Innovative Infrastructure Solutions (2024) 9:69
https://doi.org/10.1007/s41062-024-01382-z

TECHNICAL PAPER

Comparative environmental life cycle assessment of artificial fly ash aggregates and natural aggregate production in India

Hrishikesh A. Shahane[1] · **Satyajit Patel**[2]

Received: 10 November 2023 / Accepted: 25 January 2024

Abstract

A novel process for the production of angular-shaped high strength fly ash aggregates from an energetic, and environmental perspective is presented in this paper and compared with the production of natural aggregates. This study is significant because there is an increasing demand for aggregates and no published research addressing the environmental impact assessment of fly ash aggregate manufacturing. For the fly ash aggregate production, all technical, energetic, and financial aspects of the production process were evaluated at the pilot-scale production plant. Whereas, for the natural aggregate production process, site-specific data is used. The environmental impacts of aggregate production processes were assessed using SimaPro and the impact analysis methodology IMPACT 2002 + from the "cradle to gate." The results demonstrate that the production of fly ash aggregates is more desirable than natural aggregates for all environmental impact categories. Using fly ash for aggregate production avoids the impacts due to inert landfilling and extraction of basalt. The findings show that diesel and electricity are the primary sources of energy used to produce aggregates and they are principally answerable for the detrimental effects on respiratory inorganics, global warming, and non-renewable energy. A sensitivity analysis recommends that fly ash aggregate is preferable for all impact categories if the distance between the lime source and the production plant is less than 350 km. The comprehensive life cycle inventory and impact analysis aid in the decision-making process for further improvement in the production procedure of fly ash aggregates and similar life cycle assessment studies.

Keywords Fly ash utilization · Fly ash aggregates · Natural aggregates · Life-cycle assessment · Global warming

Introduction

Construction industry in India is one of the largest consumers of natural resources. The predominant materials used in the construction sector are sand, stones (as aggregates), soil (for bricks), and limestone (for cement). On the other hand, current construction practices are moving toward more sustainable approaches with greener alternate materials. Recycled materials have gained attention as sustainable alternatives to natural aggregates in various civil construction works owing to their environmental and commercial benefit.

The alternative materials commonly used in constructions instead of natural aggregates/materials are construction and demolition (C&D) waste, reclaimed concrete aggregates (RCA), crushed brick, fly ash aggregates, and industrial waste, such as slags, fly ash, glass, rubber, glass fibers [1–10]. Ottosen et al. [11] utilized the sewage sludge ash as a replacement of sand in concrete after extraction of phosphorous (P) from it. For the construction of roads in the United Arab Emirates warm-mix asphalt, reclaimed asphalt pavement, recycled construction waste, and blast furnace slag were used as a replacement of conventional materials, and its life cycle assessment (LCA) was carried out. The findings showed that there was a significant decrease in environmental impact for all parameters, including carbon dioxide equivalent, energy consumption, nitrogen oxides equivalent, particulate matter 2.5 equivalent, acidification, and land use [12]. C&D waste was successfully reused as

✉ Hrishikesh A. Shahane
shahane.hrishi@gmail.com

Satyajit Patel
spatel@amd.svnit.ac.in

1 School of Civil and Environmental Engineering, Faculty of Engineering and Built Environment, University of the Witwatersrand, Johannesburg, South Africa

2 Department of Civil Engineering, S. V. National Institute of Technology, Surat, India

Published online: 20 February 2024

substitutes for the natural aggregates in the manufacture of concrete kerbs with the fixed concrete recycling plant [13]. Similarly, a systematic environmental life cycle assessment study for reprocessing of C&D waste was presented by Jain et al. [14]. They found that coordinated recycling offers to reduce urban India's negative environmental impact simultaneously reducing the demand for virgin natural materials. Huanga and Chuieha [15] demonstrated the reuse potential of fly ash from municipal solid waste incineration and its life cycle assessment. Furthermore, Hossain et al. [16] presented the life cycle assessment for the production of natural and recycled aggregates and reported that use of recycled aggregates instead of natural aggregates can reduce around 51% of total environmental impacts. Rosado et al. [17] evaluated the environmental effect of natural aggregates and a combination of natural aggregates-reclaimed concrete aggregates for use as base and subbase materials of pavement, demonstrating that the natural aggregates-reclaimed concrete aggregates combination has positive environmental effect metrics.

A study of scientific literature shows that there are LCA studies on the management of C&D waste [18–22] and some studies on the recycling process of C&D waste [23–27]. Additionally, some studies reported LCA of C&D wastes used as material for the construction of roads and the production of concrete [16, 28–31]. Parameters like energy use, water consumption, emissions, and health concerns are reviewed and analyzed in various case situations.

Furthermore, Gomathi and Sivakumar [6] have reported a quite good performance of concrete made with artificial fly ash aggregates. Similarly, lightweight fly ash aggregates are utilized in high-grade concrete and lightweight concrete [7, 32]. Nayak [33] specified that fly ash aggregates could find promising applications in the construction of roads and embankments. Shahane and Patel [34, 35] stated that hot water cured fly ash aggregates are tough, strong, hard, and durable, meeting the requirements for road and structural concrete aggregates. So far, several researchers have confirmed the usage of fly ash aggregates as a step in protecting the environment.

Among the different alternatives to natural aggregates, the production of artificial aggregates with fly ash is one of the potential options. The primary purpose of this preference is to reduce natural resource exploitation and increase the utilization of fly ash. Due to inferior quality of the coal available in India a tremendous amount of ash in the range of 30–45% of coal is being produced [36]. On the other hand the increasing demand for aggregate in the construction industry, and indications that a detailed scientific study may make a significant input for improving the sustainability of the Indian construction sector are the motivating factors behind this research. As a result, several regulatory, technical, economic, and environmental issues of fly ash management must be investigated, particularly for the production of novel materials from it to enhance the sustainability construction sector. Construction of a 1 km long and 7 m wide (two lanes) road requires about 8500 tons of stone aggregates. Production of 1 cubic meter of concrete requires about 1.7 tons of stone aggregates. Aggregates normally fill 70–80% volume of cement concrete and asphalt concrete; hence, alternative aggregates to substitute natural aggregates would significantly reduce natural resource extraction and its associated environmental implications [37]. According to 12th five-year plan of India the need of construction industry for stone aggregates will reach roughly 10.3 billion tonnes [38]. These figures show a large need for aggregate in constructions and using marginal aggregate in a developing country could be a way to combine economics with environmental sustainability [17].

There is no published research addressing the environmental impact assessment of fly ash aggregate manufacturing and no adequate site-specific data is available to generate a comprehensive LCA investigation on the production of fly ash aggregate. The first goal of the study is to produce a complete life cycle impact assessment (LCIA) based on primary data that can help local decision-makers to choose alternative construction materials. It also aims to formulate a comprehensive and scientific analysis of the possible environmental impacts for the production of alternative aggregate, which aids in the decision-making process for further improvement in the production procedure of fly ash aggregate and similar LCA studies.

Methodology

This study's LCA approach is based on the International Organisation for Standards (ISO) 14040 [39], which has been applied in various previous research [16, 17, 37]. SimaPro® 9.0.0.49 LCA software was used to examine the impact of inventory elements on the environment and compare fly ash aggregate (FA) and natural aggregate (NA) production methods through four key phases:

1. Defining the goal, scope and system boundaries for LCA
2. Product selection and process inventory (i.e. inputs and outputs)
3. Assessment of an inventory's environmental impact data
4. Results interpretation and suggestions for enhancement

Goal and scope definition

The goal of this work is (1) to draft a regional life cycle impact assessment (LCIA) for production of fly ash aggregate (FA) in India and compare it with that of natural aggregate (NA). And (2) to conduct a comparative life cycle assessment (LCA) on the production of FA and NA based on the essential data collected from a pilot-scale production plant of fly ash aggregate and a basalt quarry, both are situated in Gujarat state of India (Appendix A- Fig. Ia).

The resulting LCIA will assist the local decision-makers to choose the most environmental friendly construction material. Additionally, it will be helpful for upcoming LCA studies on fly ash utilization. The fly ash aggregates may substitute natural aggregates for various construction applications in a ratio of 1:1 and the production of 1 ton of aggregate is defined as the functional unit for this reason.

The Indian energy mix is characterized by an extensive use of fossil fuels (about 60% (Appendix A- Fig. IIa)) [40]. Therefore, calculating the environmental impact associated with power usage in each stage of the FA and NA production Indian Energy mix is considered. The author has developed a novel method for the manufacture of angular-shaped fly ash aggregate. All the optimum parameters, e.g., binder content and its type, time, temperature and type of curing, pressure required for casting of fly ash blocks, etc., are find out and used in this study [34, 35]. After critical market survey, all technical, energetic, and financial aspects of the production process were evaluated at the pilot-scale production plant, and similar data was used in this study (Appendix A- Table Ia to Va). Data on natural aggregate production procedure was collected from the aggregate manufacturers in the basalt quarry. The concept was to gather detailed and first-hand data on quarry equipment operation, electricity, water utilization, and transportation distances that reflected actual production parameters of local natural aggregates (Appendix B- Table Ib to VIIb). The SimaPro® 9.0.0.49 computer software was used to perform the LCA assessment. At the same time basic data for secondary processes were taken from the Ecoinvent v.3.5 (2018), US LCI (2015), and EU & DK Input Output (2010) databases and was updated with Indian data wherever applicable. Figure 1a and 1b demonstrates the system boundaries schematically for FA and NA production, respectively. Capital properties such as the infrastructure of the FA and NA manufacturing facilities, buildings, equipment, and vehicles, and their maintenance were purposely eliminated because no credible data is available. IMPACT 2002 + life cycle impact assessment method has been used in this study. This method offers a viable application of the combined midpoint and endpoint approach and has already been used in other similar work [17, 21, 37]. The method used 15 impact categories: carcinogens, noncarcinogens, respiratory effects, photochemical oxidation, ionizing radiation, ozone layer depletion, aquatic ecotoxicity, terrestrial acidification/nitrification, terrestrial ecotoxicity, aquatic eutrophication, land occupation, aquatic acidification, global warming, mineral extraction, non-renewable energy; and four damage categories: human health, ecosystem quality, climate change, resources.

Life cycle inventory

Case I: Production of fly ash aggregates (FA)

The location selected for this study is Reliance thermal power station, Hazira, Surat, Gujarat, India. The aggregate production plant is within the premises of the power station with a distance of 0.1 km from fly ash silos. The plant used a total area of 6000 m^2 with a production capacity of 40 tons/day. Raw material required for the plant is fly ash, which is available free of cost within the plant premises. Hydrated

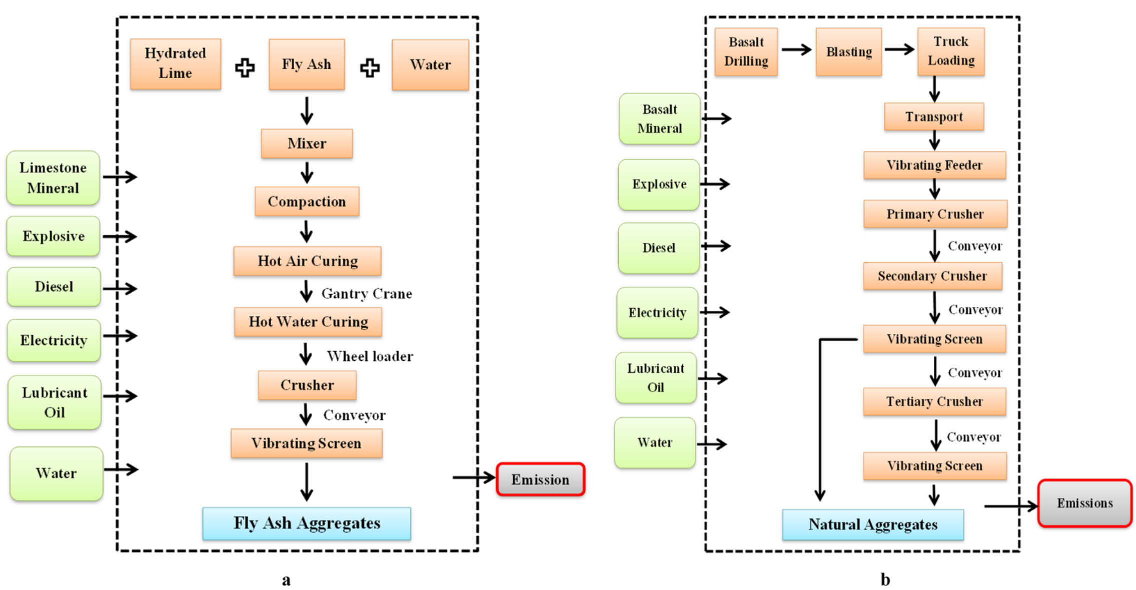


Fig. 1 System boundaries for **a** production of fly ash aggregates, **b** production of natural aggregates

lime has been transported from the source of lime, which is located 200 km from the production plant. The total burden associated with hydrated lime for its production and transportation to the plant has been considered in this study. The hydrated lime is transported to the factory and examined before being separated in silos.

The first step of fly ash aggregate production consists of mixing fly ash and lime with an appropriate percentage (98% fly ash + 2% lime) in a dry state. The dry materials (i.e., fly ash and hydrated lime) are transferred to the mixer by a screw conveyor from silos. Then the optimum quantity of water is added to it by effective means of the spray nozzle and mixed thoroughly in high shear bled mixer. After mixing, the rectangular blocks of size 230 mm × 110 mm × 60 mm were prepared using a hydraulic static press. Four blocks are produced in a single stroke and 35 tons of pressing force is applied on each block. The block-making machine produces an average of 960 blocks/h. The production plant is operated in 3 shifts, each shift consisting of 6.7 working hrs.; likewise, 19,296 numbers of the block are prepared per day. Next, prepared blocks are placed in a curing rack (500 blocks/rack) manually, and these racks are transferred into the hot air room with the portable crane. After the 6 h of hot air curing at a temperature of 50 °C crude blocks in racks are kept in the hot water bath for 24 h. at a temperature of 75 °C. Then, blocks are stockpiled at ambient temperature for 24 h. These blocks are fed into a vibratory feeder by a wheel loader and crushed by a horizontal shaft impact crusher. Finally, crushed material passes through a vibrating screen which produces different sizes of fly ash aggregates according to the construction requirement. The produced fly ash aggregates are stacked in the open-air. All the equipments are powered by electricity, and some engines require lubricating oils. The total electricity consumption during the production process has been correlated with the functional unit. The burden of raw material losses of 1% is considered in the present study.

Similarly, distance of aggregate transport to the consumer may vary with location and hence, it is not considered in the study. The avoided burdens of the fly ash landfilling and land-derived materials (basalt) due to the replacement of natural aggregates with fly ash aggregates have also been considered. As per the above data, Table 1 shows the direct and avoided burdens of each process for the production of 1 ton of fly ash aggregates.

Case II: Production of natural aggregates (NA)

The quarry considered for the study is located in Degam village of Valsad district in Gujarat, India with a total area of 5,00,000 m^2 out of which 3,00,000 m^2 are consist of exploitation area. The basalt type of rock is obtained from this quarry, which further reduces to different particle sizes of natural aggregates for various construction uses. The quarry yields 1600 ton/day aggregates, working for 16 h./day and 25 days/month. The system boundaries for production of natural aggregates with different stages and related equipment usage are schematically shown in Fig. 1b. The total water use for the perforation process is 6000 lit/day.

The basalt rock is perforated with a drill rig machine, after which explosives are positioned in the quarry and the rock is retrieved. Subsequently, the rock is loaded into a truck of 18 ton load capacity by using a hydraulic excavator having a load capacity of $3m^3$. The basalt processing facility is located at approximately 2 km from the pit. After transporting 2 km distance, this basalt is loaded into a vibrating feeder and crushed by a primary jaw crusher. Next, this crushed rock goes through a conical crusher (secondary

Table 1 Direct and avoided burdens of each process for production of 1 ton of fly ash aggregates and natural aggregates

Process	Fly ash (ton)	Basalt (ton)	Explosive (g)	Hydrated lime (ton)	Diesel (kg)	Lubricating oil (kg)	Electricity (kWh)	Water (L)	Distance (tkm)
Fly ash aggregates									
Raw materials	–	–	–	0.02	–	–	–	270	4
Mixing and compaction	–	–	–	–	–	0.001	8.950	–	–
Curing	–	–	–	–	0.850	–	0.850	180	–
Crushing and screening	–	–	–	–	0.265	0.002	0.624	–	–
Avoided impact (inert landfilling)	0.98	–	–	–	–	–	–	–	–
Avoided impact (land derived materials)	–	1.00	–	–	–	–	–	–	–
Natural aggregates									
Basalt extraction	–	1.05	150	–	0.041	0.019	–	0.07	–
Truck loading	–	–	–	–	0.265	0.017	–	–	–
Handling/transport	–	–	–	–	–	–	–	–	2.1
Crushing and screening		–	–	–	–	0.005	7.252	3.75	–

crusher) and a vibrating screen, which produces aggregates of various sizes as per the requirements. Lastly, the material goes via a tertiary crusher where good shape of aggregates of different particle sizes are produced. Several conveyor belts are used to transfer the material between the various crushers and a water sprinkler system is used to reduce dust dispersion. The equipments are powered by electricity and some engines require lubricating oils. The total power consumption in the manufacturing process has been fitted with the functional unit. The burden of aggregate losses is minimal and has not been considered in the study. Table 1 shows the direct burdens of each process for the production of 1 ton of natural aggregates.

Result and discussion

Impact assessment

To evaluate the critical sources of the impact associated with various production processes detailed life cycle analysis has been carried out and impact assessment and damage assessment (midpoint and endpoint categories) are interpreted in the present work. The findings are applicable only if the limitations and assumptions of the present work are taken into deliberation. Appendix A Table VIa shows the characterization results by impact category for production of fly ash aggregates (FA) and natural aggregates (NA). The production of FA exhibited excellent performance in terms of environmental impact in fourteen out of fifteen categories when compared to the case of NA production, demonstrating the benefits of utilization of fly ash aggregates. The NA contributes 21.60 kg CO_2 eq in the global warming midpoint category which is about four times higher than that of FA production. The results also illustrated that the FA conserved around 89% of non-renewable energy compared to NA. Even though the materials and production procedures are different, the physical and mechanical characteristics of FA and NA are comparable. Indeed, current research suggests that FA is a viable alternative material for the construction industry, particularly, for pavement applications as its performance is similar to that of NA [34, 35].

The life cycle impact assessment has also been executed according to the mandatory elements and normalization in person*year. The analysis of the normalized impacts of FA and NA production shows that six impact categories, namely, noncarcinogens, respiratory effects, terrestrial ecotoxicity, land occupation, global warming, and non-renewable energy, contribute about 98% of the total environmental impacts (Appendix A- Fig. IIIa and Appendix B- Fig. Ib). Consequently, these categories are chosen as the emphasis of the investigation. Comparable results were also presented for mix recycled aggregate production and recycled concrete aggregate production by Rosado et al. [17] and Martinez-Arguelles et al. [37].

Normalized results of selected impact categories for FA are given in Fig. 2a. Among the production process of fly ash aggregate raw materials consumption and mixing and compaction have a significant contribution to the respiratory inorganics, global warming, and non-renewable energy. This is due to the utilization of energy for the production process of hydrated lime from limestone, diesel consumption during transportation of hydrated lime from source to production plant, and electricity utilization in mixing and compaction processes. Similarly, during the mixing of raw materials very fine particles of fly ash and lime remain suspended in the air which contributes to respiratory inorganics. In addition, crushing and screening also contribute to the respiratory inorganics, global warming, and non-renewable energy category. On the contrary, the production of 1 ton of fly ash aggregate avoids the disposal of 0.98 tons of hazardous fly ash through landfilling and mining of 1 ton of basalt mineral. This significantly reduces the environmental impact of non-renewable energy, global warming, land occupation, terrestrial ecotoxicity, and respiratory effects categories.

The normalized findings of the impact assessment for production of natural aggregate are shown in Fig. 2b. The more significant influence of the categories “global warming”, “non-renewable energy” and “respiratory inorganics” for NA production are due to the basalt mining, crushing and screening. The emissions of ammonia, nitrogen oxides, and particulate matter (<2.5 mm) due to the use of diesel, explosive, and fine suspended particles of basalt during crushing and screening are the chief contributors to “respiratory inorganics” as per the data obtained from SimaPro. Furthermore, the crushing and screening process has a significant impact on the global warming and non-renewable energy categories due to the consumption of higher electricity throughout these processes. As expected, the basalt extraction also influences the “terrestrial ecotoxicity” due to aluminum mining for making explosive and “land occupation.” In fact, latest studies also show that the use of fossil fuels seems to be the chief contributor for the global warming, respiratory inorganics, and nonrenewable energy categories [17, 37, 41].

The impacts of electricity consumption associated with the mixing and compaction process for FA production (Fig. 2a) and crushing and screening operations for NA (Fig. 2b) production are found to be relatively higher than that of other processes. This is due to the Indian electricity mix (as shown in Fig. IIa Appendix A). The Indian electricity is characterized by a large use of fossil fuels, i.e., coal, lignite, gas, and diesel (about 59%). The use of fossil fuels acts as a major cause of “global warming” and “non-renewable energy” categories. According to Ruan and Unluer [42], energy was identified as the primary factor with the greatest impact on the environment of cement manufacturing also.

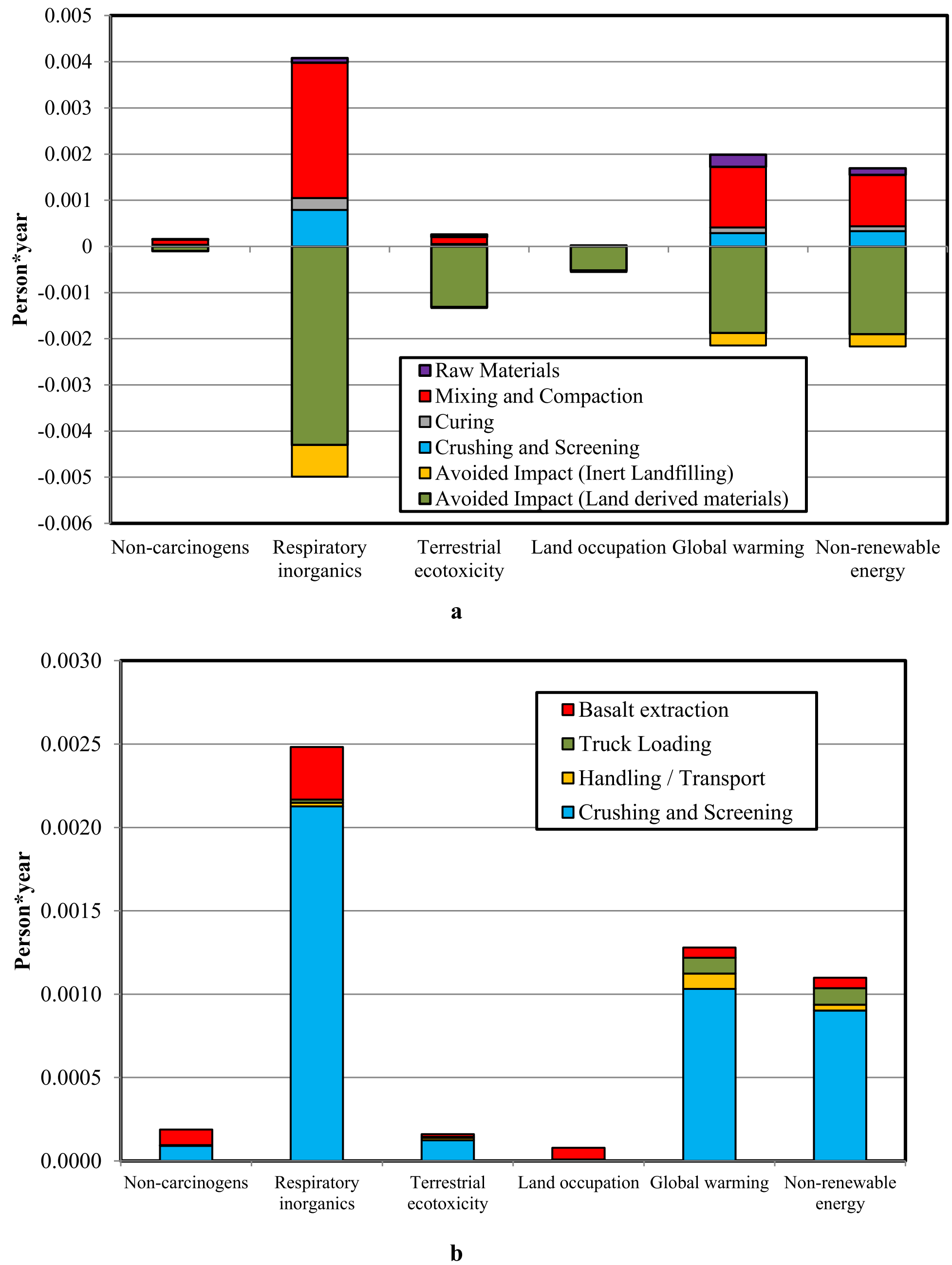
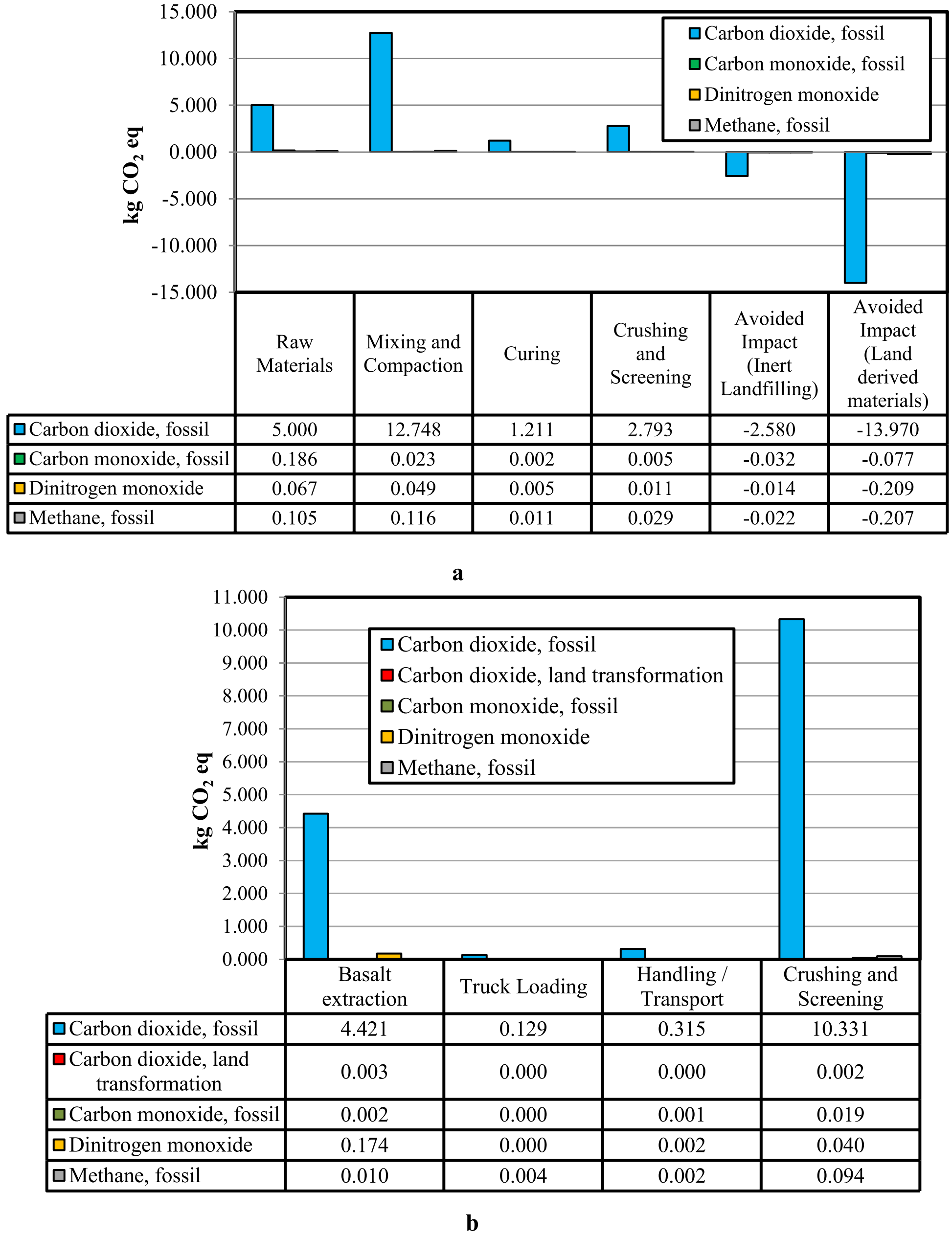


Fig. 2 Normalized impact assessment for **a** Fly ash aggregate, **b** natural aggregate production

The production process and transport distance (200 km) of hydrated lime, as well as electricity consumption for mixing and compaction of raw materials for FA production contribute on the most significant scale (90%) to "global warming" (Fig. 3a). The related CO_2 emission is about 5 kg CO_2 eq/t for the production of hydrated lime (which includes the production processes of mining, transport, crushing, screening, calcination, hydration, etc.) and its transport and 13 kg CO_2 eq/t for mixing and compaction process. Likewise, basalt extraction and crushing and screening of NA contribute on the largest scale to "global warming" (95%) with CO_2 emissions of 4.42 kg CO_2 eq/t for basalt extraction and 10.33 kg CO_2 eq/t for crushing and screening of NA (Fig. 3b).

Figure 4a shows that the consumption of diesel for the transport of lime and the utilization of electricity (hard coal) for mixing and compaction contribute 15% and 45% to "non-renewable energy," respectively. Additionally, the production and utilization of 1 ton FA in construction activity result in avoided impacts due to inert landfilling and extraction of 1 ton basalt. Ultimately, major impacts related to "global warming" and "non-renewable energy" categories are avoided.



a

	Raw Materials	Mixing and Compaction	Curing	Crushing and Screening	Avoided Impact (Inert Landfilling)	Avoided Impact (Land derived materials)
Carbon dioxide, fossil	5.000	12.748	1.211	2.793	-2.580	-13.970
Carbon monoxide, fossil	0.186	0.023	0.002	0.005	-0.032	-0.077
Dinitrogen monoxide	0.067	0.049	0.005	0.011	-0.014	-0.209
Methane, fossil	0.105	0.116	0.011	0.029	-0.022	-0.207

b

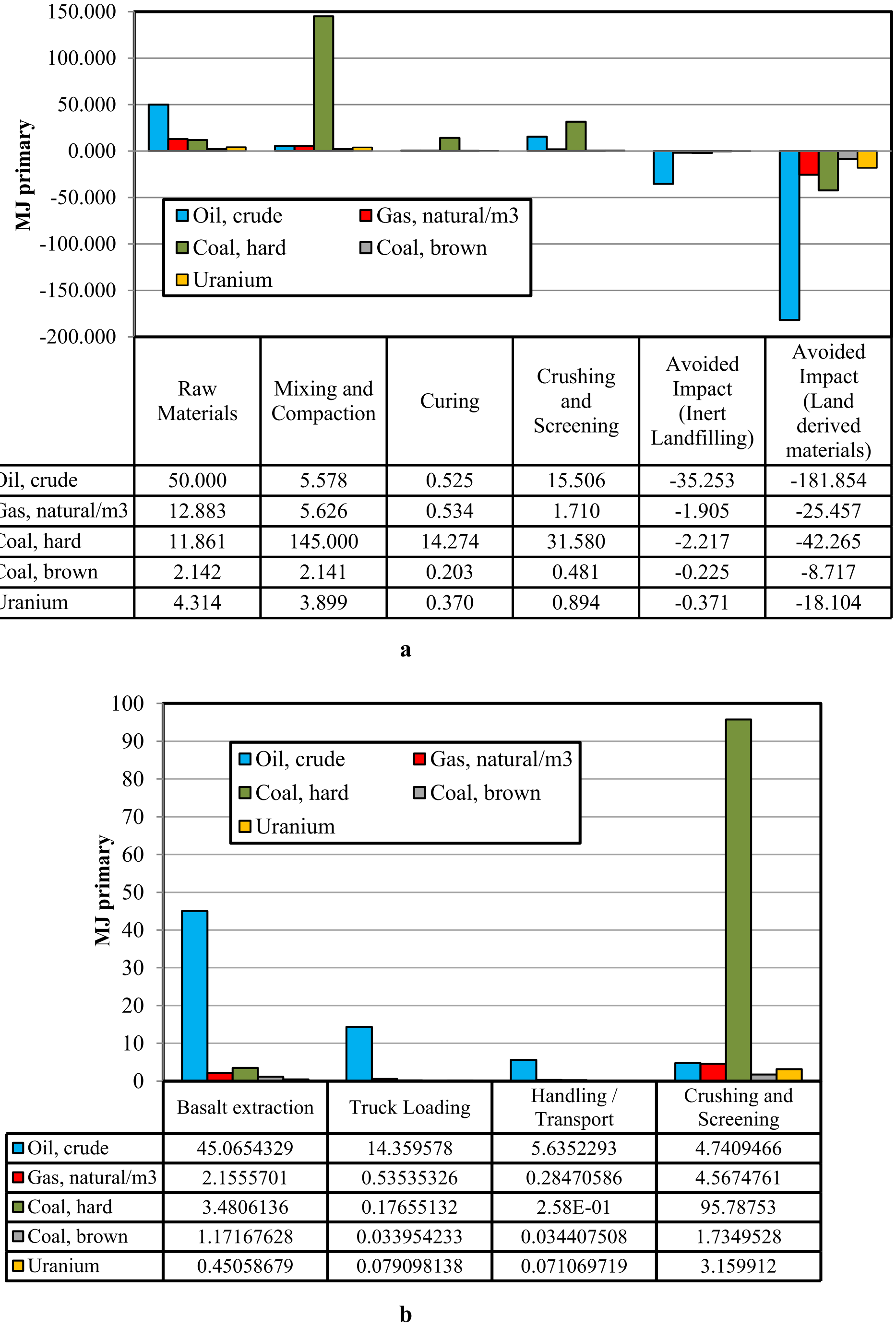
	Basalt extraction	Truck Loading	Handling / Transport	Crushing and Screening
Carbon dioxide, fossil	4.421	0.129	0.315	10.331
Carbon dioxide, land transformation	0.003	0.000	0.000	0.002
Carbon monoxide, fossil	0.002	0.000	0.001	0.019
Dinitrogen monoxide	0.174	0.000	0.002	0.040
Methane, fossil	0.010	0.004	0.002	0.094

Fig. 3 Contribution analysis for the impact category global warming for **a** Fly ash aggregate, **b** Natural aggregate production

Similarly, Basalt extraction, truck loading, handling/transport, and crushing and screening contribute about 28%, 8%, 3%, and 60%, respectively, to the "non-renewable energy" category (Fig. 4b). The higher contribution of crushing and screening is due to the use of hard coal for electricity production.

The normalized outcomes of the environmental impacts of the two examined scenarios are shown in Fig. 5a. The synthesis of fly ash aggregates benefits all the selected impact categories since it avoids the primary environmental burdens as indicated in the preceding section.

A similar comparison based on damage categories normalized results is shown in Fig. 5b. The overall performance of fly ash aggregate production appears superior, as it has significant environmental benefits in the damage categories of human health, ecosystem quality, and resources, while the natural aggregate production process has a negative impact on the climate change and human health category. Furthermore, when compared with recycled concrete aggregates in LCA studies [17, 37, 41], the production of fly ash aggregates has the most environmental benefits in all impact and damage categories.



	Raw Materials	Mixing and Compaction	Curing	Crushing and Screening	Avoided Impact (Inert Landfilling)	Avoided Impact (Land derived materials)
Oil, crude	50.000	5.578	0.525	15.506	-35.253	-181.854
Gas, natural/m3	12.883	5.626	0.534	1.710	-1.905	-25.457
Coal, hard	11.861	145.000	14.274	31.580	-2.217	-42.265
Coal, brown	2.142	2.141	0.203	0.481	-0.225	-8.717
Uranium	4.314	3.899	0.370	0.894	-0.371	-18.104

	Basalt extraction	Truck Loading	Handling / Transport	Crushing and Screening
Oil, crude	45.0654329	14.359578	5.6352293	4.7409466
Gas, natural/m3	2.1555701	0.53535326	0.28470586	4.5674761
Coal, hard	3.4806136	0.17655132	2.58E-01	95.78753
Coal, brown	1.17167628	0.033954233	0.034407508	1.7349528
Uranium	0.45058679	0.079098138	0.071069719	3.159912

Fig. 4 Contribution analysis for the impact category non-renewable energy for **a** Fly ash aggregate, **b** Natural aggregate production

Interpretation

For realistic sensitivity analysis of a LCA two criteria are mostly used, i.e., examining the impact of variation in a few key parameters and proposing a set of substitute possibilities to the base scenario [17, 21]. In this study, the first principle has been used by concentrating on a key factor, i.e., the maximum distance between the source of lime and the production plant. The aim was to determine the maximum transport distance of lime for which the environmental implications of fly ash aggregate production are comparable to that of the NA production. The analysis was carried out within a fixed distance of the basalt quarry from the crushing and screening facility at 2.1 ton-km and then, the distance between the source of lime and the production plant was gradually increased. The impact on "global warming" for production of FA and NA was found to be same for lime transport distance of 7 ton-km (which is obtained for distance of 350 km between source of lime and FA aggregate production

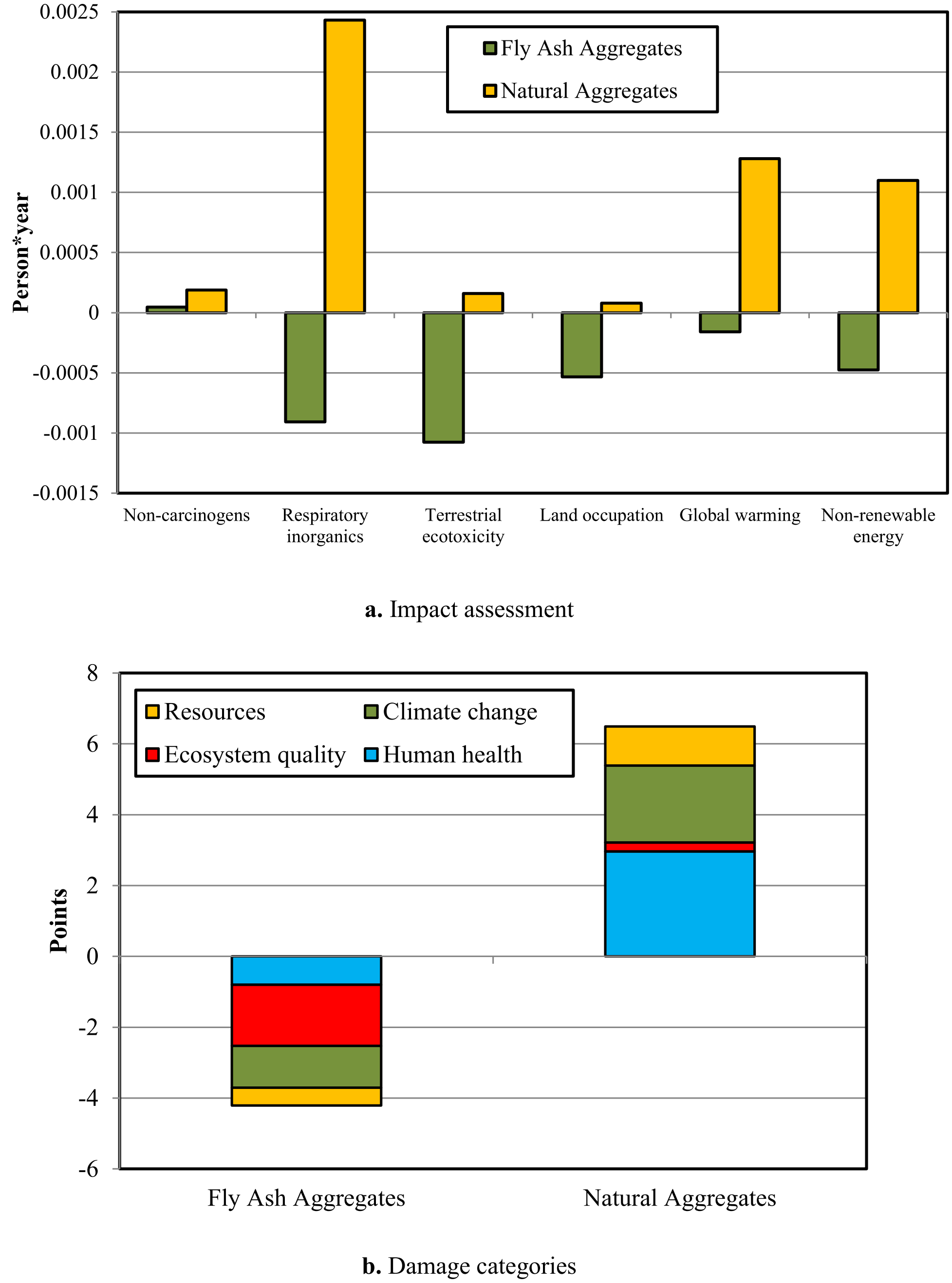


Fig. 5 Comparison normalized results for FA and NA production **a** impact assessment, **b** damage categories

plant) as shown in Fig. 6a. If the distance between source of lime and aggregate production plant is less than 350 km then impact of FA on "global warming" was found to be lower than that of NA, whereas, impact of FA and NA on "non-renewable energy" was found to be lower for lime transport distance of 39tkm (Fig. 6b). This indicates that impact of lime transport distance on "global warming" is found to be more than the impact on "non-renewable energy."

Limitations and future work

The findings of this work could be improved in a number of ways by subsequent research. The LCA study is very complex and it takes considerable effort to gather primary data for each of the unit processes. Several unit processes were modeled in the study through ecoinvent, US LCI and EU & DK input output databases. Although

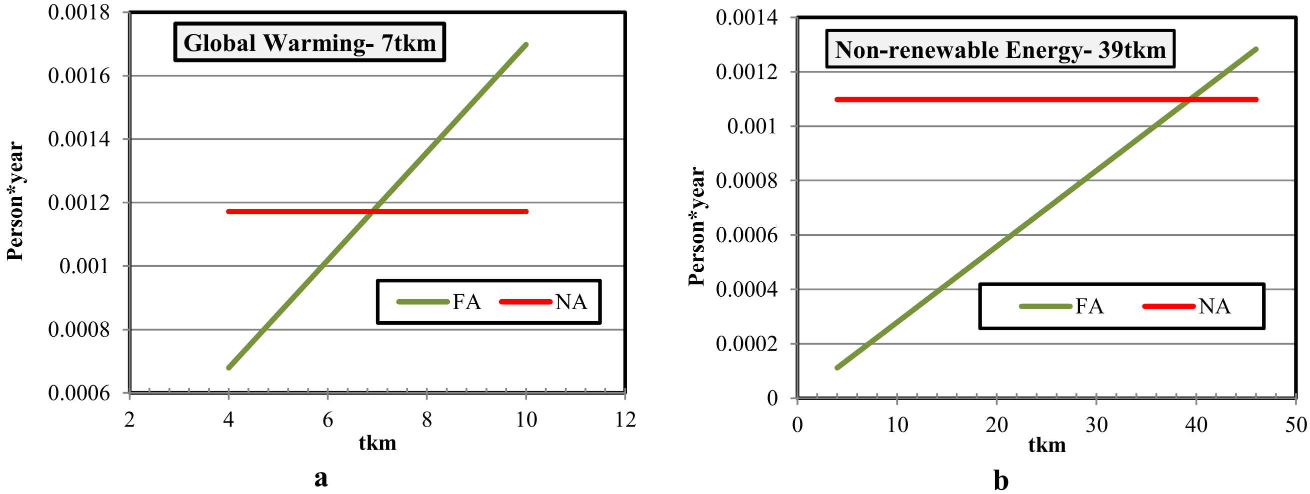


Fig. 6 Relationship between the impact categories and transport distance of lime and natural aggregates

the Indian quantum energy data have been used to set these processes according to local conditions, output of input from ecoinvent, USLCI and EU & DK databases may not be representative of an Indian scenario. Capital properties such as the infrastructure of the FA and NA manufacturing facilities, buildings, equipment, and vehicles and their maintenance were purposely eliminated because no credible data was available. Another area of improvement is the process of manufacturing of fly ash aggregates. In spite of the differences in production methods, comparisons must only be valid when materials are similar according to their mechanical and physical characteristics. Working efficacy of production plants can have main effect on life cycle assessment.

Conclusions

The environmental impact of fly ash aggregates has been carried out with a standardized LCA procedure and correlated with natural aggregates production in view of the increasing interest of national agencies, to use artificial aggregates for construction of civil infrastructures. The findings point to some important implications are given below. The findings are applicable only if the limitations and assumptions of the present work are taken into deliberation.

The hydrated lime production, transport of lime to the production plant, and mixing and compaction are the chief contributors to "respiratory inorganics," "terrestrial eco-toxicity," "land occupation," "global warming," and "non-renewable energy" impact categories for fly ash aggregates production scenario. It is hence essential to check the environmental performance of each alternative source of lime and improvement is the process of manufacturing fly ash aggregates.

The higher impacts of natural aggregate are due to the processes that utilize diesel and electricity and contribute to "respiratory inorganics," "global warming," and "non-renewable energy" categories. As Indian electricity mix is characterized by a bulky use of fossil fuels (about 60%) the process that uses electricity (in both cases) makes a significant contribution to the "global warming" and "non-renewable energy" categories. Conversely, the application of renewable energy for the production of fly ash aggregates will result in fewer effects on the environment than the current usage of fossil fuels, which reflects well for national efforts to cut GHG emissions and transition to a green economy.

The overall performance of fly ash aggregate production looks to be much better, as it has noticeable environmental benefits in all the damage categories of human health, ecosystem quality, climate change and resources. The utilization of a huge quantity of fly ash for the production of aggregate avoids the impacts due to inert landfilling and extraction of basalt.

The sensitivity analysis specifies that fly ash aggregate is the preferable alternative to natural aggregates for all the analyzed impact categories when the distance between the lime source and the aggregate production plant is up to 350 km. Alternatives to diesel-powered heavy-duty vehicles need to be investigated in as much detail as possible, especially those that use 100% electricity, biofuels, or both.

The presented results can be beneficial for further improvement in the proposed fly ash aggregate production process and similar LCA studies. Measures should be taken as a result of this study, to reduce CO_2 emissions by adopting and using green energy at aggregate production plants.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s41062-024-01382-z.

Declarations

Conflict of interest The authors declare that they do not have any known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Ethical approval This article does not contain any studies with human participants or animals performed by any of the authors.

Informed consent For this type of study, formal consent is not required.

References

1. Nistratov V, Klimenko NN, Pustynnikov IV, Long Kim V (2022) Thermal regeneration and reuse of carbon and glass fibers from waste composites. Emerg Sci J 6(5):967–984. https://doi.org/10.28991/ESJ-2022-06-05-04
2. Ambekar MS, Shahane HA (2021) Laboratory investigation of black cotton soil-fly ash-steel slag mixes. In: Proceedings of the Indian geotechnical conference 2019, lecture notes in civil engineering, vol 136, pp 717–726. https://doi.org/10.1007/978-981-33-6444-8_64
3. Alaj A, Krelani V, Numao T (2023) Effect of class F fly ash on strength properties of concrete. Civ Eng J 9(9):2249–2258. https://doi.org/10.28991/CEJ-2023-09-09-011
4. Arisha AM, Gabr A, El-Badawy R, Shwally SA (2018) Performance evaluation of construction and demolition waste materials for pavement construction in Egypt. J Mater Civ Eng 30(2):04017270. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002127
5. Sunarsih ES, Asad S, Mohd Sam AR, Kristiawan SA (2023) Properties of fly ash-slag-based geopolymer concrete with low molarity sodium hydroxide. Civ Eng J 9(2):381–392. https://doi.org/10.28991/CEJ-2023-09-02-010
6. Gomathi P, Sivakumar A (2015) Accelerated curing effects on the mechanical performance of cold bonded and sintered fly ash aggregate concrete. Constr Build Mater 75:276–287. https://doi.org/10.1016/j.conbuildmat.2014.12.108
7. Kayali O (2008) Fly ash lightweight aggregates in high-performance concrete. Constr Build Mater 12(22):2393–2399. https://doi.org/10.1016/j.conbuildmat.2007.09.001
8. Mishra MP, Shahane HA (2021) Effect of tiles waste and fly ash brick waste on permeability and strength of lower granular subbase material. In: Proceedings of the Indian geotechnical conference 2019, Lecture notes in civil engineering, vol 134, pp 359–367. https://doi.org/10.1007/978-981-33-6370-0_32
9. Patel S, Shahu JT (2016) Resilient response and permanent strain of steel slag-fly ash-dolime mix. J Mater Civ Eng 28(10):1–11. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001619
10. Tuladhara R, Marshallb A, Sivakuganc N (2020) Use of recycled concrete aggregate for pavement construction. In: Advances in construction and demolition waste recycling, pp 181–197. https://doi.org/10.1016/B978-0-12-819055-5.00010-3
11. Ottosen LM, Thornberg D, Cohen Y, Stiernström S (2022) "Utilization of acid-washed sewage sludge ash as sand or cement replacement in concrete. Resour Conserv Recycl 176:105943. https://doi.org/10.1016/j.resconrec.2021.105943
12. Hasan U, Whyte A, Jassmi HA (2020) Life cycle assessment of roadworks in United Arab Emirates: recycled construction waste, reclaimed asphalt pavement, warm-mix asphalt and blast furnace slag use against traditional approach. J Clean Prod 257:120531. https://doi.org/10.1016/j.jclepro.2020.120531
13. Gayarre FL, Pérez JG, Pérez CLC, López MS, Martínez AL (2016) Life cycle assessment for concrete kerbs manufactured with recycled aggregates. J Clean Prod 113:41–53. https://doi.org/10.1016/j.jclepro.2015.11.093
14. Jain S, Singhala S, Pandey S (2020) Environmental life cycle assessment of construction and demolition waste recycling: a case of urban India. Resour Conserv Recycl 155:104642. https://doi.org/10.1016/j.resconrec.2019.104642
15. Huanga TY, Chuieh PT (2015) Life cycle assessment of reusing fly ash from municipal solid waste incineration. Procedia Eng 118:984–991. https://doi.org/10.1016/j.proeng.2015.08.539
16. Hossain MU, Poon CS, Lo IMC, Cheng JCP (2016) Comparative environmental evaluation of aggregate production from recycled waste materials and virgin sources by LCA. Resour Conserv Recycl 109:67–77. https://doi.org/10.1016/j.resconrec.2016.02.009
17. Rosado LP, Vitale P, Penteado CSG, Arena U (2017) Life cycle assessment of natural and mixed recycled aggregate production in Brazil. J Clean Prod 151:634–642. https://doi.org/10.1016/j.jclepro.2017.03.068
18. Blengini GA, Garbarino E (2010) Resources and waste management in Turin (Italy): the role of recycled aggregates in the sustainable supply mix. J Clean Prod 18(10–110):1021–1030. https://doi.org/10.1016/j.jclepro.2010.01.027
19. Blengini GA (2009) Life cycle of buildings, demolition and recycling potential: a case study in Turin, Italy. Build Environ 24(2):319–330. https://doi.org/10.1016/j.buildenv.2008.03.007
20. Penteado CSG, Rosado PL (2016) Comparison of scenarios for the integrated management of construction and demolition waste by life cycle assessment: a case study in Brazil. Waste Manag Res 34(10):1026–1035. https://doi.org/10.1177/0734242X16657605
21. Vitale P, Arena N, Di Gregorio F, Arena U (2017) Life cycle assessment of the end of-life phase of a residential building. Waste Manag 60:311–321. https://doi.org/10.1016/j.wasman.2016.10.002
22. Zhao X, Webber R, Kalutara P, Browne W, Pienaar J (2021) Construction and demolition waste management in Australia: a mini-review. Waste Manag Res 40(1):34–46. https://doi.org/10.1177/0734242X211029446
23. Coelho A, de Brito J (2013) Environmental analysis of a construction and demolition waste recycling plant in Portugal—part I: energy consumption and CO_2 emissions. Waste Manag 33(5):1258–1267. https://doi.org/10.1016/j.wasman.2013.01.025
24. Coelho A, de Brito J (2013) Environmental analysis of a construction and demolition waste recycling plant in Portugal—part II: environmental sensitivity analysis. Waste Manag 33(1):147–161. https://doi.org/10.1016/j.wasman.2012.09.004
25. Ferronato N, Lizarazu GEG, Portillo MAG, Moresco L, Conti F, Torretta V (2021) Environmental assessment of construction and demolition waste recycling in Bolivia: Focus on transportation distances and selective collection rates. Waste Manag Res 40(6):1–13. https://doi.org/10.1177/0734242X211029170
26. Ibáñez-Forés V, Bovea MD, Simó A (2011) Life cycle assessment of ceramic tiles. Environmental and statistical analysis. Int J Life Cycle Assess 16:916–928. https://doi.org/10.1007/s11367-011-0322-6
27. Mercante IT, Bovea MD, Ibáñez-Forés V, Arena AP (2012) Life cycle assessment of construction and demolition waste management systems: a Spanish case study. Int J Life Cycle Assess 17:232–241. https://doi.org/10.1007/s11367-011-0350-2
28. Butera S, Christensen TH, Astrup TF (2015) Life cycle assessment of construction and demolition waste management. Waste Manag 44:196–205. https://doi.org/10.1016/j.wasman.2015.07.011

29. Chowdhury R, Apul D, Fry T (2010) A life cycle based environmental impacts assessment of construction materials used in road construction. Resour Conserv Recycl 54(4):250–255. https://doi.org/10.1016/j.resconrec.2009.08.007
30. Knoeri C, Sanyé-Mengual E, Althaus HJ (2013) Comparative LCA of recycled and conventional concrete for structural applications. Int J Life Cycle Assess 18:909–918. https://doi.org/10.1007/s11367-012-0544-2
31. Marinković S, Radonjanin V, Malešev M, Ignjatović I (2010) Comparative environmental assessment of natural and recycled aggregate concrete. Waste Manag 30(11):2255–2264. https://doi.org/10.1016/j.wasman.2010.04.012
32. Kockala NU, Ozturanb T (2010) Effects of lightweight fly ash aggregate properties on the behavior of lightweight concretes. J Hazard Mater 179(1–3):954–965. https://doi.org/10.1016/j.jhazmat.2010.03.098
33. Nayak B (2001) A process for manufacture of cold bonded aggregate pellet from fly ash of thermal power plant for constructional use. Indian Patent No. 216945, Patent and Trademark Office, New Delhi, India
34. Shahane HA, Patel S (2020) Influence of curing method on characteristics of environment-friendly angular shaped cold bonded fly ash aggregates. J Build Eng 35:101997. https://doi.org/10.1016/j.jobe.2020.101997
35. Shahane HA, Patel S (2022) Influence of design parameters on engineering properties of angular shaped fly ash aggregates. Constr Build Mater 327:126914. https://doi.org/10.1016/j.conbuildmat.2022.126914
36. CEA (2020) “Report on fly ash generation at coal/lignite based thermal power station and its utilization in the country for the year 2019–20” Central electricity authority, Ministry of Power, New Delhi, Government of India
37. Martinez-Arguelles G, Acosta MP, Dugarte M, Fuentes L (2019) Life cycle assessment of natural and recycled concrete aggregate production for road pavements applications in the Northern Region of Colombia: case study. Transp Res Rec. https://doi.org/10.1177/0361198119839955
38. Chinnu SN, Minnu SN, Bahurudeen A, Senthilkumar R (2021) Recycling of industrial and agricultural wastes as alternative coarse aggregates: a step towards cleaner production of concrete. Constr Build Mater 287:123056. https://doi.org/10.1016/j.conbuildmat.2021.123056
39. ISO 14044 (2006) Environmental management: life cycle assessment, life cycle impact assessment. International Organization for Standardization, Geneva
40. Installed generation capacity (fuelwise), Minisry of of Power, Government of India. https://powermin.gov.in/en/content/power-sector-glance-all-india. Accessed 10 July 2022
41. Estanqueiro B, Silvestre JD, de Brito J, Pinheiro MD (2018) Environmental life cycle assessment of coarse natural and recycled aggregates for concrete. Eur J Environ Civ Eng 22(4):429–449. https://doi.org/10.1080/19648189.2016.1197161
42. Ruan S, Unluer C (2016) Comparative life cycle assessment of reactive MgO and Portland cement production. J Clean Prod 137:258–273. https://doi.org/10.1016/j.jclepro.2016.07.071