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MONITORING AND ENVIRONMENTAL MODELING OF EARTHWORK IMPACTS: A ROAD CONSTRUCTION CASE STUDY

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ABSTRACT

This study presents the contributions of materials, earth engineering equipment and construction techniques to potential environmental impacts from the main items of typical road earthworks. To achieve this goal, the overall activity at a 1.9-km long French earthworks project site for a heavily trafficked highway was surveyed during its 2007-09 construction period. Using data collected and a numerical model of road life cycle assessment (LCA), i.e. ECORCE, six indicators could be evaluated, namely: energy consumption, global warming, acidification, eutrophication, photochemical ozone creation, and chronic human toxicity. When available, several life cycle inventories were implemented in order to appraise indicator sensitivity with respect to the considered panel of pollutants. Results also allowed estimating from an LCA point of view: i) natural resource conservation of both aggregates and soil, during the application of quicklime treatments; and ii) the duration necessary for projected traffic levels to offset the potential environmental impacts of the earthworks stage.

Keywords: road construction; life cycle assessment; earthwork items; environmental indicators; resource conservation.

1. INTRODUCTION

1.1 Background

Over the past 15 years, a general consensus has been reached to limit the environmental impacts due to human activity. The United Nations produced a text entitled the "Framework Convention on Climate Change" (or FCCC), which has gathered 192 parties in an effort to stabilize the concentrations of global warming substances in the atmosphere at levels that would prevent dangerous anthropogenic interference with the climate system (UN, 1992). In 1997, the Kyoto Protocol to the FCCC was adopted by 37 countries in order to limit global warming (UN, 1998). Since that time, many agreements have been signed, e.g. a reduction of halogens due to ozone layer depletion (UNEP, 2000), while greater attention has been focused on emitted chemical compounds that increase global acidification, eutrophication and (eco)toxicity. In 2007, the French Grenelle Environment Round Table (http://www.legrenelle-environnement.fr/-Loi-Grenelle-2-.html) led to the creation of 257 articles introduced into laws on various topics, including resource conservation. On the basis of these new laws, the private sector undertook full-scale testing and entered into private-public partnerships. The one discussed herein, i.e. the TerDouest research program, has been funded by France's National Research Agency (ANR) and conducted by the French Institute of Science and Technology for Transport, Development and Networks (Ifsttar). Support has been provided by Egis, Lhoist, Cimbeton, Charrier, La Forrezienne / Eiffage groups as well as by the French National Railway Corporation (SNCF) and Interdepartmental Directorates of Roads (DIR - Centre Region) in order to achieve these objectives. In this context, the present study examines earthwork activity for the purpose of appraising work practices through an impact assessment.

Due to the complexity of non-road equipment operating conditions, the difficulty of *in situ* data collection and the multiplicity of impacts, the risk of environmental degradation creates an unavoidable challenge in the area of earthworks, which affect both the local and global environment by: i) erecting barriers that fragment habitats; ii) modifying the interactions between organisms, e.g. noise generation that may drown out birds' singing during breeding periods or night lighting that modifies den sites and hunting spots for chiroptera; iii) affecting pH and redox conditions of soil, water and air due to treatments with various binders; and iv) producing global warming and/or (eco)toxic compounds due to the fuel burned in machines, with these compounds being transferred into various compartments of the ecosphere. To gauge the impacts of earthworks, a larger dataset is thus required than the datasets derived for aggregate extraction (Jullien *et al.*, 2012) or for asphalt pavement construction assessment (Jullien *et al.*, 2006). Any extensive environmental consideration relative to earthworks is difficult to achieve without introducing life cycle modeling tools. To the best of our knowledge, only a small amount of research has dealt with the entire life cycle of earthwork activity (Xiaodong *et al.*, 2008, 2010) or material use (Mroueh and Wahlström, 2002; Stripple, 2001).

1.2 Objectives

In accordance with the French Grenelle Environment Round Table (2007), this study seeks to:

i) draw environmental conclusions on earthwork practices, to be accomplished by surveying the relative contributions of the various items composing a typical earthworks project (with a distinction made between materials and machinery), regarding energy consumption and potential environmental impacts;

ii) understand the main parameters governing the potential impacts of local technical choices, e.g. soil treatment using quicklime. This objective implies defining an alternative technical solution for road structures and designs that had not been proposed in the RN7 development plan (for natural aggregates);

iii) propose solutions for mitigating potential earthworks impacts, to be performed by analyzing results obtained on every single earthwork item and then comparing technical solutions to a reference case: the RN7 projected road traffic.

To achieve these objectives, the Life Cycle Assessment (LCA) methodology was applied to elementary earthwork tasks responsible for generating quantifiable environmental impacts. Since databases in the literature provide no detailed inventories for pollutants emitted from earthworks and resource consumption, an extensive data collection effort took place on the study site. These data were then analyzed in order to evaluate the potential environmental impacts of the main phases observed during the earthworks stage of road construction. These phases encompass: i) production and transportation constraints relative to fuel and materials; ii) study area design, which is responsible for determining the project's earthwork volumes; and iii) construction, which includes the work and emissions generated from machinery. This dataset also allowed estimating from an LCA perspective: i) the relative impacts of machines and materials implemented, ii) the conservation of natural aggregate resources when using quicklime treatments as a substitute, and iii) the duration required for road traffic to offset the potential environmental impacts of the earthworks stage.

2. MATERIALS AND METHODS

2.1 The study area

Earthworks on French National Highway 7 (i.e. RN7) constituted the first stage of building an 8.9-km section of highway with two lanes in each direction. The study area was contained within this RN7 development plan, consisting of a 1.9-km long strip designed to relieve urban traffic, as shown at the bottom of Figure 1 (from the 0.76 to the 2.66 milepost, i.e. MP). Adjoining the study area, the longitudinal (left-hand side) and transverse (right-hand side) views of the earthworks structure are depicted at the top of Figure 1. Throughout the remainder of this text, we will refer to the main earth categories constitutive of these earthworks as "earthwork items"; they comprised the quicklime-treated fills, treated sub-base layers, enriched soils (i.e. the humic layer of the initial topsoil being stored and then used to re-vegetate the road shoulders and earthen retaining walls prior to completion of the earthworks stage), and the unusable cuts. The aggregate base and base course have not been considered herein. These items are part of the pavement and/or uppermost layers supporting the road and therefore involve different construction techniques and imported materials.

The RN7 earthworks phase lasted more than 3 years (from end of June 2006 to December 2009). During this period, over one million cubic meters of earth were engineered (i.e. either transported from their original position or locally processed) and 10 pools were excavated to reduce runoff water loading with particles and associated pollutants. RN7 geology is depicted by coarse-grained sandy and clay-silt soils with a clay content locally exceeding 30% and a wide range of gravels. Such soils are very sensitive to water and thus prone to mechanical damage; they are typically found in temperate and subtropical regions (e.g. in the loamy basins of former and current rivers) around the world. As regards the study area, a remarkable characteristic was the magnitude of cuts relative to the fills (see Fig. 1). The cuts were primarily located at 1.00 MP and 1.90 MP, whereas the fills occurred close to 2.66 MP, a situation that accounted for increases in both the amounts of unusable cuts and the average distance traveled by the moved earth.

2.2 Environmental modeling

2.2.1 Model implementation principles for an earthworks assessment

Within the LCA framework, as initiated by the TerDouest research program in 2008, Ifsttar has developed the ECORCE 1.0 application, which was initially dedicated to pavements (Ventura *et al.*, 2009, 2010) in order to evaluate the potential environmental impacts of earthworks. This new tool considers all engineered road layers and includes the initial construction and maintenance stages of pavements. The ECORCE 2.0 application currently allows for a comparison among various road construction techniques and types of materials employed, focusing on: (i) the composition and structure of the road layers under consideration, (ii) machine quantities and tasks, and (iii) the absence / presence of soil treatments. RN7 earthwork practices (implementation of several construction techniques depending on local soil characteristics) have enabled researchers to collect a wide array of data along road project lengths ranging from 150 m (Jullien *et al.*, 2006) to 1 km (Stripple, 2001) for earthwork items located in the exact same area. This collection method is therefore consistent with the LCA code of practice for comparing technical solutions at the same site; moreover, it complies with the objectives set for both the comparisons of earthwork items and the comparisons of soil treatments and natural aggregate use. Most earthwork case study assessment protocols do not allow for assessing two different technical solutions in the same place using local data collected during the works, as was the case for the RN7 project.

To correspond with the LCA practice applied to road pavements, a comparison is usually performed among several solutions that offer similar services. In this case, ECORCE has been applied to calculate a set of environmental data regarding the various earthwork items providing complementary services, i.e. treated fills, treated sub-base layers, enriched soils, and unusable cuts. Such items support the RN7 project in the form of substrates or abutments (enriched soils and unusable cuts are typically stored as earthen retaining walls adjacent to the road).

2.2.2 Building flows databases for the ECORCE application

The ECORCE application was implemented in order to perform a dual assessment of materials, i.e. those introduced for road infrastructure construction and those produced by earthmoving. This implied combining the available Life Cycle Inventories (LCI) for both the quicklime and natural aggregates put to use (Jullien *et al.*, 2012). Such a combination considers two inputs: i) French site data for materials production, and ii) energy content relative to the appropriate production (i.e. French energy and diesel production from the ELCD database, 2002-2003). As regards quicklime production, several distinct LCIs were independently examined and consulted in order to determine the sensitivity of indicators for the considered panel of pollutants. Two datasets by Stripple (2001) and Ecoinvent (2002) were initially available at the international scale (see Table 1). Since the French manufacturing processes were not available in either of the international datasets, the French Union of Lime

Producers performed an LCI suited to quicklime production in France (UPC, 2010); this inventory differed by offering: a broader array of quicklime production plants, technological achievements, and a complete list of flows (Table 1). Despite including fuel and energy production, this new LCI exhibits significantly lower energy consumption and CO_2 emissions than Stripple's. In comparison, Ecoinvent's LCI values more closely resembles those of UPC, which suggests that in order to assess the variability of environmental impacts from quicklime production with LCA, a first step may consist of limiting the scope to the LCIs derived by Stripple and UPC.

For the 3-year data collection period, the organization of earthworks was scrutinized by separating both the materials and onsite energy consumption. Daily cut and fill volumes were analyzed for every single earthwork item (upper part in Fig. 2), an approach that made it possible to assess: fuel consumption by type of machine, daily work and the corresponding earthwork item (lower part in Fig. 2). This task proved complex since the work completed by all earthmoving equipment cannot be easily isolated at any one time since all materials excavated and compacted are being moved continuously.

2.2.3 System boundaries and data limitations

Since this study focuses on the completed earthwork items and materials employed, the upstream processes (not directly related to the earthwork input / output flows) have not been included in calculations, i.e. of either machine production or the construction of quarry equipment for treating aggregates.

The LCA for the constructed earthwork items was performed by applying ECORCE with inventories for the various materials employed, machine emissions and production and distribution of consumed energy (grayish zone in Fig. 2). The list of chemical substances available in the ECORCE application has been generated from LCIs dedicated to aggregates (Jullien *et al.*, 2006, 2012), bitumen (Eurobitume, 1999), cement (Ecobilan, 2002), quicklime (UPC, 2010) and steel (IISI, 1999). Depending on company practices, these LCA calculations were typically conducted in considering a 1-m^3 functional unit of earth.

The atmospheric emissions of chemical substances from machines were estimated from daily fuel consumption data, along with the emission factors for heavy-duty vehicles (Hugrel and Joumard, 2006). Consequently, these merely consisted of daily average data. However, since uncertainties have not been assigned to data available in the literature, research is currently underway in our laboratory to evaluate variations in the emission factors of earthwork machinery as a function of activity and *in situ* geomorphic / pedological conditions that have not been considered herein.

2.2.4 Indicators description for earthwork assessment

The ECORCE application calculates six environmental indicators (Ventura *et al.*, 2009, 2010) (Table 2), namely: energy consumption (EE, in MJ), global warming potential (GWP, in kg eq. CO_2, IPCC, 2001), acidification potential (AP, in kg eq. SO_2, Goedkoop, 2001), the eutrophication index (EI, in kg eq. PO_4, Goedkoop, 2001), photochemical ozone creation potential (POCP, in kg eq. C_2H_4, Goedkoop, 2001), and chronic human toxicity potential (TP, in kg eq. 1.4 DCB, Huijbregts *et al.*, 2000). Throughout this text, we will refer to the selected panel of indicators as I_6.

Except for energy, all of the indicators introduced have been formulated in accordance with Bare and Gloria (2008) and Bare (2010) as linear combinations of weighted contributions of emissions:

$$I_j = \sum_{i=1}^{n} \alpha_i^j \, C_i^j \, m_i \qquad (1)$$

where I_j is the indicator relative to potential environmental impact "j" (e.g. GWP), α_i^j the allocation factor of emission "i" to each individual impact category (unitless [0-1], Sayagh *et al.*, 2010), C_i^j the individual contribution coefficient of emission "i" to "j" (indicator units: kg^{-1}), and m_i the mass of "i" released into the environment per m^3 of moved earth or ton of material used (including production, transportation and application). The values of these contribution coefficients are provided in Goedkoop (1996), Huijbregts *et al.* (2000) and IPCC (2007).

3. RESULTS

3.1 Model inputs: moved/engineered earth volumes and material inflows

A design in accordance with anticipated geotechnical characteristics (CSTCN, 1988) of the various earthwork items was investigated so as to analyze engineered earth volumes and amounts of imported materials introduced. The figures obtained are given in Table 3. The geotechnical characteristics of soils at the study site as well as for all RN7 earthworks were initially found to be insufficient for local reuse without preliminary treatment. The soil moisture content was too high (roughly 8%-10% m/m): the compaction curves developed from standard Proctor compaction tests indicated that the optimal moisture content was between 6% and 8%. The local soils were therefore classified as water sensitive according to the French P11-300 standard.

Quicklime (CaO) is commonly used to lower the moisture content of engineered earth. Due to the high moisture content of local soils, quicklime was imported and then added to the fills and sub-base layer. In the presence of water, CaO forms slaked lime, i.e. $Ca(OH)_2$, within a few minutes of an exothermic reaction. The emitted energy (1160 MJ t^{-1}) results in both a significant temperature rise of the treated soils and a higher dry solid content due to subsequent evaporation: the moisture content decrease is assumed to be proportional to the percentage of added quicklime (a 1%-to-1% correspondence). For this reason, the geotechnical characteristics (such as bearing capacity) of treated soils is locally enhanced. The additional amounts of quicklime were determined according to figures in the log kept for managing all daily construction activities, i.e. the quantities and durations of work, type of activities, equipment implemented, and amounts of materials and supplies received. These quicklime amounts equaled 1%-2% (m/m) of the engineered earth.

Due to quicklime treatments and the ensuing improvement in bearing capacity of treated soils, the aggregates imported from local quarries represented < 10%, i.e. 19,200 m^3, of the volume of engineered earth (Table 3). This imported amount rose to approx. 30% and 40% when used as lateral reinforcement for the treated sub-base layer and drainage course under the treated fills, respectively (Fig. 1). The remaining volume of aggregates, i.e. estimated at 6,000 m^3, was primarily used to construct the basins receiving surface water discharges. In order to reduce uncertainties, the imported aggregates (small amounts used at the RN7 site) were not taken into consideration during the LCA of earthwork items.

3.2 Model inputs: earth movements and *in situ* fuel consumption

The average distance crossed by moved earth ($\bar{L}$) was determined for every single earthwork item included in the study area and RN7 earthworks. Based on fuel tank capacity and their refill frequency, the daily fuel consumption could be evaluated for the two main categories of earth engineering equipment, namely earth movers (i.e. dumpers and trucks) and earth processers (bulldozers, excavators, graders and vibratory rollers). Once the daily fuel consumption was known, then the total fuel consumption was calculated per cubic meter of moved / engineered earth as well as per earthwork item (Table 4).

The value of $\bar{L}$ was determined by using the collected daily data within the time-location plane for *in situ* earthmoving machinery. This value was formulated as follows:

$$\bar{L}_{item} = \frac{\sum_{i=1}^{n}(L_i\ m_i)}{\sum_{i=1}^{n} m_i} \quad (2)$$

where "L_i" is the distance (measured at the metric scale, in m) between the origin and destination of the moved earth, and "m_i" the amount (in kg) of transported material. The soil density considered in Eq. 2 is that of compacted earth after being placed in fills (i.e. 2 tons m^{-3}). The density of earth placed in the earth movers was excluded since it may widely vary depending on the geological nature of soils and excavation / extraction methodology implemented (e.g. excavators, loaders, scrapers, bulldozers). The subscript "i" stands for the various earth movements relative to the considered earthwork item.

The formula for $\bar{L}$ implicitly took into account the typology, quantity and load capacity of earthmoving machinery (mostly dumpers, 8-20 m^3 capacity). Regarding all machines taken as a whole, the entire RN7 earthworks project (resp. just the 1.9-km study area section) deployed up to 85 (resp. 48) earth engineering machines including, but not restricted to, bulldozers (with a net engine power of 80-480 kW), dumpers (220-750 kW), excavators (90-420 kW), graders (130-220 kW), scrapers (270-410 kW), vibratory rollers (110-150 kW) and trucks (180-320 kW).

3.3 Potential environmental impacts: comparison of earthwork items

Figure 3 shows the contribution of each earthwork item to the potential environmental impacts of the study area. These contributions were calculated using the ECORCE application with Stripple's (top panel) and UPC (bottom panel) quicklime production LCIs and the selected I_6 environmental indicators.

Among the various earthwork items, the contribution of unusable cuts to the volume of engineered earth and associated fuel consumption was predominant, i.e. 110,000 m^3 (Table 3) and 90.9 m^3 (Table 4), respectively, or the equivalent of ~50% of overall values for the study area. Unlike the treated fills and construction of treated sub-base however, the contribution of unusable cuts to the I_6 environmental indicators amounted to 5%-40% (Stripple LCI) and 4%-34% (UPC LCI), respectively (Fig. 3). This finding confirms that the engineered earth volume and related fuel consumption are not adequate indicators for measuring the potential environmental impacts of the treated items.

In contrast with unusable cuts, the construction of treated fills accounted for 35% (i.e. 80,000 m^3, Table 3) of the engineered earth volume and 33% (i.e. [59.2] 10^3 L, Table 4) of total fuel consumption. However, treated fills induced 40%-65% (Stripple LCI) and 42%-64% (UPC LCI) of the potential overall I_6-related environmental impacts (Fig. 3). This discrepancy becomes even more significant when considering the treated sub-base layer, which represents 9% (i.e. 22,000 m^3, Table 3) of the engineered earth volume and 11% (i.e. [20.4] 10^3 L, Table 4) of total fuel consumption, while inducing 16%-30% (Stripple LCI) and 17%-31% (UPC LCI) of the potential overall I_6-related environmental impacts. More specifically, the treated items primarily contributed to the GWP indicator: I_{GWP} relative to the treated sub-base layer and fills equaled > 90%. In comparison, the generation of enriched soils and unusable cuts only amounted to < 1% and 4%-9% of I_{GWP}, respectively.

3.4 Potential environmental impacts: quicklime and machine contributions

An important parameter affecting the I_6 panel of environmental indicators was the presence / absence of quicklime treatment, thus leading us to compare the contributions of both quicklime (in terms of production, transportation and implementation) and the use of earth engineering machinery (Fig. 4).

Regarding energy consumption and emissions of global warming substances, the quicklime treatments represented 77% (Stripple LCI) and 64% (UPC LCI) of I_{EE}, and 91% (Stripple LCI) and 83% (UPC LCI) of I_{GWP}, respectively. Calculations have indicated that except for the POCP and TP indicators, the potential environmental impacts of quicklime treatment have invariably originated from the quicklime production step, i.e. 93%-87% of I_{EE}, 98%-95% of I_{GWP}, 88%-65% of I_{AP} and 83%-

56% of I_{EI}, as obtained from the Stripple and UPC LCIs, in this order. For instance, the production step yields carbon dioxide (CO_2, a low-toxicity substance, i.e. toxic at levels > 1% in the atmosphere) emissions when limestone is heated. In contrast, the *in situ* implementation (42%-45%) and on-road transportation (14%-15%) steps dominated the I_{POCP} contributions of quicklime treatment. Distance from the lime kiln measured ~150 km. This observation also was partially true for I_{TP}. *In situ* implementation and on-road transportation accounted for respectively 62% and 21% of I_{POCP} for quicklime treatment when using the Stripple LCI. Yet, these factors only accounted for < 1% and 2% when using the UPC LCI.

The potential environmental impacts from earth engineering equipment systematically exceeded that of quicklime treatment for I_{POCP}, i.e. 72% (Stripple LCI) and 73% (UPC LCI), respectively (Fig. 4). The I_{TP} of machinery only prevailed when using Stripple's quicklime production LCI (79%, top panel in Fig. 4), whereas the corresponding I_{AP} and I_{EI} only dominated when using the UPC quicklime production LCI (61% and 66%, bottom panel in Fig. 4). For these indicators, the associated quicklime treatment contributions of treated fills and the sub-base layer were minimal, i.e. 20%-16% and 46%-40%, respectively (Fig. 3). Accordingly, the POCP indicator and, to a lesser extent, I_{AP} and I_{EI} (due to its LCI sensitivity, the use of I_{TP} remains problematic) were affected by machine-related processes such as the *in situ* movements of excavated earth.

In the earthworks field, moved earth is transported from the cuts to fills and/or to the earthwork items. To maintain the frequency of earth movements, the quantity of earth movers has increased with $\bar{L}$ (from 2 to > 8 dumpers). Hence, fuel consumption varied markedly among the earthwork items, ranging from 1.4 10^3 L for enriched soils to 42 10^3 L for treated fills (Table 4). Fuel consumption by earth movers contributed to raising the POCP indicator through the emission of photochemical ozone precursors (mainly NO_x and NMOC) into the atmosphere. This was apparent from the strong positive correlations between earthwork item contributions to I_{POCP} (for both the Stripple and UPC LCIs) and the local fuel consumption: $r^2 = 0.95$, $I_{POCP}(i) = 10\ Fuel(i) + 80$, where fuel is expressed in 10^3 L and "i" refers to the given earthwork item. As regards I_{AP}, I_{EI} and I_{TP}, the r^2 values were 0.46-0.86, 0.58-0.91 and 0.96-0.23, in this order.

4. DISCUSSION

4.1 Data robustness for treated and untreated soil comparisons

To strengthen the applicability of these calculated environmental indicators, several key LCA parameters have been verified and validated. For instance, the relevance of selected pollutants with respect to the earthworks field has been examined in order to evaluate the proportion of impacts attributable to the machinery or energy production. The procedures employed for characterizing emissions were considered adequate to assess the credibility (hence uncertainty) ascribed to the chemical flows. Moreover, the contributions of each chemical substance to the various impact categories have been carefully monitored so as to update the current databases.

Differences between the considered LCIs consisted of system boundaries, a broader array of quicklime production plants, a more complete flow list and technological accomplishments (see Section 2.2.2 and Table 1). Sensitivity analyses indicated that the principal factors responsible for indicator values discrepancies with Stripple, UPC or Ecoinvent LCIs were: i) technological achievements with respect to lower energy consumption and global warming substance emissions; and ii) more complete flow list (as initiated by ISO 14040-4, 2006 and NF P01-010, 2004 standards), in this order. According to Stripple (2001) and in reading the data shown in Figure 4, a total of 9,240 MJ are consumed and 2,040 kg of CO_2 emitted per ton of quicklime produced. These amounts were about twice the values provided by UPC (2010) or Ecoinvent (2002): 4,500 / 5,800 MJ ton^{-1} and 1,080 / 960 kg (CO_2) ton^{-1}, respectively. The significantly smaller UPC energy consumption and CO_2 emissions had however limited the impact on quicklime treatment contributions, as expressed in percentages, which only decreased by < 15% (Fig. 4). This observation highlights that due to the intrinsically high energy consumption and CO_2 emissions during the production step, the contribution of quicklime to the I_{EE} and I_{GWP} indicators prevails regardless of the preferred life cycle inventory. This finding has been further substantiated by the quicklime production inventories in the Ecoinvent database (quicklime in loose pieces at the plant / quicklime milled loose at the plant, 2000-2002) (Kellenberger *et al.*, 2004).

Another critical observation is the leap in I_{TP} quicklime treatment contribution upon implementation of the UPC quicklime production LCI (Fig. 4). Such a leap was unexpected since French lime kilns from 2010 would have been expected to offer cleaner production processes than kilns from 2001 (due to the indication of lower energy consumption and CO_2 emissions). 99% of the observed increase actually originated from the PAHs, which were not available in Stripple's LCI (Table 2). PAHs are formed in flames (T > 500°C, Bittner and Howard, 1981; Frenklach *et al.*, 1984; Marinov *et al.*, 1998), presumably during the calcination of limestone whenever fuel hydrocarbons are not completely combusted. This finding was confirmed by the fact that the production step accounted for 98% of I_{TP} (UPC LCI) vs. just 18% of I_{TP} (Stripple's LCI), i.e. 720 10^3 kg eq. 1.4 DCB vs. 3,000 kg eq. 1.4 DCB, respectively. For the sake of comparison, I_{TP} with the Ecoinvent LCIs for quicklime exhibited intermediary values, i.e. 140 10^3 kg eq. 1.4 DCB (38% for the production step). It is worth noting that the lack of consistency between the LCIs implemented and the high sensitivity to a few key substances undermines the pertinence of multi-pollutant indicators such as I_{TP}. Due to the absence of uncertainties attributed to the data in the literature and the LCIs of the materials and construction techniques deployed herein, the results obtained should therefore only be considered as indicative.

4.2 Natural resource consumption: soil treatment vs. aggregate use

As previously mentioned, quicklime treatments are initially anticipated so as to optimize the use of local materials (e.g. to limit aggregate input) and minimize the output of unusable earth (and thus fuel consumption and surface occupancy). Hence, natural resource conservation (both aggregates and soil) was evaluated in terms of the mass of materials introduced and their related potential environmental impacts.

In the absence of quicklime treatment, the volume of imported aggregates used would have been equivalent to that of the treated earth, i.e. 102,000 m^3 (Table 3), which roughly represents 214,200 tons of aggregate (overall average density of the local dry - i.e. < 1% water content - 0-31.5 mm calcareous aggregate: 2.1 tons m^{-3}) and necessitates the combustion of 132,300 L of fuel (122,090 L for transportation, based on a 20-km distance between the RN7 worksite and an available quarry, plus 10,200 L for *in situ* implementation). Similar calculations have pointed out that if considered as waste, the same volume of treated earth would have necessitated the combustion of 89,050 L of fuel to be exported and used to construct artificial fills (the mean density of earth is 1.8 tons m^{-3}, and the distance to the waste disposal site is assumed to be close to 10 km). The transportation of aggregates and unusable earth also represents 8,930 and 7,650 km of on-road truck hauling, respectively. The per-kilometer fuel consumption for loaded and empty trucks equaled: 0.380 L km^{-1} and 0.304 L km^{-1}, respectively. The resulting amounts of materials and their relative contributions to study area natural resource consumption (NRC, in tons) and the I_6 panel of environmental indicators are displayed in Figure 5. These calculations were based on the French LCIs for quicklime production and aggregate extraction by UPC and Jullien *et al.* (2012), respectively.

Figure 5 shows that the contribution of quicklime exceeds that of aggregates only for I_{GWP} (x 2.3) and I_{TP} (x 5.6). This important finding demonstrates that quicklime treatment prevents the consumption of a large amount of materials from quarries (4,140 tons of limestone, with 1.77 tons of limestone being calcined per ton of quicklime produced, vs. 214,200 tons of aggregates and 183,600 tons of unusable earth removed from the RN7 site). It also highlights that depending on the indicator, quicklime treatment may cause less loading than the technical aggregate solution on the overall environment (57%, 20%, 18% and 15% of the aggregate contribution to I_{EE}, I_{AP}, I_{EI} and I_{POCP}, respectively). Comparatively speaking, when using the ECORCE application with Stripple's quicklime production LCI, the I_{EE} for quicklime treatment exceeded that of the aggregates by ~9% (2.3 10^7 MJ vs. 2.1 10^7 MJ), which signifies that due to technological achievements in terms of energy conservation and cleaner production, LCI data must be continuously adapted. A critical examination of the sensitivity of selected indicators must be undertaken in order to correctly evaluate the potential environmental impacts of the materials and earth construction techniques introduced.

Overall, the high I_{GWP} and I_{TP} values inherent in the quicklime production step (i.e. limestone calcination-induced CO_2 and PAH emissions) raise doubts over the use of quicklime in the field of earthworks. Yet on the other hand, quicklime treatments have dramatically lowered: aggregate consumption, the number of passes for rollers, the volume of unusable earth removed from the RN7 earthworks, the quantity of on/off-road heavy vehicles, and the generation of both noise and chemical compounds, which are responsible for a negative influence on global acidification, eutrophication, photochemical ozone creation and chronic human toxicity indicators.

4.3 Comparison with the projected RN7 road traffic

Lastly, the NRC and I_6 environmental indicators were calculated for the full set of RN7 earthworks (Table 5). The spatial development of RN7 earthworks was not linear; instead, it consisted of smaller earthwork areas, whose locations depended on the natural and technical obstacles that hinder progress of earth engineering equipment, as well as on the geomorphological and mechanical characteristics of local soils. All these areas were eventually merged in order to complete the entire 8.9-km long RN7 earthworks project. Accordingly, the calculations were based on data in the log used to manage daily work for the entire site; these data included: i) type, quantity, task and fuel consumption (1,587,564 L) of the earth engineering machinery; and ii) the volumes of engineered earth and amounts of imported materials for each individual earthwork item (Table 3). The consistency of the I_6

environmental indicator values was ultimately verified, a step that consisted of comparing the relative contributions of earthwork items when using the ECORCE application separately with data for both the entire RN7 earthworks (8.9 km long) and the smaller (1.9 km long) study area. The contributions of earthwork items to the I_6 panel of environmental indicators exhibited consistent trends: 0.9 < item contribution to I_6 (entire RN7 m^{-3}) / item contribution to I_6 (study area m^{-3}) < 1.4. This determination corroborates that the newly calculated values of I_6 environmental indicators and those for the study area were relatively consistent and presumably representative of the whole RN7 scope of earthworks (Table 3).

The full RN7 earthworks accounted for 3.5 10^7 kg eq. CO_2 (Stripple's LCI), 2.0 10^7 kg eq. CO_2 (UPC LCI) or 1.9 10^7 kg eq. CO_2 (Ecoinvent LCI). If an aggregate sub-base and aggregate fills had been employed instead of quicklime treatments, then these results would have amounted to: 1.2 10^7 kg eq. CO_2 (Table 5). The obtained values were compared to the projected emissions of global warming substances induced by vehicles in covering the 8.9-km long RN7 road. Assuming the RN7 traffic is equivalent to that of the main adjacent road (i.e. ~9,000 vehicles d^{-1} at 0.13 L km^{-1} of average diesel fuel consumption), then the total emissions of global warming substances (> 97% as CO_2) would reach 1.2 10^7 kg eq. CO_2 y^{-1}. Despite the uncertainties surrounding the data, this result clearly shows that RN7 road traffic offsets in less than a few years the GWP impact of the entire earthworks project (either for quicklime treatment or aggregate construction technique). Smaller values, i.e. around 2 years or less, were found for the other environmental indicators.

5. CONCLUSION

In assessing the potential environmental impacts of typical road earthworks, the contribution of treated earthwork items has typically dominated the I_6 panel of indicators. The discrepancy between the contribution of quicklime treatment and that of the equipment implemented *in situ* rendered the engineered earth volume, machine activity and/or their daily fuel consumption inadequate as an accurate gauge of the potential environmental impacts of the earthwork study area. This is likely to be a general feature of all treated earthworks, including road and railway construction.

The main findings of the present study have yielded general trends rather than highly accurate indicator values. For instance, quicklime treatment primarily affected the energy consumption and global warming potential indicators. Depending on the selected LCI, these may also drastically increase the chronic human toxicity potential through PAH emissions during the limestone calcination step. In contrast, machine-induced emissions extensively drove the photochemical ozone creation potential and, to a lesser extent, the eutrophication index and acidification potential.

Understanding the main results on this local case relative to the technical choices of soil treatment with quicklime or natural aggregates leads us to draw several conclusions. The treatments served to conserve natural resources (both aggregates and soil) and, as a result, reduced both the emissions of chemical substances and environmental impacts inherent in the aggregate extraction and transportation steps. Further research is needed however to assess the net benefits of quicklime treatment over traditional techniques (like aggregates) in terms of bearing capacity, compaction time and related changes in the thickness of earthwork items.

From an overall standpoint, the calculated potential environmental impacts of the RN7 earthworks stage were roughly equivalent to a few months / years of projected road traffic. This was significantly greater than the impacts of pavement construction and/or maintenance (i.e. a few days of road traffic, data not shown). On the other hand, earthwork items require no maintenance and their service life is expected to be considerably longer, i.e. > 100 years. It is also believed that significant impact mitigation can be achieved by using more recent machinery (e.g. mounted with diesel particulate filters) and improving operating conditions so as to decrease peak consumption and emissions. When viewed in this light therefore, earthworks are a "sustainable" investment.

TABLE CAPTIONS

Table 1: System boundaries and assumptions adopted for quicklime production LCIs available in three literature datasets. The number of outflows and functional units are also displayed.

Table 2: List of chemical substances and physicochemical parameters input into the ECORCE application calculations in order to assess the potential environmental impacts of earthwork activity. The compounds underscored and in bold letters were reported in the quicklime production inventories by Stripple and UPC, respectively.

Table 3: Summary of data on engineered earth volumes and main material inflows used in the environmental calculations for the 1.9-km long study area. The values in parentheses represent the entire (8.9 km long) RN7 earthworks project.

Table 4: Summary of data on *in situ* earth movements and related fuel consumption introduced into the environmental calculations for the 1.9-km long study area. The values in square brackets pertain to the engineered [moved + locally processed] earth.

Table 5: Environmental indicators calculated for the entire (8.9 km long) RN7 earthworks. The values in parentheses represent the smaller (1.9 km long) study area. A distinction is drawn between the impacts for quicklime treatment (with either Stripple's or UPC LCI data) and for aggregate construction techniques. The bottom row indicates the projected annual RN7 road traffic.

FIGURE CAPTIONS

Figure 1: Schematic views of the RN7 earthworks site and the smaller study area. The surface of the open (resp. filled) squares in the lateral view were set proportional to the volume of moved earth (resp. quicklime applied). The arrow lengths were set proportional to the average distance traversed by moved earth.

Figure 2: Data aggregation chart used to calculate the potential environmental impacts of the various items composing the study earthworks site. A distinction is drawn between the materials used and earth engineering equipment deployed (i.e. either earth movers or earth processers) relative to emissions.

Figure 3: Relative contributions of earthwork items to the I_6 indicators for the study area (1.9 km long). A distinction was drawn between the values obtained using Stripple's (top panel) and the UPC (bottom panel) quicklime production inventories. Definition of acronyms used for indicators: EE: consumed energy; GWP: global warming potential; AP acidification potential; EI: eutrophication index; POCP: photochemical ozone creation potential; and TP: chronic human toxicity potential.

Figure 4: Relative contributions of soil quicklime treatment and earth engineering machinery, in terms of emissions, to the I_6 indicators for the study area (1.9 km long). A distinction was drawn between the values obtained using Stripple's (top panel) and the UPC (bottom panel) quicklime production inventories. Definition of acronyms used for indicators: EE: consumed energy; GWP: global warming potential; AP: acidification potential; EI: eutrophication index; POCP: photochemical ozone creation potential; and TP: chronic human toxicity potential.

Figure 5: NRC and I_6 indicator values of quicklime treatments and aggregate (including unusable earth exportation) construction techniques for the study area (1.9 km long). The greatest contribution is set equal to 100%. Definition of acronyms used for indicators: EE: consumed energy; GWP: global warming potential; AP: acidification potential; EI: eutrophication index; POCP: photochemical ozone creation potential; and TP: chronic human toxicity potential.