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Comparative LCA of concrete with natural and recycled coarse aggregate in the New York City area

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Abstract
Purpose The purpose of the present study is to compare the environmental impacts of using coarse natural aggregate (NA) and coarse recycled concrete aggregate (RCA) to produce concrete in the New York City area, by means of a unique LCA framework that incorporates comprehensive regional data.
Methods A comparative environmental impact assessment study was performed on the critical processes of the life cycles of NA and RCA concretes. For this purpose, concrete ready-mix plants, construction and demolition waste (CDW) recycling plants, NA quarries, and other producers and distributers of concrete raw materials, in addition to CDW landfills in the New York City area, were located. NA and RCA concrete mix proportions that result in the same compressive strength of concrete were used. Also, the environmental impact that would be caused if CDW was landfilled rather than processed into RCA was measured.
Results and discussion In the New York City area, replacing NA with RCA as a concrete aggregate does not affect the environmental impact of concrete production significantly. However, if CDW is recycled only for the purpose of producing concrete aggregate, the avoided landfilling of the CDW will be a result of producing RCA concrete. When avoided landfilling is accounted for, the magnitude of some of the environmental impact indicators for RCA concrete is significantly lower than those of NA concrete (16 and 17% for acidification and smog formation, respectively). In addition, it was found that the impact from transporting RCA to ready-mix plants is on average 37% less than that caused by transporting NA to the plants. Sensitivity analyses and normalization of the results revealed that the environmental impact of changing the type of concrete aggregate from NA to RCA is negligible compared to the total environmental burden of New York City.
Conclusions If RCA concrete is used for all types of construction projects in the NYC area, achieving a significant reduction in the environmental impacts is unlikely. Future work is needed to study specific projects in the region that are categorized based on demand for transportation and cement (the largest environmental stressors of concrete production) to determine for which type of project the use of RCA concrete has the highest environmental benefits.

Keywords Coarse aggregate · Concrete · Environmental impact · Landfill · Life cycle assessment · Recycled aggregate

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1 Introduction

Approximately one billion tons of construction and demolition waste (CDW) are generated annually in the world (CDRA 2016; DG-ENV 2011). Usually more than 60% of the CDW is hard, mineral-based materials: mostly concrete, some masonry, and some porcelain. In many places in the world, the mineral portion of CDW is crushed and graded into coarse recycled concrete aggregate (RCA), fine recycled aggregate,

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and products that contain both coarse and fine recycled aggregates. These products are used primarily as road base course, construction fill, and in drainage systems. The use of RCA in concrete as a partial or full replacement of crushed stone or gravel (referred to as natural coarse aggregate (NA)) has been researched for decades (De Brito and Saikia 2013; Hansen 1992). The main motivation for using RCA in concrete is to reduce construction cost and environmental impact. In the USA, the use of RCA in concrete is almost exclusively limited to concrete road construction where no-longer serviceable to-be-replaced concrete pavements are recycled into RCA on-site with mobile crushers and used in the concrete for the new pavement (ACPA 2010; Gonzalez and Moo-Young 2004; Snyder et al. 1994). This decreases the transportation of the old concrete to landfills and decreases the amount of virgin NA that needs to be procured and transported to the construction site.

Many of the benefits of using RCA in concrete or non-concrete applications are readily apparent. By using RCA, less non-renewable natural resources, i.e., rocks or gravel, are mined and depleted, particularly in and near urban areas where construction volume is high. This leads to the reduction in the number of quarries that is further from cities and therefore the reduction in aggregate transportation distances. In addition, recycling CDW prevents the environmental impact associated with landfilling and transportation to landfills. In terms of life cycle accounting, building CDW recycling plants could lead to the production of more valuable commercial products, e.g., well-graded course recycled aggregate for concrete rather than lower value materials such as subbase, subgrade, or drainage materials. Therefore, the amount of CDW landfilling prevented can be credited to the production of the high-value recycled materials.

A common assumption by many of the researchers who have studied the mechanical properties and durability of RCA-incorporated concrete is that replacing NA with RCA reduces the environmental impact of concrete production. Using RCA may cause a reduction in the strength of the concrete (Gonzalez-Fonteboa et al. 2011; Kou and Poon 2008; Mas et al. 2012; Topçu and Şengel 2004; Yang et al. 2011; Yazdanbakhsh et al. 2017), which must be compensated for by using more cement in the concrete mix. In addition, if RCA production facilities, as compared to NA production facilities, are further from the concrete plants, producing RCA concrete increases the total transportation of concrete raw materials. Life Cycle Assessment (LCA) has been used in recent years to quantitatively compare the environmental impact of either producing NA and RCA as concrete aggregates (Estanqueiro et al. 2016; Korre and Durucan 2009) or producing NA and RCA concretes (Braunschweig et al. 2011; Knoeri et al. 2013; Marinkovic et al. 2010).

In the USA, environmental concerns have been growing and regulations limiting or restricting landfilling, and those controlling waste management, are expected to become more stringent in the future. The New York City Mayor's Office has a declared objective of generating "No Landfill Waste from the City by 2030" (OneNYC 2015). The importance of waste reuse and recycling is expected to increase. If quantitative assessments, such as LCA, show that the use of recycled aggregate in concrete can reduce the environmental impact of concrete production, it could provide incentives to the industry to build specialized CDW recycling plants that produce RCA usable in concrete, rather than those that produce lower value road base or drainage materials.

In 2014, 1.3 million t of Portland cement was used by the ready-mix concrete industry (not including the precast concrete) in New York City (DODGE 2015). Using typical concrete mix proportions, it can be estimated that nearly 5 million m^3 of ready-mix concrete are used annually in New York City for construction. Therefore, changing the type of concrete aggregate could have a significant impact on the environment. The goal of this comparative LCA study is to determine whether the environmental impacts caused by concrete production in the New York City area are significantly affected if RCA is used as coarse aggregate in all the ready-mix plants of the region. The present work is the first comparative LCA study on RCA concrete performed on an urban scale for a megacity. The study demonstrates a useful and important application of LCA to the scientific community, who can perform comparative LCA in a manner similar to that presented to demonstrate to the policy makers of municipal, state, or federal governments whether alternative solutions for making concrete in different regions are more environmentally sustainable than current methods. Another unique feature of the study is that we found the locations of almost all the concrete and raw material plants in the region (176 plants) and determined the actual distances for transporting these materials. In addition, the present study demonstrates separately the impacts of avoided landfilling, for the scenario in which the only purpose of recycling CDW, and therefore preventing it from being sent to landfills, is producing aggregates for use in concrete.

2 Previous studies

Marinkovic et al. (2010) compared the impacts of producing NA and RCA concretes based on local life cycle inventories (LCI) data and typical construction conditions in Serbia. The results of their case study showed that the impacts of aggregate and cement production phases were slightly larger for RCA concrete. Their sensitivity analyses revealed that the total environmental impact of concrete production depends on transportation distance and type of transportation for NA and RCA. They measured the limit for NA transportation distance above which the environmental impact of producing RCA concrete was lower than that of NA concrete.

Braunschweig et al. (2011) used data from a construction project in the Zurich area to perform comparative studies for two classes of concrete: high-quality structural concrete and lean (low strength) concrete. In the former case, concrete with 25% of the NA replaced with RCA by volume was compared with NA concrete. In the latter case, two types of RCA concretes (15 and 100% replacement of NA by volume with RCA) were compared with NA concrete. They found that the impacts caused by producing high-quality NA and RCA concretes are similar. However, it was found that replacing NA with RCA in lean concrete can lead to notable environmental benefits. In addition, the results showed that the amount of cement used in concrete has a major effect on the environmental impact of concrete production.

Knoeri et al. (2013) measured the life cycle impacts of 12 RCA concrete mixtures with two different cement types and compared them with NA concretes for three structural applications. They selected the RCA concrete mixtures according to Swiss construction standards and guidelines. The results showed that replacing NA with RCA leads to approximately 30% reduction in environmental impacts. However, the benefits were mainly due to accounting for recycling the steel reinforcing bars in CDW and the avoided landfilling of CDW when it is recycled to RCA.

Estanqueiro et al. (2016) used site-specific data supplied by Portuguese companies to model the life cycles of NA and RCA concretes. They found that the use of RCA in concrete leads only to some reduction in land use and respiratory health risks from inorganic particles. They found that if fine RCA is used together with coarse RCA, the environmental benefits of producing RCA concrete are more significant. They performed a number of sensitivity analyses, which revealed that the results of the comparative study are very sensitive to the transportation distances.

Ding et al. (2016) used Chinese local LCI data and mix proportions to measure the environmental impacts of producing NA concrete and RCA concretes with 50 and 100% volumetric replacement of NA with RCA. They found that replacing NA with RCA has small environmental benefits, caused by the shorter transportation distance for RCA. In addition, they found that cement content and aggregate transportation distances are the main parameters that affect CO_2 emission and energy consumption caused by concrete production.

3 Methods and materials

3.1 Goal and scope

The goal of the present study is to compare the environmental impact caused by producing and transporting concrete mix constituents (coarse and fine aggregates, cement, and water) required for producing 1 m^3 of (1) concrete with only NA used as coarse aggregate, and (2) concrete of the same compressive strength in which only RCA is used as coarse aggregate. Therefore, the functional unit in this study is defined as 1 m^3 of concrete with a specified compressive strength. This functional unit is selected based on the assumption that the only concrete property that affects the performance of concrete structures is compressive strength. Although simplistic, this is a reasonable assumption as compressive strength is the only concrete property used to design most types of concrete structural members.

A concrete mix that results in an average compressive strength of 40 MPa (5800 psi) was selected, which is often obtained when producing structural concrete with the common *design* strength of 35 MPa (5000 psi) (concrete produced for construction is proportioned to have an average compressive strength higher than the prescribed (design) strength to ensure that despite the strength variation of different concrete production batches, the design strength requirements will be satisfied). Information from the literature was used to select the concrete mix proportions required for producing NA and RCA concrete with the abovementioned average strength (Etxeberria et al. 2007) (Table 1), which is consistent with the findings from a preliminary investigation of the authors on concrete with RCAs produced by a recycling plant in the New York City area. To achieve the same compressive strength for both concrete mixtures, additional cement has been used in the RCA concrete while maintaining almost the same amount of water in both mixtures. Using additional cement results in a lower water to cement ratio, and therefore a lower workability of the fresh concrete. Additional superplasticizer has been used in the RCA concrete mixture to achieve a workability similar to that of the control NA concrete. Nevertheless, the mix proportions used in the present LCA study do not include superplasticizers as their amounts and the difference between the amounts, as shown in Table 1, are negligible: 1.4 and 1.9% of the cement mass for NA and RCA concretes, respectively (less than 0.2% of the concrete mass).

The geographical scope of the study is the metropolitan region that includes New York City and has the highest

Table 1 The mass of concrete constituents (kg) used for producing a cubic meter of NA and RCA concretes (from Etxeberria et al. (2007))

Concrete constituent	Cement	Water	NA	RCA	Sand	SP (%)*
NA concrete	300	165	1207	0	765	1.4
RCA concrete	325	162	0	1123	683	1.9

* In the present LCA study the use of superplasticizer (SP) was not accounted for

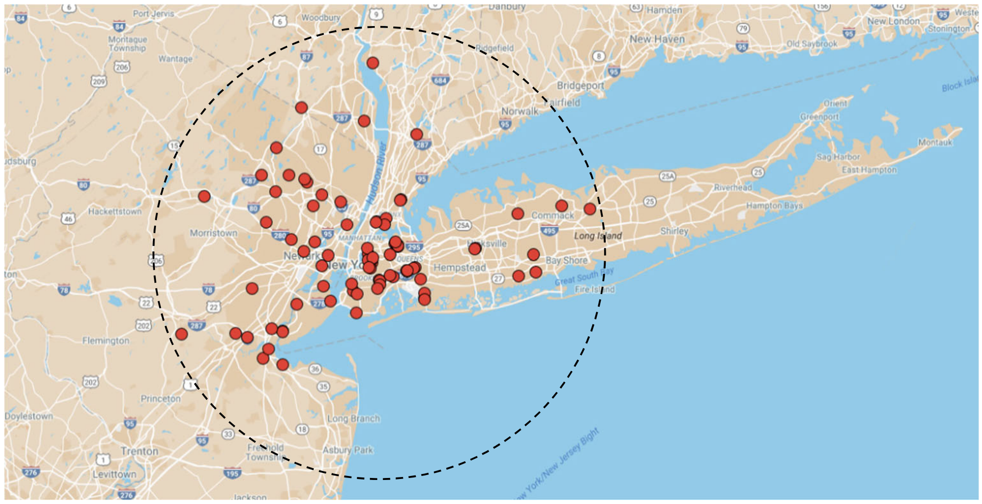

Fig. 1 New York City area (the area within the *circle*), and the location of the concrete ready-mix plants studied in the present work (Google Maps)

concentration of concrete ready-mix plants. In this study, the region is referred to as the New York City area and includes parts of New York State and New Jersey that are within a circle centered at the geographical center of New York City with a with a radius of nearly half the length of Long Island (Fig. 1). It should be noted that some of the raw materials used by the ready-mix plants to produce concrete are sourced from outside this area. The study aims to compare the environmental impacts of producing NA and RCA concretes in ready-mix plants located in the New York City area.

The concrete ready-mix plants in the area were identified and were contacted to find where their aggregates (NA and sand) and cement were obtained from. The cement and aggregate distributers and the production plants that supply the ready-mix plants were located. In addition, the location of the CDW recycling plants that produce RCA in and near the New York City area was determined. Finally, the landfills that receive CDW from the New York City area were located. Eighty-five concrete plants, 28 NA quarries and distribution terminals, 14 cement production plants and distribution terminals, 37 RCA plants, 12 sand sources (natural and manufactured), and 85 CDW landfills were identified and used in this study.

3.2 System description and assumptions

3.2.1 Concrete life cycles and sub-cycles

In this study, as demonstrated in Fig. 2, only the part of the life cycle (sub-cycle) of NA concrete and that of RCA concrete, which are different (in terms of process type or magnitude), were selected for the environmental impact assessment. It was assumed that the impacts caused by the process of concrete production (including mixing, machinery maintenance, and within-plant transportation) are the same for both NA and RCA concretes, since the aggregate type is unlikely to affect these processes. It was also assumed that both types of

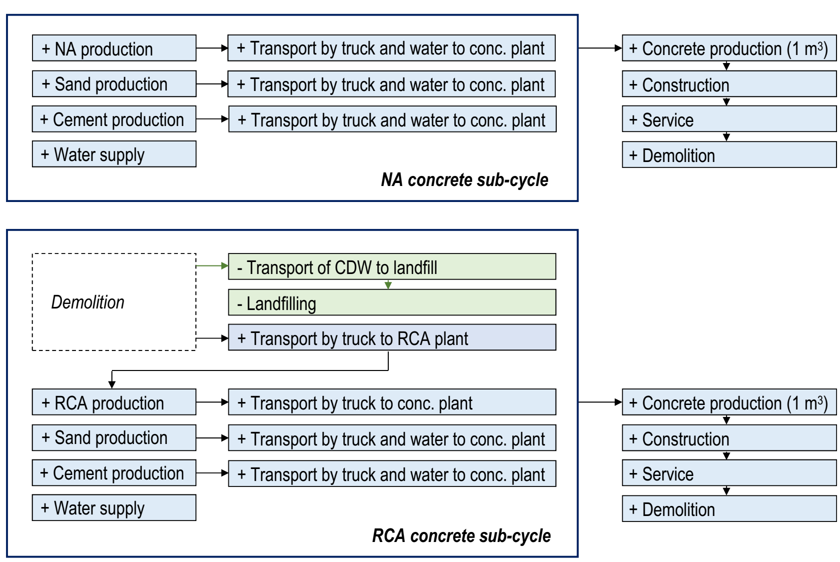

Fig. 2 The part of life cycles of NA and RCA concretes used in the comparative LCA study. In the RCA concrete sub-cycle transportation of CDW to landfill and landfilling may or may not be avoided depending on the regional realities

concrete, as long as they have the same compressive strength, have the same period of service life, and the environmental impacts caused during the service period is the same for the both types of concrete. This assumption may not be valid for all RCA concretes as some types of RCA can affect concrete durability and therefore reduce the service life of concrete. For example, use of RCA with high absorption capacity can reduce the resistance of concrete to freezing and thawing (Nagataki and Iida 2001). Also, if RCA has a high content of chlorides or sulfates, it may reduce the resistance of reinforced concrete to corrosion and sulfate attack. Service life prediction studies need to be performed to estimate the service lives of NA and RCA concretes in different applications. The environmental impacts associated with construction and demolition of buildings with concretes of the same strength are expected, and were assumed to be identical. Therefore, only the sub-cycle of producing concrete mix constituents and their transportation to ready-mix plants was assessed for each type of concrete (Fig. 2). It should be noted that the present study would be a cradle-to-gate LCA if the concrete production process was included in the sub-cycles. However, as mentioned earlier, the goal of the present study is to compare only the processes that are different in function or in magnitude.

As shown in Fig. 2, the sub-cycle for NA concrete consists of water supply, the production of NA, sand and cement, and their transportation by truck and barge to a concrete plant. To the knowledge of the authors, the concrete raw materials are not transported to the area by rail. NA, sand, and cement consumed in the New York City area are partially transported to concrete plants by barges along local waterways, especially the Hudson River and the Long Island Sound. For the RCA concrete sub-cycle, the processes of fresh water supply, sand and cement production, and transportation are similar to those of the NA concrete sub-cycle. However, the amounts of the materials used to produce NA and RCA concretes with the same compressive strength are different (Table 1), resulting in different magnitudes of impact. The processes of producing NA and RCA and the routes for transporting them to concrete plants are different. NA production plants are usually located adjacent to rock quarries. Therefore, the transportation distance between the mined rocks and the crushers/graders is minimal. However, based on interviewing several RCA production plants, the supplied CDW can be as far away as 50 mi from the recycling plant. Preparing rocks that can be fed to crushers for producing NA requires processes such as overburden removal, drilling, and blasting (typically using explosives such as ANFO) (Fisher et al. 2008; Korre and Durucan 2009). For RCA production, the crusher feed is mostly the result of the demolition process, which is performed regardless of whether the CDW is planned to be landfilled or recycled. Therefore, in this study, no portion of the demolition process was allocated to the RCA concrete sub-cycle.

Table 2 LCIA results for the impact category indicators measured in the study, including normalized values of total impacts excluding prevented landfilling, and normalized values of landfilling impacts

Category	Climate change		Acidification		Smog formation		Eutrophication		Human health		Ozone depletion	
Unit	kg CO_2 eqv.		kg SO_2 eqv.		kg O_3 eqv.		kg N eqv.		kg PM2.5 eqv.		kg CFC 11 eqv.	
Concrete type	NA	RCA	NA	RCA	NA	RCA	NA	RCA	NA	RCA	NA	RCA
Cem. prod.	2.7E+02	2.9E+02	5.3E−01	5.7E−01	9.7E+00	1.1E+01	3.3E−01	3.6E−01	1.1E−01	1.2E−01	1.0E−05	1.1E−05
Trans, truck	1.5E+01	7.7E+00	6.8E−02	3.5E−02	1.6E+00	8.3E−01	1.7E−02	8.6E−03	1.1E−02	6.0E−03	3.6E−06	1.9E−06
Trans, water	1.4E+01	1.0E+01	1.3E−01	9.3E−02	3.9E+00	2.7E+00	2.4E−02	1.7E−02	9.9E−03	7.0E−03	2.9E−06	2.0E−06
NA/RCA prod	4.6E+00	4.2E+00	2.6E−02	2.4E−02	2.8E−01	2.6E−01	6.5E−04	6.0E−04	6.3E−02	5.8E−02	8.5E−11	7.9E−11
Sand. prod	3.2E+00	2.8E+00	2.1E−02	1.9E−02	4.1E−01	3.6E−01	1.0E−02	9.1E−03	5.3E−03	4.8E−03	3.9E−07	3.5E−07
Total	3.0E+02	3.1E+02	7.7E−01	7.4E−01	1.6E+01	1.5E+01	3.8E−01	3.9E−01	2.0E−01	2.0E−01	1.7E−05	1.6E−05
Normalized total, pt.	1.25E−02	1.30E−02	8.51E−03	8.17E−03	1.14E−02	1.05E−02	1.76E−02	1.82E−02	8.25E−03	8.12E−03	1.06E−04	9.83E−05
Avoided landfilling	–	1.2E+01	–	9.4E−02	–	1.6E+00	–	2.9E−02	–	1.3E−02	–	8.0E−06
Normalized avoided landfilling, pt.	–	4.83E−04	–	1.03E−03	–	1.16E−03	–	1.32E−03	–	5.44E−04	–	4.93E−05

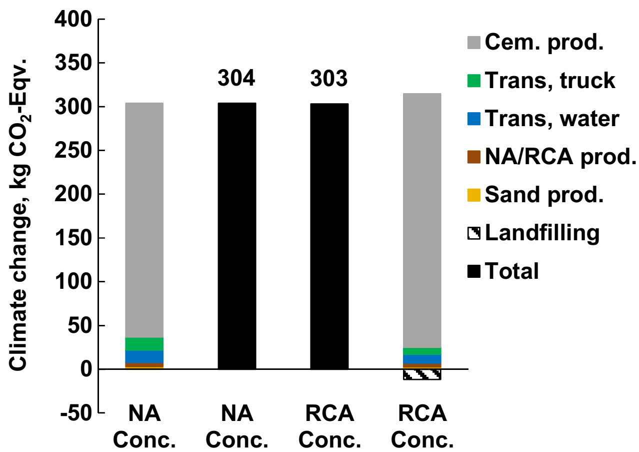

Fig. 3 Climate change potential indicator results from different processes of NA and RCA concrete sub-cycles

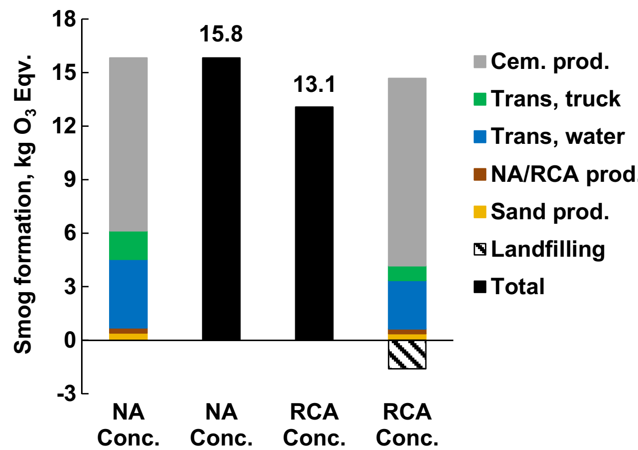

Fig. 5 Smog formation indicator results for NA and RCA concretes

3.2.2 Prevented landfilling and the usable portion of CDW

Landfilling CDW is prevented if it is recycled. However, prevented landfilling is not normally accounted for when performing an LCA for materials which have a recycled material as a constituent. According to the LCA approach proposed in the European standard EN 15806 (CEN 2012), prevented landfilling should not be considered as a benefit of using recycled materials. Silvestre et al. presented detailed rules to calculate the impacts and benefits of the end-of-life of building materials according to European standards (Silvestre et al. 2014). One logical explanation for not accounting for prevented landfilling as an added benefit in a comparative LCA study for RCA concrete is that if CDW is recycled regardless of whether the recycled CDW is used as concrete aggregate, producing RCA and using it in concrete will not be the cause of the prevented landfilling. However, in the case that the primary reason for recycling CDW is to produce concrete aggregate, the avoided landfilling is the result of using RCA in concrete. Currently, the vast majority of the CDW recycled in the New York City area is used in applications other than concrete production. However, that may not remain the case and new economic considerations, policies, and regulations may lead to using the vast majority of RCA in concrete, and to building specialized recycling plants for producing RCA for concrete. Therefore, in this study, the impacts of avoided landfilling are separately presented.

Based on the findings from interviewing a number of plant managers of CDW recycling plants, it was assumed that (1) all of the CDW received by the plants are processed into marketable materials ranging from well-graded quality aggregate down to fill materials (recycling plants are cautious about receiving materials with a notable unusable content resulting in continuous accumulation of waste in their plants), and (2) 25% of the CDW can be processed into well-graded coarse aggregate usable in concrete as a full replacement of NA. The study by Nagataki et al. shows that from 36 up to 60% of the crushed concrete can be graded into coarse aggregate depending on the crushing technique (Nagataki et al. 2004). Marinkovic et al. used the value of 60% recovery in their comparative LCA study (Marinkovic et al. 2010). In this study, 25% recovery was assumed since a portion of CDW sent to recycling plants is not concrete and also when

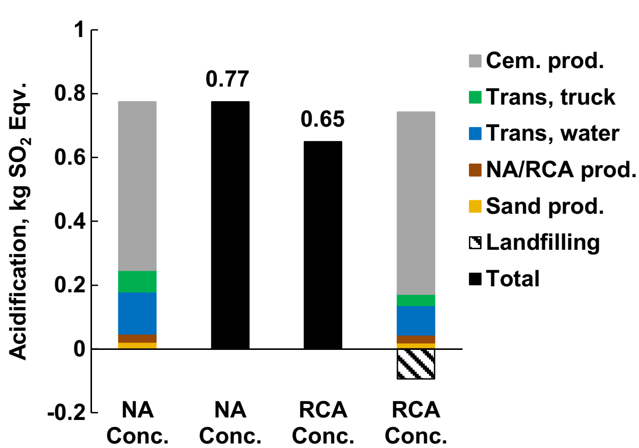

Fig. 4 Acidification indicator results for NA and RCA concretes

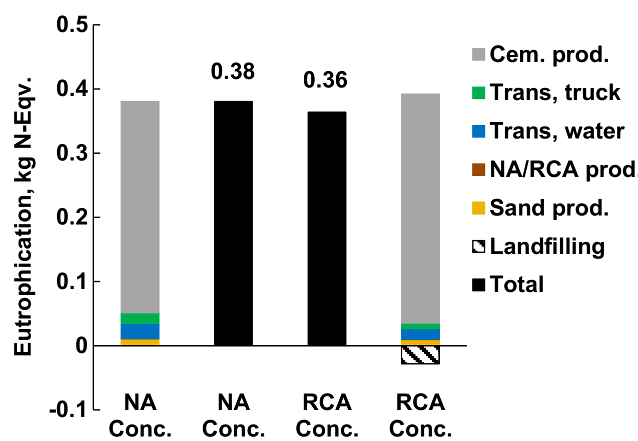

Fig. 6 Eutrophication indicator results for NA and RCA concretes

validation tests were being performed by the authors for the mix proportions presented in Table 1, the RCA "class" used for concrete production constituted approximately 25% of the products (the highest quality) of the recycling plant that provided the project with RCA. Based on the 25% recovery assumption, for each ton of RCA produced, 4 ton of CDW was regarded as being diverted from landfills. That is, all the environmental benefits of landfilling prevention were allocated to the production of RCA and none to other lower quality recycled materials. While this allocation is open to debate, the argument that supports it is that the higher quality recycled materials (well-graded RCAs) are the most profitable products of CDW recycling plants and a main reason for building the recycling facilities. A more realistic type of allocation, such as economic allocation (mass allocation is not appropriate as the value of the low quality recycled CDW is much lower than that of high-quality RCA), needs to be implemented. However, it was not possible to make a reliable estimation for the cost of different types of recycled CDW, since the prices have been changing notably over time in the New York City area.

In the comparative LCA study performed by Knoeri et al. (2013), the effect of recycling the steel reinforcing bars (rebars) embedded in the demolished concrete was considered in their impact assessment. Recycling rebars into new steel products results in less environmental impacts than producing new steel. In this study, this potential environmental benefit was not allocated to the RCA concrete sub-cycle and it was assumed that steel rebars are extracted from demolished concrete and recycled regardless of whether the concrete waste is recycled or landfilled.

3.2.3 Transportation distances

A simplified approach was used to estimate the transportation distances traveled by concrete raw materials for producing concrete. For each of the 85 concrete ready-mix facilities, the two closest cement, NA, RCA, and sand production plants were selected as those that supply the concrete mix constituents. Google Maps was used to determine the transportation distance between each of the selected plants (through distributers, if applicable) and the ready-mix plants using truck and barge routes. For each concrete mix constituent, the transportation distance used in the LCA was obtained by averaging the transportation distances, associated with that constituent, determined for all the ready-mix plants. To calculate the distance for transporting CDW to the landfills, the two closest landfills to each RCA plant were found, and the calculated distances for all the RCA plants that supplied coarse aggregate were averaged. An average distance of 25 mi for the transportation of CDW to any RCA plant was selected based on the information obtained from a number of studied recycling plants.

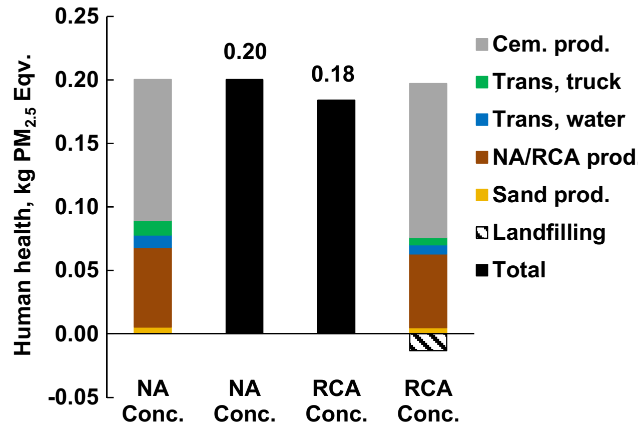

Fig. 7 Human health respiratory effect indicator results for NA and RCA concretes

3.3 Life cycle inventory and impact assessment

Commercially available life cycle inventories (LCI) from the GaBi U.S. database (GaBi 2016) and ecoinvent (Frischknecht and Rebitzer 2005) were used for transportation, sand and cement production, and landfilling processes. To the best knowledge of the authors, commercial LCIs for the process of producing RCA were not available when the present study was conducted. However, the Athena LCA Impact Estimator for Buildings (Athena 2016) has an embedded database for RCA production in North America. Athena's database is not available to the public but can be used in their software to perform life cycle impact assessment (LCIA). The Athena package was used to perform the RCA production part of the impact assessment for the RCA concrete sub-cycle and the NA production part of the impact assessment for NA concrete sub-cycle. The selected LCIs for the remaining processes of the two sub-cycles were input into GaBi for impact assessment. Detailed information about the LCIs used in this study is presented in the Appendix (Electronic Supplementary Material). Various LCIs for the process of water supply were tried in trial LCAs, and it was found that the impact of water supply,

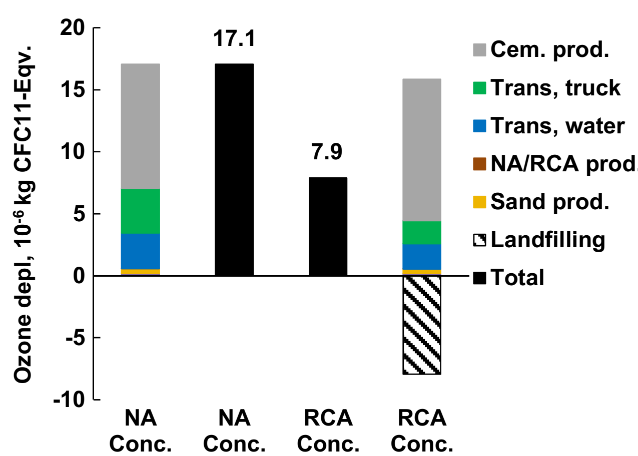

Fig. 8 Ozone depletion indicator results for NA and RCA concretes

compared to that of other processes, was negligible. Therefore, the water supply process was not incorporated in the comparative LCA. Since for the process of water transportation, a US or global LCI was not available to the authors, an LCI based on the European data was used. In addition, since the authors could not find an LCI specifically for transportation by barges pulled by tugboats, an LCI for container ships was used.

Using LCIs from regions other than that of a regional LCA can affect the accuracy of measured environmental impacts (Dong et al. 2015). Due to the limitations in the choice of LCIs in this study and the use of two different software packages (GaBi and Athena LCA Impact Estimator), the values of measured impacts are approximate. However, since the same approach was used to measure the impacts of both NA concrete and RCA concrete sub-cycles, the results can demonstrate how significant the difference between these impacts are.

Since Athena uses the TRACI 2.1 LCIA method (Bare 2011; TRACI 2016), this method was selected in the GaBi software so that the measured mid-point impact category indicators by the two software packages would be compatible and aggregated. The TRACI 2.1 impact indicators that are measured by both LCA platforms are reported in this study. These indicators are climate change potential, acidification, smog formation, eutrophication, human health (respiratory effects), and ozone depletion. These mid-point impact categories are used by public and private organizations as a basis for evaluating environmental and natural resource policies. TRACI was developed by the US Environmental Protection Agency (EPA) and is used in various sustainability evaluation applications including the US Green Building Council's LEED Certification (LEED 2016). Both the software platforms used in this study follow the standard protocol of LCA according to ISO 14040-14044 (ISO 2006). The impacts were normalized using the latest TRACI normalization factors available for the USA, measured for year 2008 (Ryberg et al. 2014). A normalized impact value represents the number of average American individuals who produces the same quantity of impact every year.

4 Results and discussion

The results for the environmental impact category indicators measured in this study are presented in Table 2. The normalized values of the indicators calculated using TRACI normalization factors are also presented in the table. The results show that for all impact categories, the environmental impact caused by transporting RCA to concrete plants is 37% smaller than that caused by transporting NA to the plants.

Figures 3, 4, 5, 6, 7, 8, and 9 present the LCIA results for each impact category. In Fig. 3, the magnitudes of the climate change potential indicator from each process in the sub-cycles of NA and RCA concretes (the leftmost and rightmost bars, respectively), as well as the total impact for each type of concrete, including the avoided landfilling (the middle bars), are presented. These results show that the vast majority of the climate change potency is caused by the production of cement.

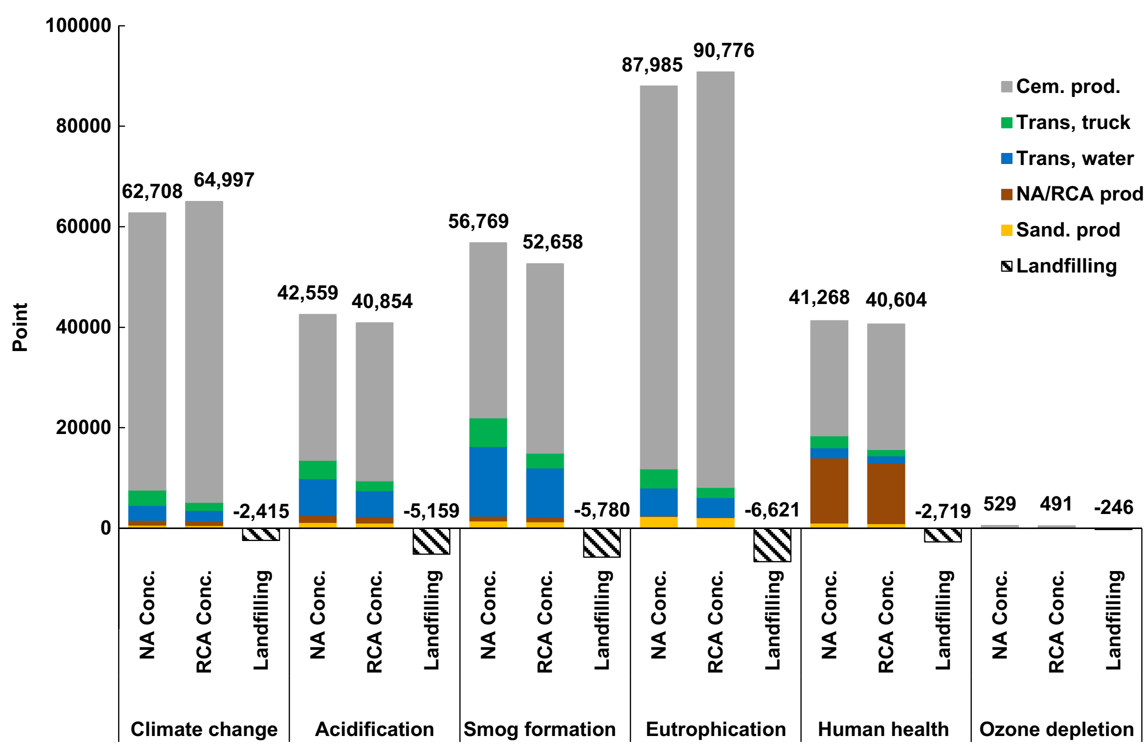

Fig. 9 Normalized values of environmental impacts caused by producing 5 million m^3 of concrete (the approximate amount of concrete produced annually in New York City). The impacts of prevented landfilling are presented separately

The cement used in NA and RCA concretes accounts for 267 and 290 kg of CO_2 equivalent, respectively. Since the distances for transporting RCA to concrete plants are lower than those for transporting NA, the global warming potentials for NA and RCA concrete sub-cycles, excluding landfilling, have the similar values of 304 and 315 kg of CO_2 equivalent, respectively. If avoided landfilling is accounted for, the global warming potential for RCA concrete sub-cycle will be 303 kg of CO_2 equivalent.

Figure 4 presents the acidification impact for NA and RCA concretes. If landfilling prevention is excluded from the analysis, NA and RCA concretes would have the similar acidification potentials of 0.77 and 0.74 kg SO_2 equivalent, respectively. This is due to the fact that in the RCA sub-cycle higher cement demand has been offset by lower overall transportation, particularly marine transportation. Water transportation has a notable impact on acidification, since the combustion of marine fuel results in the emission of oxides of nitrogen and sulfur, two main acidification stressors. Landfilling avoidance reduces the total acidification impact of RCA concrete from 0.74 to 0.65 kg SO_2 equivalent. Compared to acidification, smog formation is more influenced by transportation (Fig. 5). Therefore, even when landfilling is not included in the analysis, smog formation from the RCA concrete sub-cycle is less than that from the NA concrete sub-cycle (14.7 and 15.8 kg O_3 equivalent, respectively). Incorporating the effect of landfilling avoidance in the analysis reduces the total smog formation indicator for RCA concrete from 14.7 to 13.1 kg O_3 equivalent.

The eutrophication, human health respiratory effects, and ozone depletion impact indicators for NA and RCA concretes are presented in Figs. 6, 7, and 8. When landfilling prevention is disregarded, the eutrophication indicator of RCA concrete is only slightly larger than that of NA concrete (0.39 and 0.38 kg N equivalent, respectively) and reduces from 0.39 to 0.36 kg N equivalent when landfilling prevention is included in impact measurement. For both human health and ozone depletion categories, the impact indicators for RCA concrete sub-cycles are lower than those of NA concrete even when the avoided landfilling is disregarded. However, since ozone depletion potential values for both sub-cycles are very small, this indicator should not be used for comparison as the results may be the product of data noise.

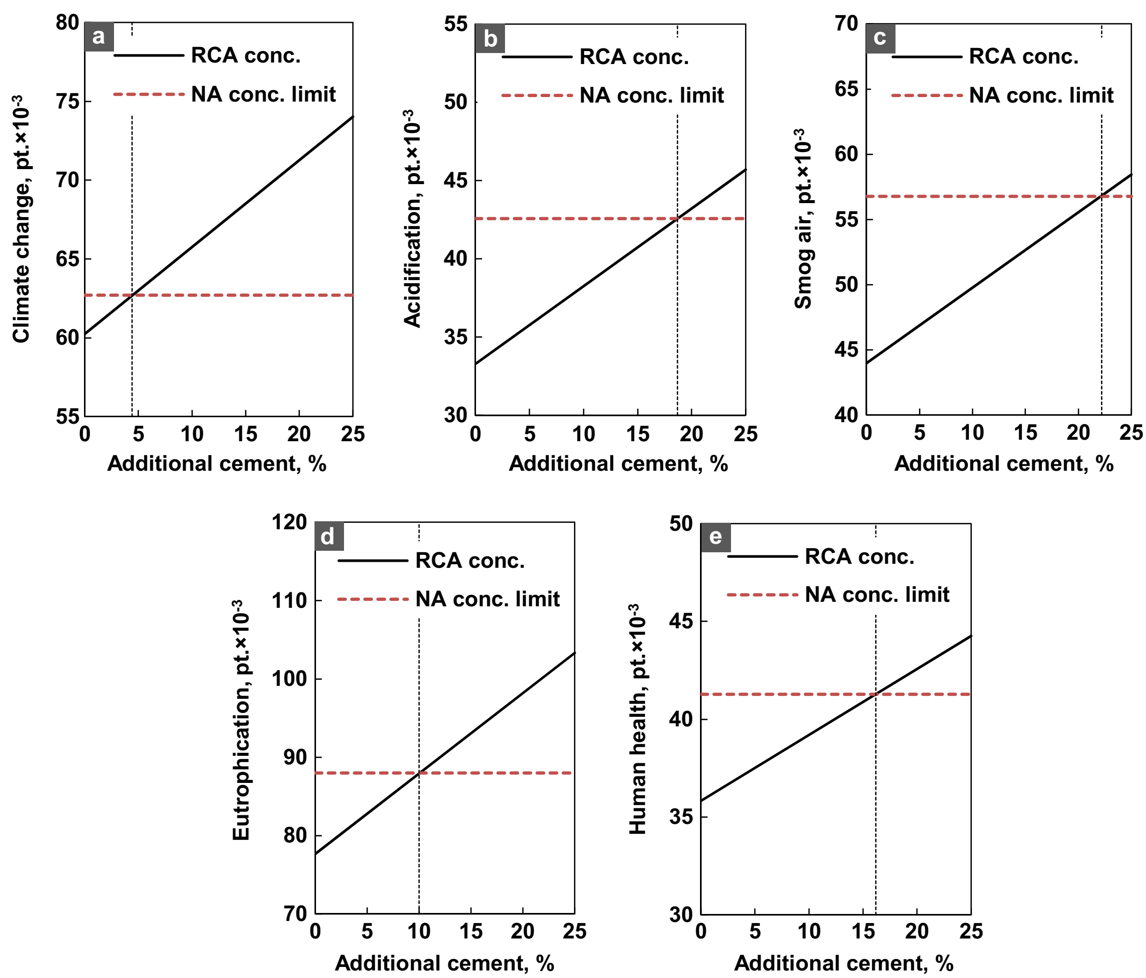

Fig. 10 The effect of the required additional cement for RCA concrete on (**a**) climate change, (**b**) acidification, (**c**) smog formation, (**d**) eutrophication, and (**e**) human health. *Dashed lines* indicate the impact caused by the production of NA concrete

Figure 9 presents normalized impact indicators (without accounting for prevented landfilling) for 5 million m^3 of concrete, which is currently the approximate amount of concrete produced annually in New York City. The differences between the indicator values for NA and RCA concretes are not significantly large. The difference is 2300 points for global warming, 1700 points for acidification, 4100 points for smog formation, 2800 points for eutrophication, 660 points for human health, and 40 points for ozone depletion potential. Considering the fact that the population of New York City is currently more than eight million, this means that changing the aggregate type from NA to RCA for concrete production in the New York City has the same environmental impact as that caused by increasing or reducing the city population by only a few thousands (less than 0.05% of the total population).

The RCA concrete mix used in this study has 8% more cement than the NA concrete. The findings of a number of past studies (Fathifazl et al. 2009; Knaack and Kurama 2014) show that, depending on the type of RCA, the mix proportions of RCA concrete and the composition of CDW used to produce RCA, additional cement may not be required to achieve the same compressive strength as that of NA concrete. This is the case even if the NA is mostly or fully replaced with RCA. Figure 10 shows the effect of the required additional cement for RCA concrete, ranging from 0 to 25%, on different environmental impact indicators. The results presented in Fig. 10 are the normalized values of the impacts caused by producing 5 million m^3 of concrete (annual concrete production in New York City). These findings show that the required additional cement for producing RCA concrete, below which the impact of producing RCA concrete is less than that of NA concrete, are 4.4% for climate change potential, 10.0% for eutrophication, 18.7% for acidification, 16.2% for human health, and 22.2% for smog formation. Also, the results show that even if no additional cement is required for RCA concrete, the environmental benefits of producing RCA concrete in New York City are not significant. These benefits are 2500 points for climate change, 10,000 points for eutrophication, 9000 points for acidification, 5500 points for human health, and 13,000 points for smog formation: benefits that can be achieved if the population of New York City is reduced by between 0.03 and 0.15%.

5 Conclusions

The environmental impacts of producing NA and RCA concretes in the New York City area were measured by means of a unique and comprehensive LCA framework. The work constitutes the first urban-scale study on the use of RCA concrete in a megacity. The real locations of the vast majority of concrete production plants, producers of concrete constituents that are used for concrete production in the area, and the CDW landfills in the region were found and used in the study. The following conclusions can be made from the results.

- If the prevented landfilling of CDW that is recycled into RCA and used in concrete is accounted for the environmental impact of producing RCA concrete is significantly lower than that of NA concrete. However, prevented landfilling can be accounted for only if the main purpose of recycling CDW is producing RCA for use in concrete.
- When prevented landfilling is not accounted for, the environmental impacts of producing NA and RCA concretes are similar, since the impact caused by the demand for additional cement for RCA concrete is offset by the shorter transportation distance between RCA sources (as opposed to NA quarries) and concrete ready-mix plants.
- The results of the sensitivity analyses show that even if no additional cement is required for producing a functional unit of RCA concrete, the environmental benefits of producing RCA concrete in the New York City area are not significant. That is, however, when RCA is supplied by CDW recycling plants and not by on-site mobile facilities.
- The findings of this study are in agreement with the main conclusions of the past studies comparing the environmental impacts of producing NA and RCA concretes: (1) the environmental impacts are sensitive to the demand for cement and aggregate transportation distances and (2) replacing NA with RCA in concrete does not have a major impact on the environment.
- It is important to perform project-specific analyses to determine in what types of construction projects the use of RCA (either as concrete aggregate or unbonded aggregate) can lead to the maximum environmental benefits. It is expected that the benefits are the highest for the projects in which old concrete is recycled in the demolition site by mobile facilities, and used for construction at the same site. However, the significance of the environmental benefits needs to be quantified.

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