delivery not suitable for DfMA implementation. Methods that can enable a concurrent and integrated project delivery, like the establishment of an interdisciplinary design team, are thus preferred. Such methods can better involve the manufacturing and construction experience into the design. In this way, the determined DfMA principles can be appropriately followed without sacrificing the aesthetics and structural performance of the building.

CONCLUSION

This study investigates the implementation of DfMA in a real prefabricated bamboo building project. It was found that the application of DfMA principles to construction projects requires the designer to fully consider the ease of manufacture and construction in the design phase. Knowledge about manufacture and construction should be provided to the designer as early as possible. Therefore, the establishment of a multi-disciplinary design team might be one of the prerequisites for DfMA implementation. A more effective way to implement DfMA could be the adoption of a more integrated project delivery method, like Engineer–Procure–Construct (EPC), which can largely remove the fragmentation of project stakeholders.

The case study also shows the use of parametric design tool to facilitate the implementation of DfMA, and reveals benefits of DfMA including the increased productivity and quality, reduced production duration, and decreased waste. However, it should be noted that DfMA is complex and incorporates several distinct elements, the data reported in this study may not be enough to illustration the full breadth of DfMA's benefits. Future work can be conducted to further analyze the implementation of DfMA in other types of construction projects.

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Environmental Implications of Quarry Rock Dust: A Sustainable Alternative Material to Sand in Concrete

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ABSTRACT

Sand is a vital natural resource of our ecosystem, yet the construction industry is threatening its availability. Excessive mining of sand imposes adverse effects on our environment, and this problem is becoming extremely severe as it is exposing the river ecosystem and endangering marine biodiversity across the world (i.e., Tamil Nadu in India, Poyang in China, and California in the United States). Quarry rock dust (QRD), a waste obtained during the quarrying process is a significant source of air pollution yet has the potential of becoming a sustainable and economical alternative to sand in concrete. Studies confirmed that replacing sand in conventional concrete with QRD increases its durability and robustness by ten percent. The objective of this study is to determine QRD's environmental implications through carbon footprint analysis. To achieve this, the research utilizes one of the very few case studies of Barbados Quarry site that produces more than 35,000 tons of aggregates per month and 500,000 tons of QRD is produced as a by-product. This research prepares a preliminary life cycle analysis of QRD, its carbon dioxide emissions as well as the economical analysis of QRD. The findings of this study promote the use of QRD considering its less environmental impact in comparison to sand when used in concrete. The study also encourages a paradigm shift in concrete practices, which not only paves for a more resilient alternative to concrete but also a more sustainable construction process.

KEYWORDS: Environmental Implication; Quarry Rock Dust; Sustainability; Construction Waste; Alternatives in Concrete Mixes

INTRODUCTION

Construction materials are one of the major sources of greenhouse gases (GHG). Cement, aggregate, and sand are the best examples of such materials that are extensively utilized during the construction process, especially in concrete structures, posing adverse environmental concerns. Research studies conducted on Life Cycle Assessment (LCA) of concrete have shown that the production of cement produces enormous amounts of greenhouse gases that ultimately lead to global warming (Hendriks et al. 2003). Similarly, an LCA study about aggregate production in Iran indicated that about 2.88 million tons of CO_2 equivalent emissions are produced from the consumption of 1.48 million tons of oil per year (Ghanbari et al. 2017). The United States is one of the largest aggregate producers from quarries, with 2 billion tons of aggregates produced every year. Furthermore, it is expected to rise to 2.5 billion tons by 2020 (Ghanbari et al. 2017; Kankam et al. 2017). Quarry rock dust (QRD), which is a waste obtained as a by-product from the quarrying process of aggregate is also produced in large amounts and then disposed into landfills causing air and land pollution as well as triggering severe impacts on the peoples' health and wellbeing. Experimental studies tested the use of this by-product in concrete and reported that the depth of water penetration for QRD based concrete and conventional concrete was 10mm and 16mm respectively, indicating that the permeability of QRD based concrete is lower compared to controlled concrete.

Moreover, QRD based concrete has comparatively 10-15% higher strength than traditional concrete (Kankam et al. 2017). Previous research studies assumed greater impacts of QRD on the environment, especially that the QRD require additional processes, washing, and refining, to be suitable in concrete. Despite such an assumption, there remains a literature gap pertaining to the QRD environmental implications. Hence, the preliminary LCA of QRD gives an opportunity to measure how its life cycle contributes to an extensive set of environmental indicators, which may include damaging the human health, ecosystem and causes depletion to our finite resource. However, in this research, only preliminary carbon footprint analysis is conducted based on energy consumed to determine CO_2 emitted from the operation of equipment used to produce aggregate and QRD.

LITERATURE REVIEW

For over many centuries, sand has been the most prevalent construction material, and its demand continues to rise, especially that sand is predominant in connecting structures as well as integral in various building finishes. Excessive mining of sand causes river degradation, bank erosion, higher greenhouse gases emissions and the compound effect leads to sea level rise (Frederik et al. 2010). Also, the extraction of instream sand from rivers could cause significant changes in river channel morphology, which eventually leads to the destruction of the aquatic ecosystem and riparian habitat (Ashraf et al. 2011). Despite these undesirable consequences of natural mining of sand, its integration in construction, especially in concrete is immense (Saviour 2012). Such continuous exploitation of natural sand for construction will lead to a shortage of sand in specific regions as well as increasing its price. In fact, the gradual increase in fuel prices has reflected on an increase in the cost of sand associated with transportation costs. Additionally, another study demonstrates that reverting to the purchase of low-quality sand pose an increased risk of negatively impacting the structure and durability of building finishes (Peckenham et al. 2009). With a shortage of sand caused by excessive mining, the cost is expected to escalate even more (Horvath 2004). As a result, the cost of sand has escalated even at places where sand is available in abundance. Nowadays, many researchers are exploring the incorporation of QRD in concrete mix design by partially replacing sand with QRD for more sustainable and economic perspectives. To this end, QRD can be utilized in concrete without impairing the strength and durability of the structures.

An enormous amount of quarry dust is produced due to different quarrying activities including (a) extraction processes (such as drilling and blasting, loading and hauling, overburden removal); (b) rock preparation (such as primary crushing, pre-screening and screening); and (c) further processing activities like secondary, tertiary comminution stages, and screening and treatment stages (Safiuddin et al. 2010). In general, the by-product of quarry rock is composed of analogous mineral substances found in solid rock and soil, and QRD is inert or non-hazardous by nature (Radikesh P. Nanda 2010). However, environmental settings such as exposure to inappropriate atmospheric conditions (e.g., disaggregation in surface or groundwater), may transform QRD physically and chemically. Such exposure transforms QRD to hazardous, and develops detrimental effects on the environment and the peoples' health and wellbeing (Ghadebo and Bankole 2007). Thus, to reduce such environmental impacts as well as embrace sustainability within the construction industry, the utilization of QRD has been explored in concrete mix designs. The increasing human and environmental constraints require such sustainable alternatives to modern construction problems (Mohamed ElZomor and Kristen Parrish 2016). For instance, construction projects are becoming progressively larger and more complex in terms of management of scarce resources such as materials (Ahuja et al. 1994). The abundance of QRD, as well as its low-cost, and sustainable and efficient end-product contributes to successful project executions. Such efficacious projects are vital in maintaining service throughout the nation (ElZomor et al. 2018).

Hudson et al. (1997) studied the performance of concrete by adding quarry dust instead of sand using trial mixes of 3-20% partial replacement and a fixed water to cement ratio of 0.7. Their study found that the permeability of concrete, as well as the rate of liquid ingression, decreased when the increase in percentage replacement of sand is within 20%. Similarly, Devi and Kannan (2011) highlighted the use of quarry dust as fine aggregate in concrete supporting the strength and corrosion properties of quarry dust-based concrete along with an organic inhibitor, Triethanolamine. Their findings reveal that 100% sand replacement with 2% Triethanolamine could delay corrosion as well as increases strength and durability in reinforced concrete structures. A comparison also related to the concrete modulus of elasticity for replacement of sand at different levels including 0%, 25% and 100% by weight and found that the use of QRD produced concrete with improved mechanical properties (Kankam et al. 2017).

OBJECTIVE AND SCOPE

A Quarry rock has several stages in its lifecycle, and in each stage, there is an impact on the environment. However, a quarry rock dust is produced as a by-product during the process of producing coarse aggregates in the crushing unit, and its life cycle greenhouse gases emissions (LC-GHG) is identical to the aggregate production. The quarry rock dust particles from the crushing unit are obtained in different sizes which are either disposed in land or utilized in road construction projects based on type and size of dust produced. But these dust particles cannot be directly used in concrete without including an additional step, which is a refining process. With the use of EvoWash Sand Washing technology (M2500), the QRD is sieved, washed, and dried to form a refined QRD. The obtained QRD from EvoWash Sand Washing technology (M2500) is suitable to be added in concrete. Hence, through preliminary carbon footprint analysis, this research provides comparisons between the carbon dioxide emissions of sand and quarry rock dust based on their resource and environmental profile. In fact, the comparisons are more valid when their services, end-uses, and duration are the same, i.e., the use in concrete mix designs. Therefore, the primary objectives of this analysis are:

a. To identify the suitable processes of quarry rock dust production for use in concrete.
b. To conduct preliminary carbon footprint analysis of QRD based on the method of production.
c. To compare carbon dioxide emissions between sand and QRD.

The use of QRD in concrete is beneficial not only in terms of strength and durability but also the reduction of environmental impacts. However, there is no evidence whether its production process which involves the use of EvoWash sand washing technology (M2500 E3) for refining and washing QRD from the quarry site has lower environmental implications (Global 2017). Considering that the use of QRD has been progressing in many countries like India, Ghana, France, United Kingdom, and Italy, it is significant that comprehensive studies are conducted to identify its life cycle assessment. Such studies would support providing an engineered decision on material choices with reduced environmental implications, thus confirming whether the use of

QRD in conventional concrete mixes is more sustainable than sand.

METHODOLOGY

Case Study

This research seeks to study the environmental impacts including carbon footprint, CO_2 emissions and energy consumption, when utilizing quarry rock dust, as a sustainable alternative material to sand in concrete. A case study approach is adopted in this research, as it is a reliable approach for apprehending comprehensive information. The study chose one of the few case studies of a quarry site, which is in Barbados known as Coral limestone quarry site. Geographically, there are huge deposits of limestone in this area of Barbados, and CDE Global operates 250 tons per hour crushing plant processing coral limestone. The quarry site produces over 35,000 tons of aggregate per month where 500,000 tons of the minus 6mm of waste material stockpiles in the site. This waste, when processed using the EvoWash Sand Washing technology (M2500) over 500 tons of refined quarry rock dust, is produced every day suitable for use in concrete to partially replace sand. The M2500 model of EvoWash sand washing accepts 100 tons per hour of crushed QRD such as limestone, and the final product makes up to 31 tons per hour of the feed which represents 31% of the original material (Global 2017).

Preliminary Carbon footprint analysis

In this study, CO_2 emissions and energy consumption are the primary variables evaluated for determining the carbon footprint that is emitted from the production of QRD. Initially, the processes involved in the production of quarry rock dust and its refining procedures are identified as shown in Figure (1). Based on identified processes, the quarry assessment for this study is divided into two parts. The first section will focus on aggregate production and activities associated with it. The second section is related to refining and washing of quarry rock dust to make it a practical and marketable product. As shown in Figure (1), the process involved in the production of aggregate and QRD includes:

a. Using single arm jumbo drilling machine and Tovex explosive for drilling and blasting of limestone, sandstone, marble, and granite, among others, in the quarry site which breaks down the bedrock into transportable sizes.
b. A single front end loader is then, used to load the crushed rock into haul trucks. These haul trucks are repeatedly used for hauling of materials continuously between primary crusher and quarry.
c. Finally, the haul truck transports the material up to the primary crusher where coarse aggregates are produced, and as a result the quarry rock dust is produced as a by-product.

Similarly, the processing life cycle phase of QRD generally incorporates primary crushing, scalping screening, secondary crushing, tertiary crushing, quaternary crushing, and final screening. The fragments of QRD vary among different rock types. Based on research studies, limestone quarry and dolomite quarry provide 20-25% quarry dust and sandstone/gritstone up to 35% quarry dust. Also, based on the level of dust (e.g., <75 μm), the use of QRD may be restricted, and in such condition, an aggregate washing may become necessary thus adding an extra step to the process. Indeed, the factors like extraction method used for quarrying, processing route, and type of rock influences the generation of QRD and their end characteristics like composition, particle size, and shape. Finally, the obtained QRD is then fed to the feeder in EvoWash sand washing technology (M2500) where QRD is washed and dried.

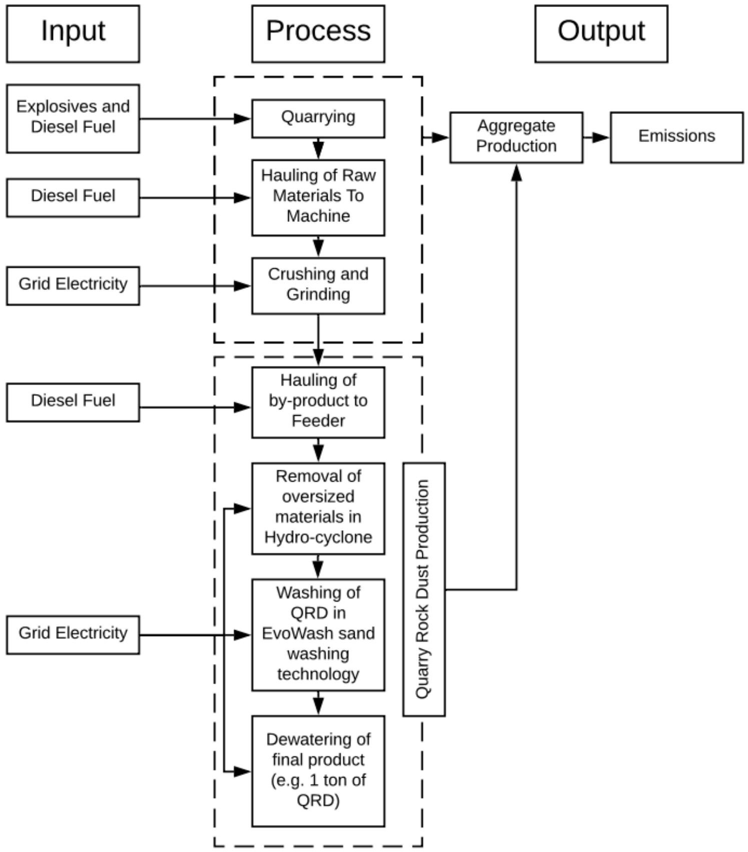

Figure 1. Systematic approach to QRD production process

RESULTS AND DISCUSSION

The guidelines of the US Environmental Protection Agency (EPA) is used for determining CO_2 emissions from different equipment in the quarry site (EPA 1990). The computation of energy consumed on each of the stages is conducted based on equation (1) where P stands for Power rating of each equipment and h stands for operating hours of each of the equipment. Equation (2) provides values for CO_2 emissions where E represents emissions, A represents energy consumption, EF represents the emission factor, and ER stands for efficiency percentage to reduce emission. The effect of ER is ignored in equation (2) to increase the confidence of this preliminary study. Furthermore, electrical and diesel emissions that result from energy consumption are estimated separately.

$$A = P\,x\,h \qquad \text{Equation (1)}$$

$$E = A\,x\,EF\,x\left(1 - \frac{ER}{100}\right) \qquad \text{Equation (2)}$$

By using equation (1), corresponding values of energy consumption of each of the equipment were determined. The values of total energy consumed by equipment in extraction and mining and crushing and screening unit were obtained based on the study of life cycle assessment of aggregate production (Ghanbari et al. 2017). Additionally, the energy consumed by EvoWash sand washing technology was determined from the case study of Barbados (Global 2017). Figure (2) shows the energy consumed by different equipment in each stage of quarry rock dust production where crushing unit and hydraulic excavator consume higher energy of 647 and 610

Kwhr, respectively. On the other hand, the energy consumed by Evo wash sand washing technology is relatively lower in relation to the energy consumed in the other two stages of quarrying.

Based on the EPA guidelines, the research determined the corresponding values of CO_2 emissions by using equation (2). The values of emission factor in equation (2) are determined based on the type of energy source used by the equipment. For instance, for electric and diesel, the corresponding values of the emission factor are 1.2 and 3.02, respectively. Therefore, the highest carbon footprint was obtained in the extraction and mining stage with the emission of 1,347 tons of CO_2 year whereas Evo Wash technology has the lowest carbon footprint of 122.85 tons of carbon dioxide equivalent per year, as shown in Figure (3). Additionally, Singh et al. (2017) indicated that one ton of conventional concrete emits 410 Kg/m^3 of carbon dioxide. On the other hand, carbon dioxide emissions from marble dust based concrete (i.e. by-product from marble quarry) are reduced to 350 Kg/m^3 when using quarry rock dust as a partial replacement in concrete mixes. Therefore, the use of quarry rock dust has lower carbon footprint both during its production phase as well as when used in concrete.

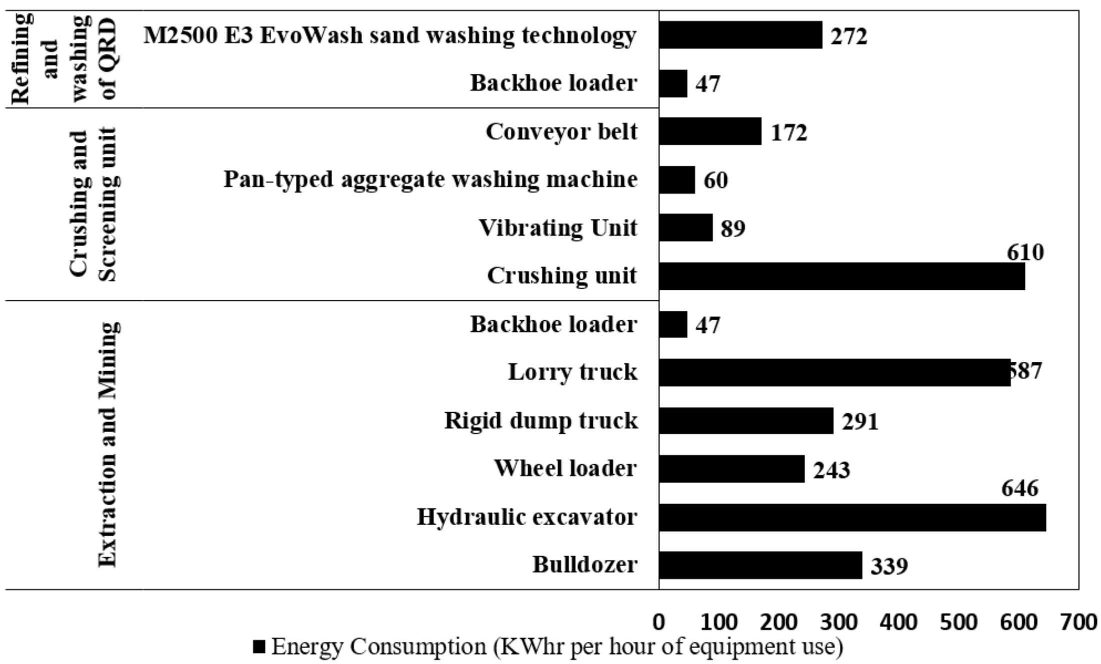

Figure 2. Energy consumed by equipment in each quarrying process stage

Cost Estimates

Quarry rock dust as a by-product is an economical substitute material in concrete mixes especially that it is easily available, free and in abundance. During crushing aggregates in quarry sites, most of the obtained dust is either improperly disposed or end up used in road construction. Such dust particles could be utilized in concrete by replacing sand at different percentages. Studies have investigated partial replacement of sand by quarry dust at 25%, 50%, 75% and 100% (Ilangovana et al. 2008). Based on these different percentages of replacement, the cost also varies. According to Singh et al. (2017), the cost for 1 m^3 concrete with substitution of sand by 25% of QRD is estimated to be $36.05 based on India's cost breakdown of concrete. In figure 4, the corresponding quantities of different concrete materials (Kg/m^3) multiplied by their unit rate

(USD/Kg) provide the total cost of each material in concrete mix (USD/m^3). Here, due to ample availability of water for construction purpose, the rate of water is assumed to be zero and the corresponding total cost is also obtained as zero. Furthermore, the results of the cost estimates indicate that the price of QRD (i.e. \$2.04/m^3) is lower than other materials in the concrete mix.

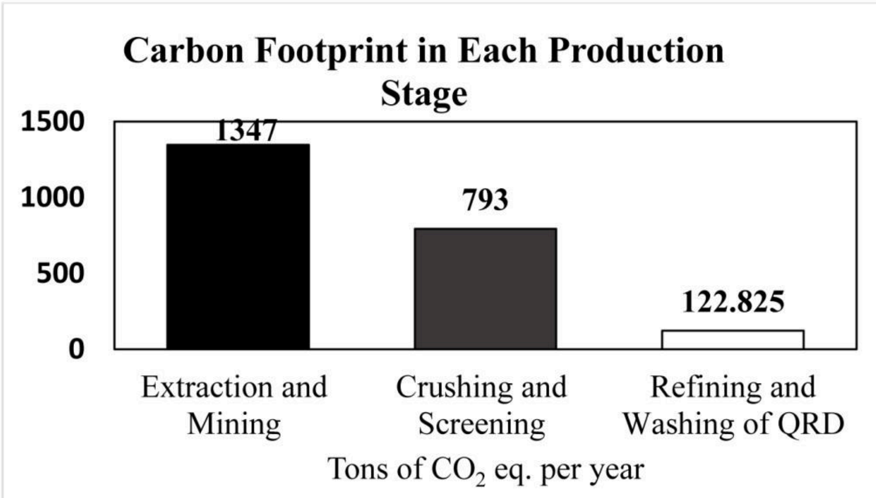

Figure 3. CO_2 emissions in each stage of QRD production

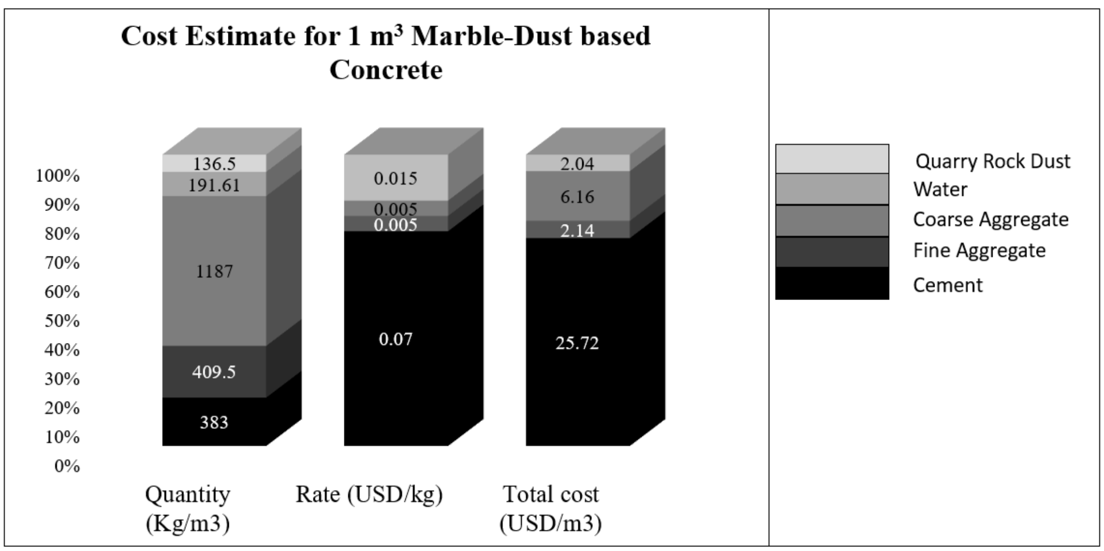

Figure 4. Cost estimates for 1 m^3 of Concrete with 25% replacement of sand with QRD

LIMITATION AND FUTURE WORK

The quarrying process of mineral products and their by-products involves exploration, manufacture, processing, and transportation where each process is responsible for emissions throughout the quarrying activities. However, there is no data available on fugitive emissions, like leakages from quarrying equipment, and any other mining operation processes. Hence, one limitation of the analysis exists due to the lack of a comprehensive database dedicated to some special quarrying conditions. Another limitation was associated with the scarcity of data of Quarry sites in the US that produced refined QRD, resulting in an incomplete life cycle assessment. Rather the study provided valuable information and analyses that could trigger future studies.

Future research work can study assessment of all possible greenhouse gases (GHG) emissions associated with the production of quarry rock dust that can be integrated into concrete mixes. Additionally, future studies may (1) focus on the juxtaposition of QRD based concrete and conventional concrete in terms of their life cycle greenhouse gases emission; and (2) analyze whether the use of QRD in concrete is more sustainable and durable than sand.

CONCLUSION

Quarrying of limestone, marble, and granite produce QRD as a by-product material; therefore, the CO_2 emission for QRD is equivalent to that of aggregates produced in quarry site. Furthermore, the additional processing required for washing and refining of quarry rock dust have a relatively lower carbon footprint based on the method of production. In fact, refining and washing of QRD produces 122.825 tons of CO_2 equivalent per year whereas mining of sand produces 4.6 kg of CO_2 per tons of sand indicating that mining of sand produces more carbon footprint annually. Certainly, the production and use of QRD in concrete has less carbon footprint than natural river sand because with each ton of sand mined from rivers there is equivalent production of 4.6 Kg of CO_2. This research study is significant from a technical and practical perspective, especially because it provides an engineering and sustainable solution. Therefore, by integrating waste into the construction industry the dependency on natural resources is ultimately reduced. The findings of the study could be useful for practitioners, and professionals who seek to promote and utilize sustainable materials in construction industry. Additionally, enhancing the properties of concrete with QRD eventually result in a robust and resilient structure, thereby, offering paradigm shift in waste management and construction practices.

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