiency and cost-effectiveness of satisfying multiple customer requirements, as well as the ease of marketing and communication. As demand for EPDs is increasing worldwide, EPDs can help manufacturers increase their presence in the global market (Bergman and Taylor, 2011). EPDs enable producers to perform environmental disclosure while keeping their proprietary data confidential (da Silva et al., 2007). Producers can also use EPDs to identify the potential opportunities for internal production improvements (Braune et al., 2007), granted that consistent methodology is used.

In addition to being used as a communication tool, numerous sources also specify the potential use of EPDs in procurement. ISO 14025 indicates that EPDs can be used to help purchasers make informed decisions by considering environmental performance (ISO, 2006). EPDs have the potential to provide for a meaningful comparison of functionally equivalent products (Bergman and Taylor, 2011). Toniolo et al. (2019) investigated European EPDs developed under 20 program operators and showed the correlation between European National Action Plans (NAPs) with GPP principles and a high number of available EPDs (Toniolo et al., 2019). However, regardless of the recognized potential, the current use of EPDs in GPP is still limited (Ganassali et al., 2018). Common environmental criteria used in GPP include energy efficiency, water efficiency, toxic chemical content, and use of renewable resources (Testa et al., 2016). Although LCA can be used to calculate these parameters, its use to inform GPP is still uncommon (Igarashi et al., 2015; Parikka-Alhola, 2008; Testa et al., 2016b). Due to a lack of personnel with LCA knowledge, technical and economic burden of LCA, environmental impact analysis in support of GPP is typically simplified (Parikka-Alhola and Nissinen, 2012). As public authorities care about preserving non-discrimination and transparency, as well as the balance of cost, social, and environmental considerations, EPDs partially satisfy their GPP needs (Jelse and Peerens, 2018). Relatively high costs of EPD production can reduce competitiveness of smaller enterprises in GPP (Jelse and Peerens, 2018).

Currently, most construction material EPDs facilitate a business-to-business communication of cradle-to-gate environmental impacts. While this limits the scope, EPDs can be treated as building blocks and a data source in LCA with a broader scope (e.g., cradle-to-grave). The producers typically have limited control of their product after it leaves the gate. It is, therefore, reasonable for producers to pass cradle-to-gate results to practitioners who possess more reliable information about the product use (Santero and Hendry, 2016). As data collection and life cycle impact assessment (LCIA) are the most laborious parts of LCA, leveraging EPDs as a data source can facilitate and promote LCA (da Silva et al., 2007). Moreover, da Silva et al. (2007) argued that, as EPDs are based on standardized and transparent processes, they can provide for more transparency and consistency as data sources compared to commercial LCA databases. Strazza et al. (2016) evaluated the use of EPDs of glass and plastic bottles as data sources for cradle-to-grave LCA instead of using commercial LCA databases, and average bottle production parameters from the literature. In this study, EPDs were identified as preferable because of higher specificity, data quality, and avoidance of environmental impacts overestimation (Strazza et al., 2016).

2.2. Consistency and harmonization issues

Of late, EPD programs have grown significantly. However, the development of PCRs was largely done separately and often not in coordination among industries and organizations. The questions of consistency and comparability of EPDs produced under one PCR, as well as a lack of harmonization among PCRs that are related in the supply chain by co-products, have been raised in the literature.

Ingwersen and Stevenson (2012) argued that some PCRs include issues that can compromise comparability of the resulting EPDs and prevent users from making comparable claims. They have identified product category definition, the lack of common data sources, regional differences, and types of environmental claims as the potential areas of improvement (Ingwersen and Stevenson, 2012). PCRs with higher level of prescriptiveness provide for higher comparability of the resulting EPDs (Subramanian et al., 2012). Several studies were conducted to evaluate alignment between different EPD programs and investigate potential harmonization pathways. Subramanian et al. (2012) investigated a total of 11 PCRs for four product categories (i.e., dairy, horticultural products, wood particle board, laundry detergent) and concluded that differences exist in scope, reported impacts, general requirements, and purpose of PCR. The need for global harmonization of PCRs was emphasized because products are often used outside of the production country (Subramanian et al., 2012). Hunsager et al. (2014) reviewed 27 programs and identified several potential protocols for improved PCR alignment. Minkov et al. (2015) analyzed 39 programs and concluded that 75 percent satisfy ISO requirements. Gelowitz and McArthur (2017) compared 50 EPDs produced under 13 PCRs for building products and identified that over 80 percent of EPDs missed information required in ISO 14025, which obfuscated transparency and clarity. Authors identified inconsistencies in life cycle impact assessment methodology, environmental indicators, and background data sources (Gelowitz and McArthur, 2017). Mukherjee et al., (2020) identified harmonization, technical, and organizational challenges for PCRs of pavement materials. Harmonization approaches identified in the literature include mutual recognition among PCRs, as well as the development of more detailed guidelines for PCR development to supplement ISO 14025 (Minkov et al., 2015). Hunsager et al. (2014) emphasized the importance of the improved external third-party verification of EPDs. Improved stakeholder participation was also recognized as an important consideration for EPD program credibility (Minkov et al., 2015; Hunsager et al., 2014).

An overall literature agreement is that the improved consistency of EPDs produced under the same PCR and harmonization of PCRs of different industries are critical. Ultimately, the improved consistency and harmony among EPD programs is a key prerequisite for the efficient pursuit of environmental improvements. As indicated by Draucker et al. (2011), lack of consensus and harmonization among assessment methodologies may lead to division among stakeholders, lack of trust in the market, and the additional postponement in the improvement of environmental performance.

3. Methodology

The overarching goal of this study, shown in Fig. 1, is to determine frameworks and methods that ensure environmental improvements when EPDs are used in the domain of pavements and involve stakeholders in environmental pursuits. Based on ISO 14025, the purpose of EPDs is to facilitate the continuous market-driven environmental improvement of products. However, ensuring that the improvement will be achieved requires technical prerequisites regarding EPD comparability and PCR harmonization (Fig. 1). The current use of EPD as a communication tool can increase awareness of sustainability but does not guarantee improvements per se. To ensure environmental improvements for materials, consistent and comparable EPDs can be used as a procurement aid that informs material selection. Furthermore, to ensure environmental improvements for pavements while using EPDs as a data source, underlying PCRs should be harmonized. (Note that in this study, the improved comparability of EPDs pertains to EPDs produced under one PCR, while the PCR harmonization refers to reaching the consistency of PCRs of different products that are related in the supply chain—in this case, pavement materials.) As indicated in Fig. 1, a shift in EPD use from a communication tool to procurement aid and data source requires stricter prerequisites, however has the potential to provide for improvements on a broader scale. To that end, this study aims to define specific prerequisites, challenges, and, implementation pathways for the various uses of pavement material EPDs to ensure environmental improvements and engage stakeholders. By doing so, the role of EPDs is leveraged from the communication tool to procurement aid and a data source.

As an initial step, EPD programs of relevant pavement materials were reviewed to evaluate their mutual methodological consistency (Step 1a). Concrete EPDs available to-date were reviewed as a case study that demonstrates how the guidelines of PCR translate into EPDs (Step 1b). Subsequently, the perspectives of key stakeholders on the issues of EPD comparability and PCR harmonization were assessed as a part of a workshop at the American Center for Life Cycle Assessment (ACLCA) annual conference (Step 2). Lastly, to inform the use of EPDs to achieve environmental improvements for pavements, a cradle-to-grave pavement LCA product system was developed. The fit of EPDs and the potential to use pavement LCA in parallel with the current pavement design process were investigated (Step 3). Based on these steps, the key prerequisites, challenges, and opportunities to leverage the use of EPDs to achieve environmental improvements, both in the domain of materials and pavements, were identified. Accordingly, the potential implementation routes conducive to long-term environmental improvements and stakeholder collaboration following the current bottom-up initiatives were outlined.

4. North American PCRs of paving materials

This section summarizes the current EPD programs of the following pavement materials in North America: asphalt mixtures, concrete mixtures, cement, and aggregate, as these materials contribute to the significant portion of pavement material footprint. PCRs of other building materials (i.e., flat glass, mineral wool, structural steel, precast concrete, carbon steel reinforcing bars) are also available but were out of the scope of this study.

The PCR for asphalt mixtures was created in 2016 by the National Asphalt Pavement Association (NAPA) and is valid from 2017 to 2022 (NAPA, 2016). Stakeholders from the asphalt industry, public, and private owners of transportation assets were involved in the development (Mukherjee and Dylla, 2017).

The PCR for portland cement concrete was initially published in 2013 under Carbon Leadership Forum (CLF) and with the National Ready Mixed Concrete Association (NRMCA) as a program operator and stakeholders from concrete industry and academia (referred to concrete PCR v 1.1, hereafter) (Carbon Leadership Forum, 2013). This PCR lasted until March of 2019. The industry average EPDs for concrete were developed for the U.S.A. (NRMCA, 2016) and Canada (CRMCA, 2017). On the expiration, concrete PCR was updated in March 2019, with NSF International as a program operator (NSF International, 2019). The new concrete PCR is compliant to ISO 21930 (ISO, 2017) and has a 5-year validity period (referred to as Concrete PCR v 2.0, hereafter). This document was created through the collaboration of stakeholders from the building industry (i.e., manufacturers, organizations), users, Oregon Department of Environmental Quality (DEQ), and LCA experts.

The PCR for construction aggregates was issued in 2016 under

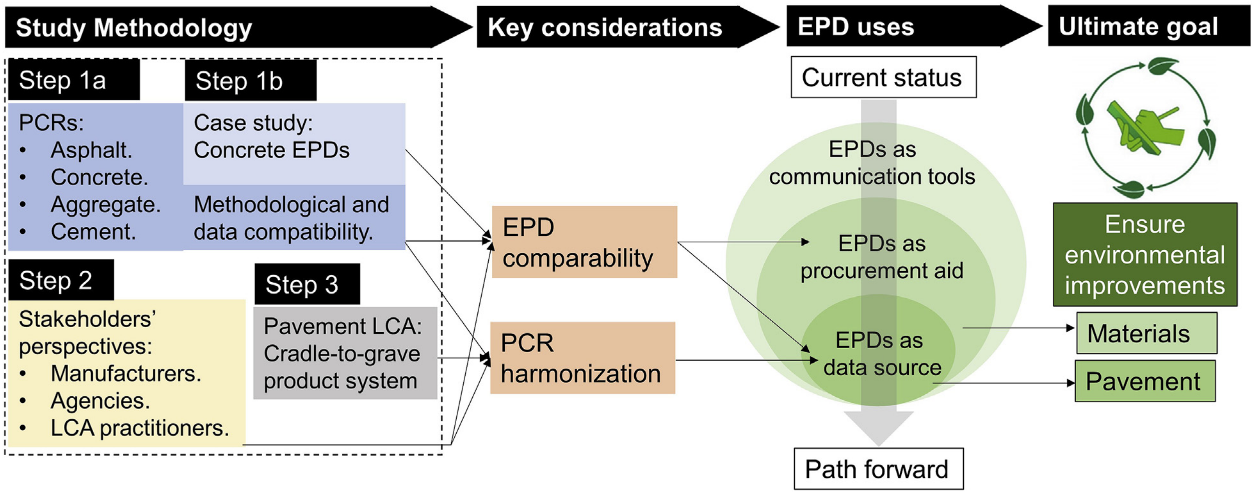

Fig. 1. Step-by-step study overview.

the American Society of Testing and Materials (ASTM) as a program operator (ASTM International, 2017). Construction aggregates include sand, gravel, crushed stone, crushed concrete, iron slag, steel slag, or any combination thereof. The interested parties involved in the PCR development were producers and suppliers of construction materials—aggregates, primarily, industry associations, and academia.

ASTM also served as a program operator for the two PCRs for cementitious products, issued in 2014, with a 5-year validity period. One PCR pertains to portland, blended hydraulic, masonry, mortar, and plastic cements (ASTM International, 2014a), while the other covers ground granulated blast furnace slag (i.e., slag cement) (ASTM International, 2014b). Industry average EPDs for portland and slag cement were also created by Portland Cement Association and Slag Cement Association (PCA, 2016; Slag Cement Association, 2015).

Additives, admixtures, and other chemicals were recognized as a data gap (NAPA, 2016). In Europe, the PCR for concrete admixtures was developed by Institut fur Bauen and Unwelt (IBU) and European Federation of Concrete Admixtures (EFCA) (IBU, 2014). Model European EPDs that represent conservative estimations of environmental impacts of admixtures production are available (IBU, 2014). Comparable efforts in the U.S.A. are yet to be undertaken. However, as concrete, asphalt, and their constituents are typically produced locally, establishing PCRs for these materials is likely prioritized over admixtures.

5. Consistency of PCRs

As evident from Section 4, PCRs for different materials were created by different entities and with different stakeholders involved. As no overarching authority was overseeing and harmonizing these efforts, some inconsistencies have emerged (Mukherjee et al., 2020). As stated earlier, EPD production was in part a bottom-up effort initiated by producers (Mukherjee and Dylla, 2017). However, in the case of concrete, EPD production was incentivized through green building systems relevant to vertical construction. For instance, one LEED v4 credit is awarded for the submission of 20 EPDs. One more LEED credit can be earned if the products that constitute at least 50 percent of cost demonstrate impacts below industry average in at least three categories. Therefore, the consistency and comparability of EPDs in the case of building products was likely a secondary concern. Additionally, purchasing considerations of the public and private sector also differ. Therefore, EPDs suitable in one context may not satisfy the requirements of the other.

Methodological compatibility and compatibility of data sources are discussed in the following sections, aiming to evaluate the potential suitability of EPDs in GPP, as well as a data source in pavement LCA in a way that provides for an unambiguous assessment of the environmental performance and potential benefits.

5.1. Methodological consistency

In the most general terms, the reviewed PCRs follow the same cradle-to-gate scope and include raw materials acquisition, transportation, and manufacturing (phases A1, A2, and A3). Cutoff criteria, impact assessment methodology, and mandatory reported impact categories closely correspond among the PCRs. Methodological differences among PCRs and their implications on the EPD comparability, compatibility as a data source, and pursuit of environmental improvements are discussed as follows.

Regarding use in procurement, the validity period of PCRs and EPDs is an important concern. All reviewed PCRs have a 5-year validity period. Cement, aggregate, and concrete EPDs developed under these PCRs also last for 5 years from the publishing date. Conversely, asphalt EPDs are valid until the end of the PCR's validity. The advantage of the approach taken by the asphalt industry is that there are no concurrently valid EPDs produced under different PCRs, which provides for comparability.

Regarding EPD use as a data source, the difference in the declared unit among the PCRs is noteworthy. The declared unit for concrete is volumetric (1 m^3), while the declared unit for asphalt is mass-based (a short ton). This difference likely stems from the units in which the material is typically purchased. If used in pavement LCA, EPDs may have to be complemented with the density to ensure mass balance. The declared units for aggregate and cement are mass-based. Table 1 presents a summary of the impact categories specified in different PCRs. As seen in Table 1, the required environmental impacts are the same in all PCRs. In addition to mandatory impact categories, the concrete PCR v 1.1 specifies several optional impact categories, which are not included in aggregate and cement PCRs. The concrete PCR v 2.0 specifies carbon sequestration as an optional impact category, however, the details on how this impact should be evaluated are not specified. Differences exist in reporting of energy and resource use among the PCRs.

Table 1
Impact categories and inventory terms specified in different PCRs.

	PCR	Asphalt	Concrete PCR v 1.1	Concrete PCR v 2.0	Aggregate	Portland cement	ISO 21930
Impact categories	Global warming potential	R	R	R	R	R	R
	Acidification potential	R	R	R	R	R	R
	Eutrophication potential	R	R	R	R	R	R
	Smog creation potential	R	R	R	R	R	R
	Ozone depletion potential	R	R	R	R	R	R
Energy consumption inventory	Nonrenewable fossil fuel energy	R*	R	R	R	R	R
	Nonrenewable nuclear energy		R		R	R	
	Renewable energy (solar, wind, hydro, geothermal)	R*	R	N	R	R	N
	Renewable energy (biomass)		R		R	R	
Resource consumption inventory	Non-renewable material resources	N	R	R	R	R	R
	Renewable material resources	N	R	N	R	R	N
	Fresh water consumption	R	R	R	R	R	R
	Non-hazardous waste	N	R	N	R	R	N
	Hazardous waste	N	R	N	R	R	N
Optional impact categories	Carbon emissions from biofuel consumption	N	O	N	N	N	N
	Energy from waste recovery	N	O	N	N	N	N
	Carbon sequestered in product	N	O	O	N	N	O
	Total waste disposed/recycled/reused	N	O	R	N	N	R
	Content declaration/chemical of concern	N	O	N	N	N	O
	Particulate matter emission	N	O	N	N	N	N

Note: R-requested, O- optional, N- not specified; *- fuels reported both as material and as energy.

For instance, the asphalt PCR does not specify waste reporting, due to the assumption that the asphalt production is a closed-loop process with no waste output. In other PCRs, waste production is reported as 'hazardous' and 'nonhazardous' waste or total waste, as shown in Table 1. The asphalt PCR does not prescribe reporting of renewable and nonrenewable material resources, while this assessment is part of aggregate, cement, and the concrete PCR v. 1.1. Renewable and nonrenewable energy consumption is mandated in all PCRs, either in separated categories shown in Table 1, or aggregated. The exception is the concrete PCR v 2.0, which requires only reporting of non-renewable energy and material consumption. Consequentially, while pavement material EPDs can potentially be used to estimate the environmental impacts in LCA analysis with a broader scope, energy, and materials inventory would be challenging. Table 1 also summarizes the requirements of ISO 21930, which is a new standard intended to facilitate consistent reporting of EPDs of building products. As seen in Table 1, mandatory impact categories of ISO 21930 match those of current PCRs. However, in terms of energy and material inventory, ISO 21930 is flexible, as the reporting of the use of primary, secondary resources, water, abiotic depletion potential, and waste are required but the respective impact categories are not accurately defined. This may cause further ambiguities in the assessment if EPDs are used as a data source.

Another methodological inconsistency that can have an impact on EPD use as a data source is the allocation of slag (Mukherjee et al., 2020). In aggregate PCR, steel slag aggregate is considered with the economic allocation, while in all other PCRs, slag is treated as a byproduct with no economic value, accounted through the upstream transportation. The PCR for steel products defines slag as a co-product and recommends system expansion (SCS Global Services, 2015). Slag is an example of a product that crosses boundaries of different industries that produce or use slag and, as such, should be treated with caution to avoid omission or double counting. This example illustrates the necessity to harmonize PCRs across the industry sectors that share system boundaries for adequate accounting in pavement LCA.

5.2. Consistency of data sources

LCA is data-intensive. Hence the data quality and selection of background data sources from PCRs directly translate into the reliability of EPD (Mukherjee et al., 2020). All reviewed PCRs require users to report the assessment of data quality in terms of technological, temporal, geographical representativeness, completeness, and reliability. The background data sources for the two concrete PCRs and asphalt PCR are listed in Table 2. In the aggregate and cement PCRs, background data sources are not specified. Differences in background data choices among PCRs relevant to EPD comparability and PCR harmonization are discussed as follows.

Concrete PCR v 1.1 recommends background data sources, while the PCR v 2.0 prescribes background data sources, as does the asphalt PCR. Prescribed background data sources provide for a higher level of consistency and comparability of EPDs (Subramanian et al., 2012; Minkov et al., 2015) and are thus favorable in GPP. When background data is prescribed, the results reported on EPD should reflect actual differences in the production process, which enables a sound assessment of environmental improvements. As the cement and aggregate PCRs do not address the background data, the comparability of the resulting EPDs can be compromised. In the asphalt PCR, flows that should be covered by primary (i.e., foreground) versus secondary (i.e., background) data are differentiated, which is recommended in Guidance to PCR Development (Minkov et al., 2015). This practice is not part of any of the other PCRs analyzed in this study.

The comparison of data sources in the current concrete and asphalt PCRs in Table 2 indicates a consensus on the background data for portland cement and transportation. Conversely, the prescribed data sources for other flows differ. Mukherjee et al., (2020) argued that while asphalt PCR prescribes public data sources, thereby prioritizing data availability and transparency, concrete PCR includes proprietary background data sources, which indicates the prioritization of data quality. It is also likely that proprietary databases provide higher convenience compared to public data sources. In the context of GPP, in which transparency, inclusiveness,

Table 2
Data sources in concrete and asphalt PCRs.

Prescribed vs. recommended	Concrete PCR (Carbon Leadership Forum, 2013)	Concrete PCR (NSF International, 2019)	Asphalt PCR (NAPA, 2016)	Data Ownership
	Recommended	Prescribed	Prescribed	
Portland cement	NREL (2012)	PCA (2016)	PCA (2016)	Material manufacturers (industry)
Fly ash	Considered as recovered material	Considered as recovered material	Not applicable	
Slag cement	LCI of Slag Cement, U.S.A. version 2003	Slag Cement Association (2015)	Cutoff rule	
Natural aggregate	ecoinvent or GaBi	ecoinvent 3.4. world version 2001	Marceau et al. (2007)	
Crushed aggregate	ecoinvent or GaBi	ecoinvent 3.4. world version 2001	Marceau et al. (2007)	
Admixtures	EFCA version 2005	EFCA, 2015 (IBU, 2014)	No data currently	
Water	Site specific data	ecoinvent 3.4.	Not applicable	Background data
Crude oil at refinery	Not specified	Not specified	NREL (2012)	
Natural gas at refinery	Not specified	Not specified	NREL (2012)	
Transportation	NREL or EPA	NREL (2012)	NREL (2012)	
Electricity generation	US EPA eGrid	ecoinvent 3.4. U.S.A. version 2015	Greet version 2015 vevers	
Electricity emissions	NREL (2012)	Not applicable	Not specified	
Site generated electricity	NREL (2012)	NREL (2012)	Not specified	

and low-cost play key roles, public background data sources may be preferential (Jelse and Peerens, 2018), assuming that the quality of the data is not compromised. Therefore, the development of quality public background data is a pivotal component to support GPP of pavements and pavement materials. Initiatives such as Federal LCA Commons focused on making Federal LCA data publicly available can underpin and support GPP efforts in numerous domains (USDA- Research Education and Economics, 2018). Table 2 also includes the data ownership, representing the likely source of the data if stakeholder involvement is a priority. For materials, manufacturers are the data owners, while the common flows such as water, transportation, and energy can be considered as background data.

6. Review of concrete EPDs

The concrete industry started developing EPDs before other material industries. When this research was conducted, numerous publicly available concrete EPDs produced under the PCR v 1.1 were available. In this section, those EPDs were reviewed and assessed in terms of data quality and background data sources to evaluate their comparability and suitability in GPP. The review included a total of 77 available EPDs documents, with over 1200 concrete mixtures from ready mix plants in North America. Most EPDs report impacts of multiple concrete mixtures produced in one facility. For this analysis, 77 EPDs were clustered into 31 groups. Each group included all available EPDs pertinent to one plant, created by one EPD developer, using one set of background data. Such clustering provided for the analysis of background data choices, regardless of the number of mixtures included in EPD.

6.1. Data quality

Fig. 2 shows five data quality categories of the background data used in different EPD groups, namely technological, temporal, geographical representativeness, completeness, and reliability (Carbon Leadership Forum, 2013). The data quality is reported by the EPD developer and evaluated through the third-party verification process. Ratings on the vertical axis follow the grading system: poor = 1, fair = 2, good = 3, very good = 4. The numbers associated with each flow in the legend of Fig. 2 indicate the number of EPD groups included in the analysis.

The technological representativeness, completeness, and reliability of the data assessment shown in Fig. 2 vary from 'good' to 'very good' (grades from 3.18 to 3.53 for all flows). On the other hand, data quality in terms of geographical and temporal representativeness ranges from 'fair' to 'very good' and is generally lower than the previous three categories (grades 2.87 and 2.97 on average for all flows). Variability in reported data quality expressed as a standard deviation of grades ranges from 30 percent of the grade up to one grade. For the technological representativeness of fuels and slag cement, and completeness for the fuels, there was no variation in the reported data quality, however, this is likely due to the limited number of EPD groups reporting data quality for slag cement and fuels. The analysis of reported data quality indicates that the room for improvement exists in the geographical and temporal representativeness of the background datasets. This may be because the available databases generally originate from Europe. Additionally, the relatively low temporal representativeness may indicate that some data is obsolete. These findings underscore the need for the development of the quality U.S.A.-based datasets with regular update mechanisms.

6.2. Data sources

Fig. 3 presents the distribution of the data sources used to develop concrete EPDs. The number listed in the title of each subchart shows the number of EPD groups included in the analysis—corresponding to the number listed in the legend of Fig. 3. As seen in Fig. 3, the data for aggregate primarily originated from the ecoinvent and GaBi. One EPD group utilized aggregate EPD, which provides an example of EPDs of material constituents used as data sources in EPDs of composite materials. For portland cement, the most EPD groups used GaBi. Three EPD groups relied on PCA's industry average EPD (PCA, 2016). In one EPD group, primary data for cement production was used, as the facility produces both cement and concrete. For slag cement, 80 percent of EPDs used Slag Cement Association industry average EPD (Slag Cement Association, 2015). However, the use of slag cement was reported in only 10 EPD groups. GaBi was the most frequently occurring data source for water. Although water consumption is reported in every EPD, the data for water processing has been reported in 23 out of 31 EPD groups. The data for admixtures largely originates from EFCA model EPDs (IBU, 2014), while some EPDs developed by BASF Chemicals used the combination of GaBi and the primary BASF proprietary data for admixtures. Electricity, fuels, and transportation data are important parts of LCA for most common products. In most of the analyzed EPDs, electricity data sources were ecoinvent and GaBi.

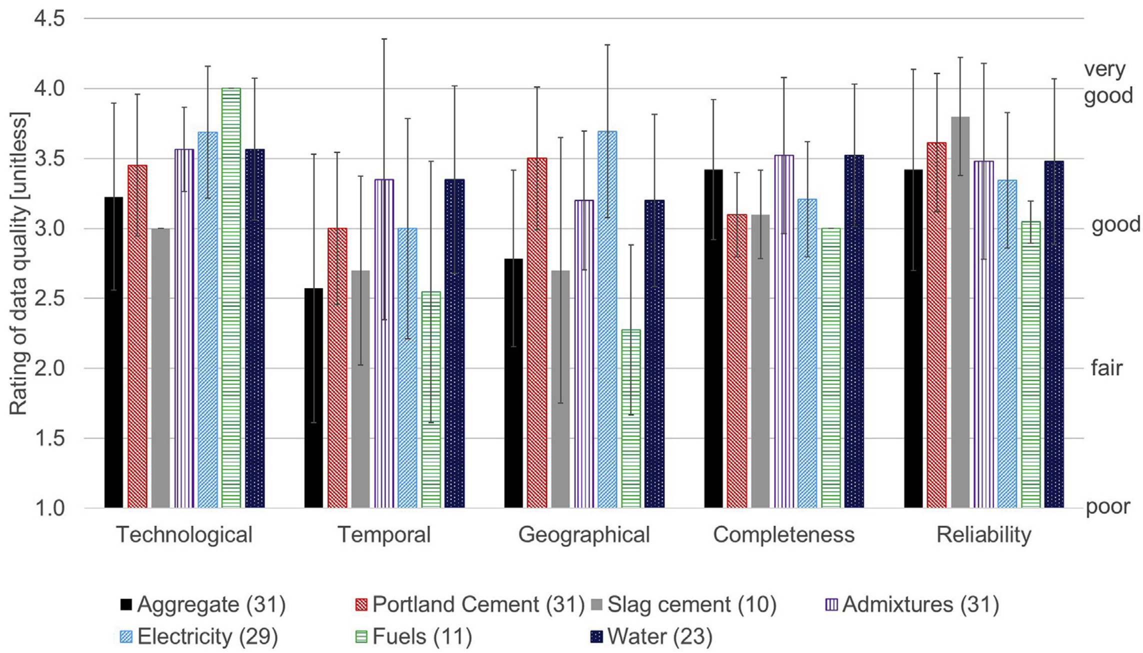

Fig. 2. Assessment of data quality for concrete EPDs.

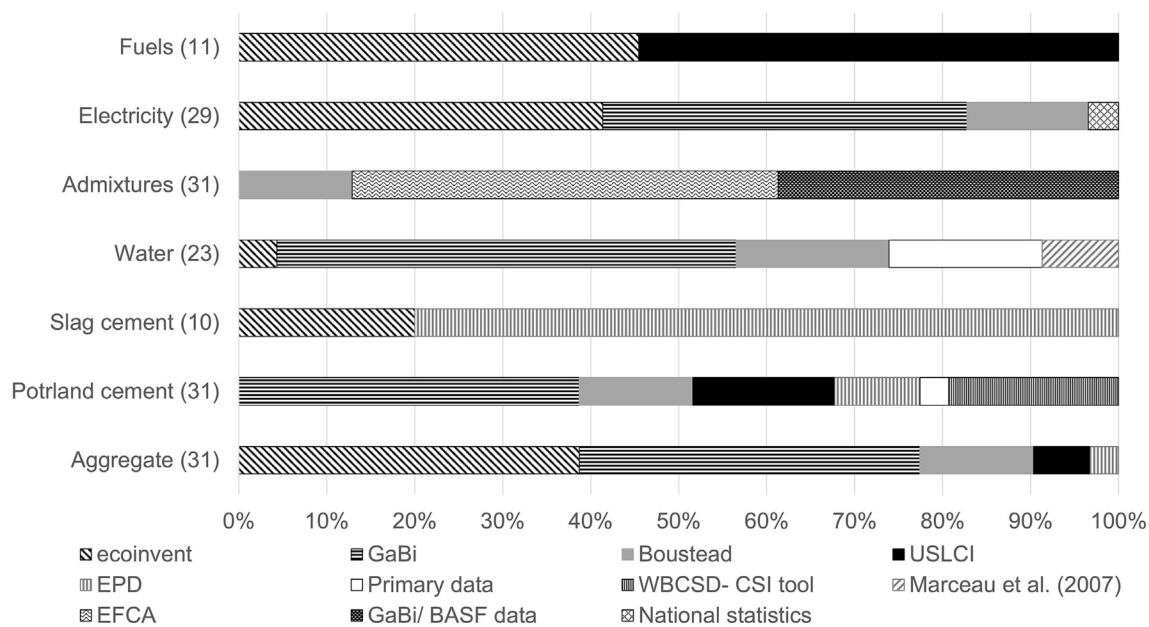

Fig. 3. Use of data sources used to develop concrete EPDs.
Note: *The data category 'EPD' pertains to facility-specific aggregate EPD in the case of aggregate, industry average EPD in the case of Portland cement* (PCA, 2016)*, and industry average EPD in the case of slag cement* (Slag Cement Association, 2015).

USLCI database was most used for fuels, followed by ecoinvent. Data sources for fuel were reported for only 11 out of 31 EPD groups, therefore this assessment may be incomplete.

The results summarized in Figs. 3 and 4 indicate that considerable variability exists in both data sources and data quality among EPDs produced under concrete PCR v 1.1. As a result, the comparability of these EPDs may be hindered. The difference in environmental impacts may stem from the difference in production efficiency or from the variations in the underlying data. Accordingly, the actual impact reductions resulting from production improvements cannot be guaranteed by these EPDs, which may lead to poorly informed GPP decisions. As the concrete PCR v 2.0 prescribes the background data, it is expected that the comparability of the future EPDs will be improved. Nonetheless, some of these older EPDs are still valid and their use in procurement should be performed with caution.

7. Stakeholders' perspectives

Communication with stakeholders during the development of PCR has been identified as an important area of improvement for current PCRs (Minkov et al., 2015; Hunsager et al., 2014). This

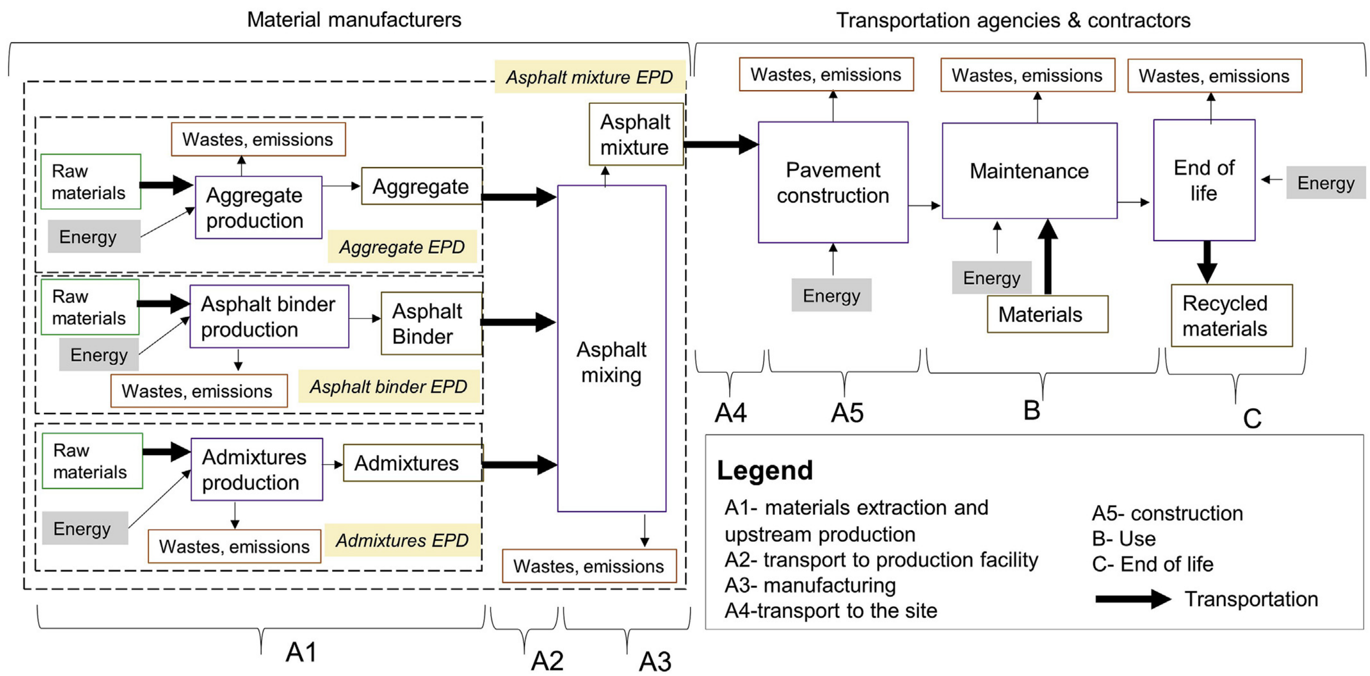

Fig. 4. An example of asphalt pavement product system for LCA for cradle-to-grave scope.

section summarizes the discussion with three stakeholder groups at the ACLCA workshop: material manufacturers, public government agencies, and LCA consultants. Stakeholders perspectives on the current EPD programs and important future developments were gathered using the following questions:

- What does your stakeholder group care about when it comes to EPDs and their use in GPP?
- What issues with EPDs exist that concern your stakeholder group?
- What issues do you consider the most urgent to address?
- What solutions do you propose for moving forward?

After 30-min discussions in breakout groups, representatives of each group reported the key discussion points, summarized as follows.

7.1. Industry (material manufacturers)

Material producers want EPDs to be reflective of continuous improvements in their production efficiency and emissions reduction. Additionally, the producers expect that their production improvements demonstrated through EPDs will be rewarded at the market. Current EPDs, however, report the footprint of the production at one point in time (Bergman and Taylor, 2011) and do not report relative improvements. EPDs last up to 5 years, which is a relatively long period, considering that production changes can be made more frequently. Accordingly, there is a need for tools and systems that enable EPD updates in a time- and cost-effective fashion. An optimization feature, to inform material manufacturers of ‘hot spots’ and improvement opportunities, is currently not available in EPD software packages, despite the manufacturers’ interest.

Industry representatives stated that the fairness of product representation is an important concern. The representativeness can be improved by specifying appropriate performance characteristics of a product, making sure that PCRs reflect industry dynamics, level of comprehensiveness required, and by harmonization of PCRs. Increasing the specificity of material’s performance metrics required in PCRs is expected to provide for more appropriate product representation and improved comparability of EPDs. Additionally, simplifying EPD formatting can also improve comparability and ease of communication. To improve and facilitate the verification process, EPD software packages should break a procedure into smaller elements and provide several checkpoints to validate if the results are within a reasonable range. The current legislation specifies the use of facility-specific EPDs (California Legislative Organization, 2017), while the product-specific EPDs may be more applicable in GPP and product selection. The tradeoff between comprehensiveness and level of effort to produce EPDs was also discussed. The need for time, financial resources, and staff are also recognized as a crucial need.

7.2. Government agencies

The representatives of government agencies recognized the need to improve the consistency and comparability of EPDs. Potential solutions they proposed include the prescription of consistent background datasets and making sure that the products are represented by the appropriate performance metrics. Agency representatives argued that EPD programs should be reflective of the geographic specificities and local material production. Agencies would like to have the capability of assessing tradeoffs and making decisions between the actions that can be taken now—pertinent to material selection, design selection, construction versus those that can be performed in the future phases—maintenance, use, end-of-life. Agencies are also concerned with network-level impacts, whereas the use of EPDs is mainly focused on material cradle-to-gate impacts specific to the project level. To that end, EPDs are perceived as not applicable to inform decisions on a larger scale, unless the systematic long-term collection is undertaken and put into perspective through LCA with a broader scope. However, it recognized that short-term decisions on material and pavement design selection also influence pavement performance throughout life. The use of EPDs to assess new technologies and foster innovation is seen as rigid because the engineering performance of the new materials must be established first. Agencies are interested in identifying material constituents and processes with high environmental impacts for which informed material selection can create sizeable benefits. The efforts of EPDs collection were acknowledged as important for the assessment of local material production. The use of EPDs as a data source for pavement LCA with cradle-to-grave scope is perceived as feasible. However, the comparison of multi-material designs (e.g., concrete versus asphalt pavement design) necessitates harmonization among EPD programs of these materials based on industry-wide consensus. A broader industry consensus among EPDs programs is identified as a key priority for successful environmental reductions using EPDs.

7.3. LCA consultants

The LCA consultants are concerned about EPD comparability. They acknowledge that the consistent prescribed background data to produce EPDs is a key element towards improved consistency and comparability and that PCR harmonization is a necessary next step. Nationwide PCR programs from Europe were identified as examples of how PCR consistency can be achieved. Currently, EPDs are produced one-by-one and the production takes a substantial effort and resources. Automation of EPD production and parts of the review and verification process is expected to reduce costs per EPD, increase the number of available EPDs, and improve their consistency. This is aligned with the needs of industry, as such systems would also facilitate the continuous production assessment, EPD updates, and improvement credits. In Europe, automation efforts were made because of policies and legislation (top-down), similar to nationwide PCR programs. In the U.S.A., however, EPD production started from the bottom-up, while the legislation was introduced afterward and, for now, solely at the State or city level. Additionally, LCA practitioners recognized the need for education of EPD users—primarily material producers and agencies—on how to interpret EPDs and make educated decisions based on their content.

8. Pavement LCA

Interests to improve the sustainability of pavement infrastructure throughout the life cycle have increased in the last decade (Van Dam et al., 2015). LCA was recognized as a suitable methodology to quantify the environmental impacts of pavements, however, its current use is mainly in research and not in the decision-making (Butt et al., 2015). The overarching conclusion of the two review studies is that considerable variability exists in LCA elements such as scope and functional unit, LCA tools, and background data (Santero et al. 2010, 2011; AzariJafari et al., 2016). The Federal Highway Administration (FHWA) developed the Pavement LCA Framework in 2016 (Harvey et al., 2016). The FHWA Sustainable Pavements Roadmap from 2017 specified that the lack of reliable, affordable, and regionally-specific input data is as a major obstacle for pavement LCA implementation in the (FHWA, 2017). As pavement infrastructure is typically public, important considerations of public procurement, such as non-discrimination and transparency, apply to pavements (Jelse and Peerens, 2018; Maeck and Redant, 2018). As specified in Section 7, agency practitioners recognize that materials are an important component of the pavement life cycle, however, their interests also include subsequent life-cycle phases, as well as the pavement network. Accordingly, the investigation of the pavement LCA framework and data sources for cradle-to-grave analysis has merit. Potential data sources for pavement LCA reflective of the ownership of the data, transparency, cost-effectiveness, and environmental improvements are discussed as follows.

Fig. 4 shows a simplified schematic of the asphalt pavement product system, with the data ownership specified at the top. As seen in Fig. 4, the material manufacturers control and own the data on material production (i.e. phases A1–3). The life cycle stages beyond material production (i.e. phases A4–C) include construction, maintenance and rehabilitation (M&R), and end-of-life (EOL) and fall under the responsibility of transportation agencies and contractors executing construction activities. The use phase is excluded from this scheme because a) the models and data pertinent to the aspects of the use phase are still underdeveloped (Santero et al., 2011; AzariJafari et al., 2016), and b) for comparative assertions, it can be assumed that the compared designs would present the equivalent use phase impacts. Following the data ownership in Fig. 4, fit of EPDs for material production phases in pavement LCA is analyzed further.

The production of each material constituent is enclosed by a dashed box in Fig. 4, which indicates a system boundary that would be used for an EPD. Production of material constituents such as aggregate, asphalt binder, and admixtures, as well as the engineered material such as asphalt mixture can be represented by EPDs, as shown in Fig. 4. In the case of concrete pavements, EPDs for aggregate, cement, and admixtures can be used in the product system and/or in an EPD for a concrete mixture. There are several advantages of EPDs as material data sources in pavement LCA over proprietary data sources. First, as pavement infrastructure is typically public, important considerations of public procurement, such as non-discrimination and transparency, apply to pavements (Jelse and Peerens, 2018; Maeck and Redant, 2018). EPDs are publicly available or provided by material producers upon a request, which makes them more accessible to agencies compared to proprietary data sources. Second, pavement materials are typically engineered and locally produced, while the LCIA data from the commercial databases may not appropriately reflect local production and specific mixture designs. Third, the use of EPDs includes material producers in environmental initiatives, enabling them to disclose their production impacts, while keeping proprietary data confidential, and encouraging improvements along the supply chain. Lastly, since EPDs are already produced and included in existing GPP efforts, it is worthwhile leveraging the existing momentum to build the frameworks for efficient data transfer and pursuit of environmental improvements. A disadvantage of EPDs is that they aggregate a life-cycle inventory into a handful of mid-point indicators, which can undermine the details of the supply chain.

Fig. 4 also indicates that flows such as transportation (i.e., thick black arrows) and energy (i.e., gray rectangles) are common for multiple life cycle phases and production of various constituents. These flows are typically considered as background data. The proprietary databases are often used in LCAs for these common flows because of the convenience and perceived data quality. Disadvantages of the proprietary databases, however, are cost and the lack of transparency. As stated in Section 5 regarding PCR development, the need for reliable and transparent public data sources is also the key need when it comes to pavement LCA and initiatives such as Federal LCA Commons can play a key role in deployment (USDA, 2018).

From a technical perspective, to integrate EPDs into pavement LCA, all combined LCA analyses must be consistent regarding methodological and data choices. That necessitates the harmonization of all relevant PCRs in terms of all relevant methodological elements, as well as the alignment of pavement LCA with the harmonized PCRs. Specifically, methodological choices include the impact assessment method, allocation, data consistency for primary and secondary data sources, treatment of proxies, chosen impact categories. The choice of background data sources is critical in this regard. The same harmonized background data must be used in all EPDs and pavement life cycle phases following material production to ensure for the technically sound assessment. Ostensibly, the implementation of this framework heavily depends on stakeholders' consensus and efficacious data collection and transfer. Building information model (BIM) is an example of a system that can facilitate the collection, storage, and transfer of environmental data (i.e. EPDs and other data of interest)—in addition to parameters (i.e., cost, material quantities, etc.) that are typically collected by the agencies.

9. Potential implementation routes

Based on the state-of-the-art in pavement material EPD programs (Sections 5 and 6), stakeholders' perspectives (Section 7), and suitability of EPDs in pavement LCA (Section 8), the potential implementation routes were identified and outlined in Fig. 5. The goal of this process was to leverage EPDs from the application as a communication tool—present use—toward the use as material procurement aid a—envisioned in the current legislation and a data source in pavement LCA. The scheme in Fig. 5 is conducive to continuous and long-term environmental improvements, which are the key to the successful adoption of green practices (Lundberg and Marklund, 2012).

9.1. Step 1 — using EPDs as a communication tool

Step 1 is based on the use of EPDs as a communication tool, like the current work done in California for selecting building materials. In this phase, EPDs can be encouraged or required as a part of bidding documentation, however, no decisions should be made based on their content. The main outcome of this phase is the education of stakeholders on EPDs and environmental performance, expedited production of EPDs, and increased stakeholder communication. This phase would also entail the improvements of systems for data collection within agencies and automation of EPD tools by the industry.

9.2. Step 2 — using EPDs as a material procurement aid

In Step 2, EPDs can be leveraged as a material procurement aid and used to develop benchmarks. However, the advancement to Step 2 is contingent on improved comparability of EPDs. That can be done by making PCRs more prescriptive (Minkov et al., 2015) regarding methodological and data choices. PCR's prescriptiveness also relates to the product representation: by requiring the appropriate performance characteristics on EPDs, functionally equivalent products can easily be identified and informed comparisons made. It is assumed that each PCR program operator will undertake the necessary efforts to make their PCR prescriptive, such that resulting EPDs are consistent and comparable. Educational efforts started in Step 1 can improve stakeholders' knowledge and encourage their involvement in PCR updates, leading to improved credibility and quality of PCRs.

In Step 2, the procurement practice can incentivize use of materials which demonstrate environmental impacts below the predefined benchmark. In that case, the development of benchmarks is a critical component. Benchmarks can be developed using industry-average EPDs—currently industry average EPDs for concrete, portland cement, and slag cement are available (CAC, 2016; NRMCA, 2016; PCA, 2016; Slag Cement Association, 2015). Alternatively, benchmarks can be set using previously collected EPDs. The use of industry averages as benchmarks may be convenient, however, it may not reflect the local material production. Using previously collected EPDs to define benchmarks may yield more accurate estimations of local production, but it may be resource-intensive and necessitate the advanced data management.

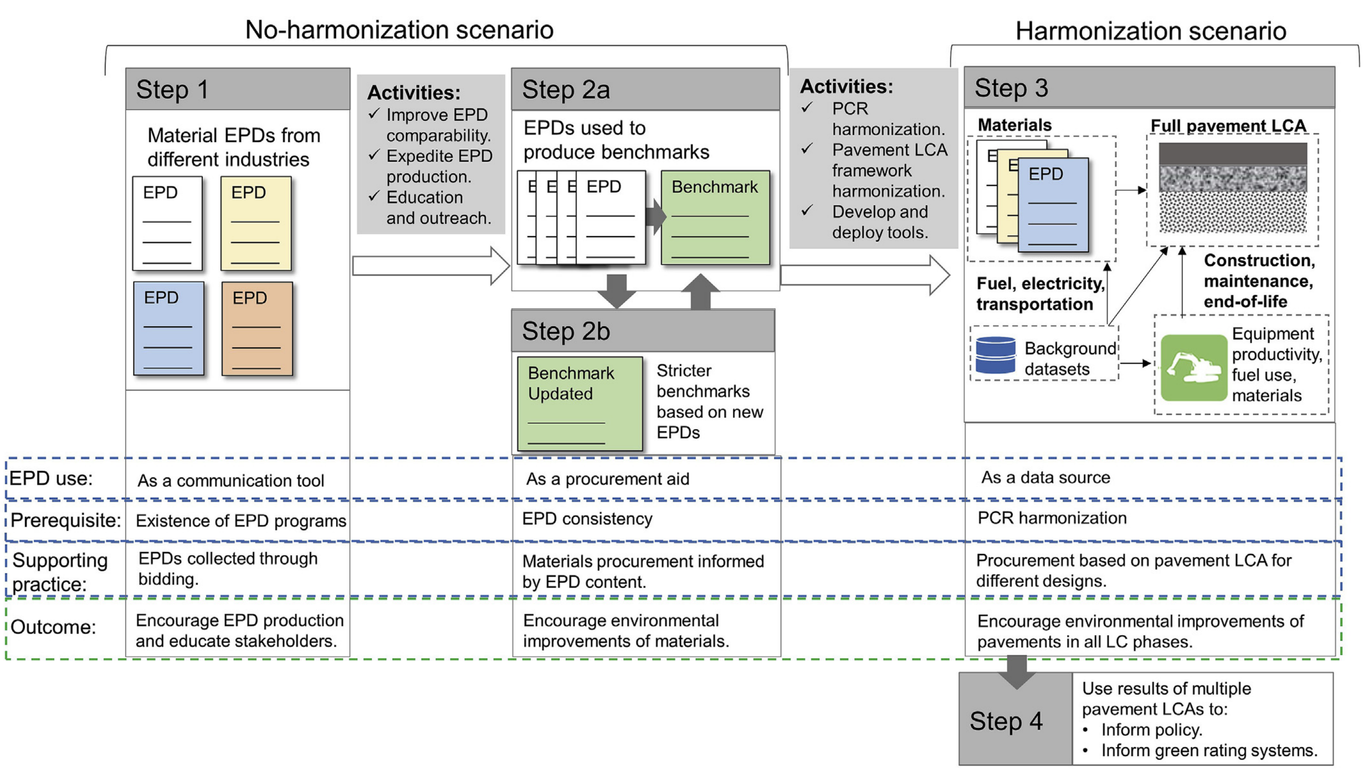

Fig. 5. Potential step-by-step implementation routes that leverage the role of EPDs and provide for improvements of environmental performance of materials and pavements.

Benchmarks must not only be material-specific but also be divided into different functional categories, which ties back to the appropriate product representation. For each functional category of every material, a representative sample of EPDs should be collected to develop relevant benchmark. Benchmarks must be realistic and set such that a significant percentage of the market can attain them (Carbon Leadership Forum, 2019). Step 2a denotes a gradual development of stricter benchmarks to encourage continuous improvement.

9.3. Step 3 — using EPDs as a data source for pavement LCA

While the Steps 1 and 2 focus on EPD collection and materials selection informed by the environmental performance, in Step 3 the analysis is expanded to pavements. Setting forth the systems and tools for cradle-to-grave pavement LCA can inform pavement design selection considering environmental performance. That is a comprehensive undertaking, with a lot of space for inconsistencies that can lead to unsound and inappropriate comparisons, controversy, and, ultimately, poorly informed decisions. Therefore, before proceeding to Step 3, several prerequisites should be satisfied.

Fig. 5-Step 3 shows a simplified cradle-to-grave pavement LCA product system, analogous to that in Fig. 2, with material flows represented by EPDs and common background data in every LCA phase. The prerequisite for Step 3 is the harmonization of PCRs for the materials that are used jointly on paving projects. As previously discussed in Fig. 2, harmonized background datasets figuring in all EPDs and in pavement LCA should be established in this step. Furthermore, the advantages of common public background datasets in support of the low cost of the analysis and transparency elaborated in Section 6 and 8 is applicable in Step 3. Lastly, open-source pavement LCA tools based on the established pavement LCA framework, connected to the identified public background datasets are also needed in Step 3. DOTs can use the open-source tool with generic material and construction inputs to develop a benchmark for pavement design for bidding. Contractors would use the same tool to develop their estimations of pavement environmental impacts using specific data (e.g., construction estimates, material-specific EPDs, etc.) and demonstrate that their design meets the benchmark defined by DOT. Transparent benchmark development and fair comparison of bids would facilitate GPP acceptance and expedite its adoption. Additionally, this approach can promote the improvement of pavement footprint in all life cycle phases.

Step 4 would emerge from Step 3. The results of multiple pavement LCAs produced under the consistent framework and background data can be used to assess the environmental performance of different solutions (e.g., different recycled materials) and to inform specifications. Additionally, results of multiple LCAs can be used to provide a more substantial basis for awarding environmental credits in pavement green rating systems.

Finally, it is noteworthy that Steps 3 and 4 require harmonization among PCRs of different materials, which is contingent on the industry consensus. If industry collaboration is not established, these steps cannot be developed in a technically sound manner, which can hinder the efficient improvements of environmental performance of pavement infrastructure.

10. Future developments

In addition to identified key developments, a few more potential future initiatives should be considered.

The appropriate definition of a product was mentioned as a key element of EPD comparability in Section 7 and 9. Based on the current PCRs, asphalt mixtures are defined using production temperature, while concrete mixtures are defined through compressive strength. However, other material parameters also merit consideration. For instance, structural concrete used in vertical construction is typically not exposed to the environment, and compressive strength is sufficient for the structural design. On the other hand, for paving concrete, in addition to mechanical performance, durability parameters are critical (Hooton, 2019), as well as workability and air entrainment. Material specifications for both asphalt and concrete are rapidly moving from prescriptive to performance-based (Weiss et al., 2018). To ensure the relevance, EPD programs should closely follow the developments in other material engineering domains.

To-date PCRs pertain to concrete and asphalt mixtures produced in plants. However, paving concrete and asphalt are often produced in on-site portable plants, used on a project basis. The impacts of plant transportation, assembling, and disassembling should be considered in EPD, however, this type of production is not currently addressed.

11. Conclusions

This study investigated the possible use of pavement material EPDs as procurement aid and data source in a manner that ensures environmental improvements and involves stakeholders in the environmental pursuits. Through the review of current PCRs and EPDs, communication with stakeholders, and analysis of cradle-to-grave pavement LCA, relevant prerequisites, challenges, and implementation routes were identified.

The use of EPDs to inform material procurement can ensure environmental footprint reduction only if EPDs are consistent and comparable, which stems from the PCR's prescriptiveness. PCRs that prescribe background data, provide accurate product description, specify flows represented with foreground versus background data, have the potential to facilitate environmental improvements and well-informed decisions. Tools for streamlined EPD development and procurement practices that reward production improvements can also play a key role in efficient material footprint reduction.

EPDs can be favorable data sources for materials in pavement LCA compared to proprietary databases for achieving environmental improvements. EPDs reflect local production, include the industry in sustainability-related initiatives, encourage improvements in the supply chain, and provide for both transparency and privacy of proprietary data. The use of EPDs as a data source in pavement LCA can ensure improvements in the environmental footprint of pavements only if the overall harmonization of all relevant PCRs is achieved. Furthermore, all methodological components of pavement LCA should also be aligned with that of harmonized PCRs. Tools and systems for streamlined and consistent analysis and data transfer are crucial components of this undertaking.

The availability of quality U.S.A.-specific public background data sources with consistent update mechanisms should encourage overall harmonization and reduce the cost of LCA and EPD production. Moreover, public background data can provide for transparency and inclusivity, which are key considerations of GPP. Lastly, following the bottom-up approach initiated in the U.S.A., stakeholder involvement is critical. Education and enhanced communication across the supply chain are necessary for thorough data collection and efficacious improvements.

CRediT authorship contribution statement

Milena Rangelov: Data curation, Conceptualization, study conception and design, data collection, Formal analysis, analysis

and interpretation of results, Writing - original draft, draft manuscript preparation and revision. **Heather Dylla:** Data curation, Conceptualization, study conception and design, data collection, Formal analysis, analysis and interpretation of results, Writing - original draft, draft manuscript preparation and revision. **Amlan Mukherjee:** Data curation, data collection, Formal analysis, analysis and interpretation of results, Writing - original draft, draft manuscript preparation and revision. **Nadarajah Sivaneswaran:** Formal analysis, analysis and interpretation of results, Writing - original draft, draft manuscript preparation and revision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

Adham, K., Siwar, C., 2012. Empirical investigation of government green procurement (GGP) practices in Malaysia. OIDA Int. J. Sustain. Dev. 4, 77–88.
Akenroye, T.O., Oyegoke, A.S., Eyo, A.B., 2013. Development of a framework for the implementation of green public procurement in Nigeria. Int. J. Procure. Manag. 6, 1–23.
Antón, L.Á., Díaz, J., 2014. Integration of LCA and BIM for sustainable construction. Int. J. Soc. Behav. Educ. Econ. Bus. Ind. Eng. 8, 1378–1382.
ASTM International, 2014a. Product Category Rules for Preparing Environmental Product Declaration for Portland, Blended Hydraulic, Masonry, Mortar, and Plastic (Stucco) Cements.
ASTM International, 2014b. Product Category Rules for Slag Cement UN CPC 374.
ASTM International, 2017. Product Category Rules for Preparing an Environmental Product Declaration for Construction Aggregates: Natural Aggregate, Crushed Concrete, and Iron/Steel Furnace Slag.
AzariJafari, H., Yahia, A., Amor, M. Ben, 2016. Life cycle assessment of pavements: reviewing research challenges and opportunities. J. Clean. Prod. 112, 2187–2197.
Bergman, R., Taylor, A., 2011. EPD-environmental product declarations for wood products—an application of life cycle information about forest products. For. Prod. J. 61, 192–201.
Bohari, A.A.M., Skitmore, M., Xia, B., Teo, M., 2017. Green oriented procurement for building projects: preliminary findings from Malaysia. J. Clean. Prod. 148, 690–700.
Braune, A., Kreißig, J., Sedlbauer, K., 2007. The use of EPDs in building assessment–towards the complete picture. Sustain. Constr. Pract. 299–304.
Butt, A.A., Toller, S., Birgisson, B., 2015. Life cycle assessment for the green procurement of roads: a way forward. J. Clean. Prod. 90, 163–170.
California Legislative Organization, 2017. Buy Clean California Act [3500 - 3505].
Canadian Ready Mixed Concrete Association (CRMCA), 2017. CRMCA Member Industry-Wide EPD for Canadian Ready-Mixed Concrete.
Carbon Leadership Forum, 2013. Product Category Rules for Concrete.
Carbon Leadership Forum, 2019. Buy Clean Washington: Study Overview. Carbon Leadership Forum.
Cement Association of Canada (CAC), 2016. Environmental Product Declaration (EPD): General Use (GU) and Portland- Limestone (GUL) Cements.
Chiappinelli, O., Zipperer, V., 2017. Using public procurement as a decarbonisation policy: a look at Germany. DIW Econ. Bull. 7, 523–532.
da Silva, L.S., Grecea, D., Krigsvoll, G., Gervásio, H., Blok, R., Aktuglu, Y., 2007. LCA databases (EPD vs Generic data). Sustain. Constr. Integr. Approach to Life-time Struct. Eng. 13.
Draucker, L., Kaufman, S., ter Kuile, R., Meinrenken, C., 2011. Moving forward on product carbon footprint standards. J. Ind. Ecol. 15, 169–171.
EFCA, 2015. Environmental Product Declaration as Per ISO 14025 and EN 15804. Concrete Admixtures- Air Entrainers. EFCA. Declaration number: EPD-EFC-20150086-IAG1-EN.
European Comission, 2008. Public Procurement for a Better Environment. s.l. : Communication from the Commission to the European Parliament, the Council, the European Economic and Social Commitee and the Committee of the Regions. Brussels, Belgium: European Commission.
FHWA, 2017. Sustainable Pavements Program Road Map. FHWA-HIF-17-029. U.S. Department of Transportation, FHWA, Washington, DC, USA.
Ganassali, S., Lavagna, M., Campioli, A., Saporetti, S., 2018. Green public procurement and construction sector: EPD and LCA based benchmarks of the whole-building. In: Designing Sustainable Technologies, Products and Policies. Springer, pp. 503–513.
Gelowitz, M.D.C., McArthur, J.J., 2016. Investigating the effect of environmental product declaration adoption in LEED® on the construction industry: a case study. Procedia Eng 145, 58–65.
Gelowitz, M.D.C., McArthur, J.J., 2017. Comparison of type III environmental product declarations for construction products: material sourcing and harmonization evaluation. J. Clean. Prod. 157, 125–133.
Harvey, J.T., Meijer, J., Ozer, H., Al-Qadi, I.L., Saboon, A., Kendall, A., 2016. Pavement Life Cycle Assessment Framework (FHWA-HIF-16-014). Federal Highway Administration (FHWA), Washington, DC, USA.
Hooton, R.D., 2019. Future directions for design, specification, testing, and construction of durable concrete structures. Cement Concr. Res. 124, 105827.
Hunsager, E.A., Bach, M., Breuer, L., 2014. An institutional analysis of EPD programs and a global PCR registry. Int. J. Life Cycle Assess. 19, 786–795.
Institut Bauen and Umwelt (IBU), 2014. Product Category Rules for Construction Products Part B Requirements on the EPD for Concrete Admixtures.
Igarashi, M., de Boer, L., Michelsen, O., 2015. Investigating the anatomy of supplier selection in green public procurement. J. Clean. Prod. 108, 442–450.
Ingwersen, W.W., Stevenson, M.J., 2012. Can we compare the environmental performance of this product to that one? An update on the development of product category rules and future challenges toward alignment. J. Clean. Prod. 24, 102–108.
ISO, 1999a. ISO 14024. Environmental Labels and Declarations- Principles and Procedures (Type I Environmental Labeling). Int. Organ. Stand. Geneva, Switz.
ISO, 1999b. ISO 14021. Environmental Labels and Declarations- Self-Declared Environmental Claims (Type II Environmental Labeling). Int. Organ. Stand. Geneva, Switz.
ISO, I.S.O., 2006. Environmental Labels and Declarations—type III Environmental Declarations—Principles and Procedures. Int. Organ. Stand., Geneva, Switz, p. 14025.
ISO, 2017. ISO 21930: 2017- Sustainability in Buildings and Civil Engineering Works- Core Rules for Environmental Product Declarations of Construction Products and Services. Int. Organ. Stand. Geneva, Switz.
Jelse, K., Peerens, K., 2018. Using LCA and EPD in public procurement within the construction sector. In: Designing Sustainable Technologies, Products and Policies. Springer, pp. 499–502.
Lundberg, S., Marklund, P.-O., 2012. Green Public Procurement as an Environmental Policy Instrument: Cost Effectiveness. Univ., Department of Economics.
Maeck, J., Redant, K., 2018. Moving toward green public procurement in Belgium. In: Proceedings of 7th Transport Research Arena (TRA). Vienna, Austria.
Marceau, M., Nisbet, M.A., Van Geem, M.G., 2007. Life Cycle Inventory of Portland Cement Concrete. Portland Cement Association.
Ministerie van Verkeer and Waterstaat, 2015. Green public procurement. The Rijkswaterstaat approach [WWW Document]. URL. http://primes-eu.net/media/8772517/6_presentation-riga-blue-version-pp.pdf.
Minkov, N., Schneider, L., Lehmann, A., Finkbeiner, M., 2015. Type III environmental declaration programmes and harmonization of product category rules: status quo and practical challenges. J. Clean. Prod. 94, 235–246.
Minnesota Legislature, 2019a. Minnesota Bill HF2203: Buy Clean Minnesota Act.
Minnesota Legislature, 2019b. Minesotta Bill HF2204: Maximum Acceptable Global Warming Potential.
Mukherjee, A., Bhat, C., Harvey, J., 2020. Challenges in Meeting Data Needs for Use of Environmental Product Declarations in Pavement Design and Construction: State of Practice and Future Scope. No. FHWA-HRT-20-022. Federal Highway Administration. Office of Infrastructure Research and Development. United States.
Mukherjee, A., Dylla, H., 2017. Challenges to using environmental product declarations in communicating life-cycle assessment results: case of the asphalt industry. Transport. Res. Rec. 2639, 84–92.
National Asphalt Pavement Association (NAPA), 2016. Product Category Rules for Asphalt Mixtures.
National Ready Mixed Concrete Association (NRMCA), 2016. NRMCA Member Industry-Wide EPD for Ready Mixed Concrete.
National Renewable Energy Laboratory, 2012. U.S. Life cycle inventory database [WWW Document]. URL. https://www.lcacommons.gov/nrel/search. accessed 9.20.08.
NSF International, 2019. Product Category Rule for Environmental Product Declarations for Concrete.
Oregon Concrete and Aggregates Production Association (OCAPA), Oregon Department of Environmental Quality (DEQ), 2016. Oregon Concrete Environmental Product Declaration (EPD) Program.
Parikka-Alhola, K., 2008. Promoting environmentally sound furniture by green public procurement. Ecol. Econ. 68, 472–485.
Parikka-Alhola, K., Nissinen, A., 2012. Environmental impacts and the most economically advantageous tender in public procurement. J. Public Procure. 12, 43–80.
Portland Cement Association (PCA), 2016. Environmental Product Declaration (EPD) for Portland Cements (Per ASTM C150. ASTM C1157, AASHTO M85 or CSA A3001).
Sanchez, A., Lehtiranta, L., Hampson, K., Kenley, R., 2013. Sustainable infrastructure procurement in Australia: standard vs. project practices. Sustain. Infrastruct. Procure. Aust. Stand. vs. Proj. Pract.
Santero, N., Hendry, J., 2016. Harmonization of LCA methodologies for the metal and mining industry. Int. J. Life Cycle Assess. 21, 1543–1553.
Santero, N., Masanet, E., Horvath, A., 2010. Life Cycle Assessment of Pavements: a

Critical Review of Existing Literature and Research. Lawrence Berkeley National Lab, Berkeley, CA, USA. URL: https://escholarship.org/uc/item/8632v9cc.

Santero, N.J., Masanet, E., Horvath, A., 2011. Life-cycle assessment of pavements Part II: filling the research gaps. Resour. Conserv. Recycl. 55, 810–818.

SCS Global Services, 2015. North American Product Category Rule for Designated Steel Construction Products.

Simonen, K.L., Haselbach, L.M., 2012. Environmental product declarations for building materials and products: US policy and market drivers. In: Proceedings of the International Symposium on Life Cycle Assessment and Construction. IFSTTAR.

Slag Cement Association, 2015. Industry Average EPD for Slag Cement.

Sparks, D.G., 2018. Exploring Public Procurement as a Mechanism for Transitioning to Low-Carbon Buildings. Doctoral Dissertation. Queensland University Institute of Technology.

Strazza, C., Del Borghi, A., Magrassi, F., Gallo, M., 2016. Using environmental product declaration as source of data for life cycle assessment: a case study. J. Clean. Prod. 112, 333–342.

Strömberg, L., 2017. Conceptual framework for calculation of climate performance with pre-verified LCA-tools. J. Civ. Eng. Archit. 11, 29–37.

Subramanian, V., Ingwersen, W., Hensler, C., Collie, H., 2012. Comparing product category rules from different programs: learned outcomes towards global alignment. Int. J. Life Cycle Assess. 17, 892–903.

Testa, F., Grappio, P., Gusmerotti, N.M., Iraldo, F., Frey, M., 2016. Examining green public procurement using content analysis: existing difficulties for procurers and useful recommendations. Environ. Dev. Sustain. 18, 197–219.

Toniolo, S., Mazzi, A., Simonetto, M., Zuliani, F., Scipioni, A., 2019. Mapping diffusion of Environmental Product Declarations released by European program operators. Sustain. Prod. Consum. 17, 85–94.

USDA- Research Education and Economics, 2018. Cooperation on Data, Research, and Information Systems for Life Cycle Assessment Analysis. Federal LCA Commons Memorandum of Agreement and Understanding.

Van Dam, T., Harvey, J., Muench, S., Smith, K., 2015. Towards Sustainable Pavement Systems: a Reference Document. No. FHWA-HIF-15-002. Federal Highway Administration (FHWA), Washington, DC, USA.

Weiss, W.J., Spragg, R.P., Isgor, O.B., Ley, M.T., Van Dam, T., 2018. Toward performance specifications for concrete: linking resistivity, RCPT and diffusion predictions using the formation factor for use in specifications. In: High Tech Concrete: where Technology and Engineering Meet. Springer, pp. 2057–2065.

Zhu, Q., Geng, Y., Sarkis, J., 2013. Motivating green public procurement in China: an individual level perspective. J. Environ. Manag. 126, 85–95.