Research Article

Life-Cycle Assessment of High-Strength Concrete Mixtures with Copper Slag as Sand Replacement

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Aggregate consumption rates have now exceeded natural renewal rates, signaling shortages both locally and globally. Even more concerning is that the worldwide markets for construction aggregates are projected to grow at an annual rate of 5.2% in the near future. This increase is attributed to rapid population growth coupled with the economic development worldwide. In terms of material availability, one of the most vulnerable regions is the Asia-Pacific region specifically, Singapore, where there is higher demand but limited availability of natural sand and gravel for use as aggregates in concrete construction projects. This paper focuses mainly on the environmental impacts of fine aggregate alternatives used in high-strength concrete applications in Singapore, which is one of the major global importers of natural sand following China. Singapore has been experiencing political and environmental challenges linked to the shortage of natural sand use as aggregates, even while the demand is increasing in the construction sector. Copper slag, a readily available waste material from shipyards in Singapore, is a possible replacement material for a portion of the natural sand in concrete mixtures, thus sustaining the projected growth in the region. A life-cycle assessment approach is applied to investigate the environmental impacts of copper slag and its alternative use as natural sand in high-strength concrete applications in Singapore. The system boundary consists of the major production processes of concrete constituents (including Portland cement and fine and coarse aggregates, with CS considered as fine aggregate) from a cradle-to-gate perspective, consisting of relevant life-cycle phases of raw materials extraction, transportation, and production processes at the relevant facility where the production occurs. Output from the assessment is provided in terms of embodied energy use and air emissions of concrete mixes with varying percentages of copper slag as fine aggregate. Results show that environmental impacts of aggregates decrease with the increasing substitution rate of natural sand with copper slag when calculated on the basis per unit volume of the concrete mix. For example, 40% and 100% sand replacements with copper slag result in a reduction of 8% and 40% in embodied energy, 12% and 30% in global warming potential, 8% and 41% in acidification, and 7% and 35% in particulate matter formation, respectively. Normalized impacts (i.e., normalized with respect to compressive strength) are observed to remain at almost similar levels for concrete mixes with up to 40% natural sand having been replaced with copper slag. Therefore, it is recommended that replacement of fine aggregates by 40–50% of copper slag (by weight) will produce concrete mixtures with comparable environmental impacts while maintaining feasible durability and strength properties.

1. Introduction

Concrete is the most commonly used construction material today. Among the major reasons for concrete’s popularity are its flexibility and adaptability; its low maintenance requirements during the service life of the structures; and the economic and widespread accessibility of its constituents [1]. Every year, more than 11 billion tonnes of concrete are estimated to be manufactured globally [2]. The substantial manufacturing and consumption cycle of concrete has a significant environmental impact, making the current concrete industry unsustainable. To date, global concrete manufacturing accounts for more than five percent, about 2.1 billion tonnes of the human-related greenhouse gases (GHGs) annually, mostly attributable to the production of cement clinker [3]. In recent years, researchers have focused mainly on cement production and the associated environmental impacts since cement is considered as the
high-energy intensive constituent of concrete [4–9]. While cement is a major source of GHGs, the manufacturing of concrete requires extensive quarrying for the production of fine and coarse aggregates used in concrete mixtures. Fine aggregates mixed in concrete are mainly sand and gravel and are derived from natural sources, referred to as natural mineral aggregates [1]. The environmental impact associated with quarrying of natural sand and gravel, which make up about 70–80% of the concrete volume, can be significant, especially in regions with higher demand and limited availability [3].

In most concrete mixtures, aggregates are more or less chemically inert, namely, nonreactive. However, some aggregates react with the alkaline pore solution in concrete, causing expansion and cracking over a period of time [10]. Nonreactive fine aggregates used in concrete are already becoming rarer as quarries are being depleted [11]. In recent years, aggregate consumption rates have exceeded natural renewal rates and the worldwide market for construction aggregates is projected to grow further at a rate of 5.2% annually [12]. This increase, which can be attributed to the rapid population growth coupled with economic development, is raising political and trade-related concerns. In the near future, world population growth from 2015 to 2050 is predicted to be 32% (i.e., from 7.35 billion to 9.73 billion people), whereas in Asia, the growth rate is expected to be 20% (i.e., from 4.39 billion to 5.27 billion people), and in the Asia-Pacific region specifically, the rate is expected to be 25% (i.e., from 633 million to 792 million people) [13].

Following this anticipated growth in population accompanied with gross domestic product (GDP) levels, the Asia-Pacific region is expected to grow much faster compared to the rest of the world [14]. Although growth in the Chinese market is projected to slow down in the near future, as of 2015 China remains by far the largest national consumer of aggregates, representing nearly half of all global sales [12]. Hence, Asia will continue to be dependent on imported materials to facilitate continued manufacturing growth and increasing material standards of living. Table 1 provides a summary of the top five global importers of stone, sand, and gravel: note the huge volumes of imports of these goods in Asia, mainly China, Singapore, and India. Currently, the regions with higher levels of demand and imports of natural resources are more susceptible to the depletion of these resources; thus, it is an issue that cannot be ignored. This study focused solely on Singapore since it is the world’s highest per capita consumer of aggregates, at a level of 5.4 million tonnes per person [16].

The factors that can be controlled to reduce the demand for natural aggregates are limited. The consumption of aggregates can be slowed down through the utilization of alternative materials and/or recycled materials in concrete applications [17]. Recycled concrete can substitute aggregate mainly in lightweight concrete mixes. Concrete made with 100% of recycled coarse aggregates has 20–25% less compressive strength than conventional concrete at 28 days, with the same effective water/cement ratio and cement quantity [18]. Therefore, the authors suggest recycled aggregates should be used in concretes with low-to-medium compressive strength (20–45 MPa). However, recycled aggregates are not recommended for use in aggressive environments and require stricter quality control than for natural aggregates [19].

The substitution of natural aggregates with recycled glass as aggregate in concrete mixtures has been investigated by a number of researchers [20–22]. Results from these studies vary. Park et al. [21] studied the recyclability of waste glass as fine aggregate and results showed decreases in workability, strength, and the freezing-thawing resistance of concrete with the increasing amounts of waste glass. Shayan and Xu [23] stated that concrete mixtures containing glass aggregates are susceptible to expansion and cracking due to possible alkali-silica reactions (ASR) between glass aggregates and the high alkalinity of the pore solution in concrete. Other researchers have suggested grinding the waste glass into a fine glass powder in concrete to eliminate the ASR. Test results from Kou and Poon [20] concluded that the ASR expansion of concrete specimens with recycled glass was reduced by the use of fly ash. Based on this research, feasible use of waste glass as aggregates requires incorporating a suitable pozzolanic material such as fly ash, ground blast furnace slag, or metakaolin in the concrete mixture [20]. The industrial by-products from the refining of metals, such as copper slag (CS) from matte smelting and refining of copper, could be a feasible solution for producing high-strength concrete since incorporating CS as an aggregate enhances the durability of concrete mixtures without compromising the strength and other mechanical properties [24]. Studies reviewed by Al-Jabri et al. [25] and Al-Jabri et al. [24] also verify that concrete specimens containing CS as fine aggregates meet strength and durability design requirements. Moreover, CS has considerably low cost while its application as a fine aggregate in concrete production offers many environmental benefits in terms of waste recycling and reduction in environmental issues related to landfills.

This paper focuses on the consumption of aggregates and its associated environmental impacts in Singapore. Singapore needs to import all of its aggregates, which is becoming more and more problematic with increasing demand and environmental/political concerns after Indonesia’s 2007 embargo, which was followed by Malaysia, Cambodia, and Vietnam banning sales of natural sand to Singapore [26]. As an alternative to natural sand, Singapore has ready access to CS, the use of which is justified in concrete mixtures as fine

### Table 1: Top five global importers of stone, sand, and gravel [15].

<table>
<thead>
<tr>
<th>Country</th>
<th>Trade value, total for 2010–2014</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>$13,621,826,061</td>
</tr>
<tr>
<td>Netherlands</td>
<td>$2,946,963,029</td>
</tr>
<tr>
<td>Singapore</td>
<td>$2,825,197,760</td>
</tr>
<tr>
<td>Germany</td>
<td>$2,755,605,436</td>
</tr>
<tr>
<td>India</td>
<td>$2,695,719,208</td>
</tr>
<tr>
<td>Others</td>
<td>$35,127,603,231</td>
</tr>
<tr>
<td></td>
<td>$59,972,914,725</td>
</tr>
</tbody>
</table>

aggregates to facilitate construction activities. A life-cycle assessment (LCA) approach is applied to investigate the environmental impacts of CS and its alternative use as natural sand in high-strength concrete applications in Singapore.

2. Copper Slag (CS) as Fine Aggregate Substitute in Concrete

A number of criteria are relevant in the selection of alternative materials that can be substituted for aggregates in concrete applications, including (1) low cost, (2) compatibility with other constituents of concrete, and (3) compatibility with concrete design properties [27]. Based on these three criteria, one of the promising solutions to sand and gravel shortage is the use of solid waste materials such as copper slag (CS), which is the by-product material from the matte smelting and refining processes of copper manufacturing. It is estimated that each tonne of copper generates an average of 2.6 tonnes of CS [28–30]. Approximately 25 million tonnes of CS has been generated annually worldwide. The amount of CS produced in the United States and Japan is about four and two million tonnes per year, respectively [31]. Originally imported from Japan, Singapore has been utilizing CS as an abrasive material for removing rust and marine deposits from ships through sandblasting. After repetitive recycle and reuse, the CS loses its original abrasive property with no beneficial use thereafter, and in the past, it has been disposed of in landfills. As a result, Singapore needs to dispose of about 0.4 million tonnes of washed CS annually [32].

There have been several examples of the use of washed CS in the construction industry as a substitute for aggregates, both in cement mortar and concrete [24, 25, 30, 31, 33, 34]. The use of washed CS as a sand replacement in concrete mixtures has been shown to exhibit advantages in terms of durability and mechanical properties [24, 31]. The analysis of the effects of CS aggregate on the sulfate attack resistance and the depth of carbonation has shown no significant attack and a slower rate of carbonation by using CS [33, 34]. Similarly, Al-Jabri et al. [24] concluded that concrete mixture with copper slag (replacing up to 40% of sand) has higher durability than the mixes with 100% sand. Wu et al. [31] showed that the workability of concrete mixtures with 40% CS replacement increased remarkably. However, Al-Jabri et al. [25] indicated that concrete with CS as a fine aggregate exhibits a higher probability of bleeding in samples because of their high density and/or water content for a given slump of concrete, which is attributed to the high specific gravity of copper slag.

The substitution of up to 40–50% CS as a sand replacement in concrete mixtures yielded comparable compressive, tensile, and flexural strengths to that of the concrete mixture with 100% sand [25]. Since this paper uses the concrete mix designs from Wu et al. [31] in LCA calculations, it is essential to provide a brief background on strength properties of mixes with varying CS proportions. Figure 1 compares the selected concrete mixtures with respect to their 7-day, 28-day, and 90-day compressive strength values and workability. The slump line shows that the workability of mixtures with 40% CS has improved remarkably by 150% [31]. However, concrete mixtures with higher than 60% replacement of sand result in considerably lower compressive strength for all ages, while workability of mixtures with CS is improved considerably. The flexural strength also has a slight growth. Moreover, the dynamic compressive strength at the CS replacement level is higher than or equal to that of the control mix at the strain rates of \(~100\,\text{s}^{-1}\), \(~200\,\text{s}^{-1}\), and \(~300\,\text{s}^{-1}\) (Figure 2). Overall, the results show that the strength of concrete mixes with less than 40% CS replacement is comparable to or better with respect to the Mix 1 with 100% OPC.

As cited above, the majority of studies in the literature recommend that washed CS in the range of 40–50% by weight could potentially replace fine aggregates in concrete mixtures without compromising the design requirements. It is important to note that washed CS (WCS) is derived by reprocessing (cleaning and washing with tap water and drying) CS used in the first place as an abrasive in grit-blast cleaning of ships and refineries [35]. WCS has essentially the same chemical composition as the original CS, and therefore, they can be considered as the same material, possibly with some variations in their particle size grading [36]. Besides workability and mechanical advantages, recycling CS in concrete mixtures eliminates the solid waste disposal in limited landfill surface of Singapore.

In the following sections of this paper, an LCA approach is utilized to further understand the life-cycle environmental impacts of high-strength concrete mixtures with washed CS replacement as fine aggregates. Material properties and mix designs are based on Wu et al. [31] study, where the concrete is assumed to be applied in construction projects in Singapore.

3. Case Study: Environmental and Trade-Related Impacts of Aggregate Consumption in Singapore

Singapore consumes concrete in about 95% of its construction projects [31]. Consequent to the economic growth in the country, concrete consumption in Singapore has increased from 10 million cubic meters (m$^3$) in 2010 to 15 million m$^3$ in 2014 [37]. Consequently, aggregate use in Singapore has reached a total of 60 million tonnes, 38 million tonnes of which consists of imported natural sand as of 2014 [15]. Singapore is currently experiencing a shortage of natural sand supply due to the unavailability of sand from its major importer, Indonesia. Export of sand to Singapore was found to be responsible for the disappearance of about 24 Indonesian sand islands [38, 39]. Therefore, in 2007, Indonesia banned sand exports over land use and environmental and political concerns [31]. Other countries, including Cambodia, Vietnam, and Malaysia, also banned sales of natural sand to Singapore over environmental concerns. To ensure its future economic viability while growing in a sustainable manner, it is essential that Singapore’s construction projects have access...
to alternative materials that are viable substitutes for natural sand and gravel.

3.1. Copper Slag (CS) Availability in Singapore. The shortage of landfill area for waste disposal and the high cost of landfilling necessitate the finding alternative use of CS in Singapore. Therefore, recycling of CS as fine aggregates in concrete mixtures supports government’s goals towards sustainable development and construction. In response to Indonesia’s ban on sand extraction, Singapore has begun to use washed CS disposed from shipyards to compensate for the reduction in sand imports. In the past, washed CS from shipyards was dumped in landfill sites on the island of Pulau Semakau for a decade, which has now reached its capacity [32]. In addition, there have been ongoing environmental concerns about the leaching of heavy metals from washed CS into soil and ground water. Lim and Chu [40] addressed the leaching behavior of the spent CS and assessed its suitability for use in land reclamation without chemical pretreatment in Singapore. Test results from the study showed that the concentrations of the regulated heavy metals leached from the material at pH 5.0 were significantly lower than the maximum concentrations for their toxicity limits referred by US EPA’s Toxicity Characteristic Leaching Procedure (TCLP). It was also
found that the material is unlikely to cause significant change in the redox condition of the subsurface environment over a long-term period, ruling out the possibility of acid generation and excessive leaching of the material. In addition, the material is rather stable in its redox characteristics. Additionally, Shi et al. [30] provide the latest Malaysian and U.S. regulatory limits for the leachability of copper, nickel, lead, and zinc ions from copper slag, concluding that it is not considered hazardous waste when used in concrete. Hence, by containing this waste material in concrete, one can not only remove the environmental concerns but also add value to it as an alternative for natural sand.

From a policy perspective, Singapore’s Building and Construction Authority (BCA) took the lead to promote the use of alternative/substitute materials and approved the use of replacing a portion of sand with CS. In addition, they extended 100% CS use to all nonstructural concrete without the need for official approval from BCA. Within the scope of Environmental Protection–Sustainable Construction guidelines, green mark points can be achieved by recycling washed CS from approved sources to replace coarse and fine aggregates for concrete production of main building elements [41, 42].

3.2. Material Properties Used in LCA Calculations. In LCA calculations, material properties and their proportioning in concrete mixtures are taken from the study of Wu et al. [31]. In Section 2 of this paper, strength and workability properties of the six concrete mixes are discussed. Table 2 presents the concrete mix constituents, with varying percentages of natural sand replaced with CS at an incremental rate of 20% by weight.

The concrete mixtures conformed to the British Standards, BS 1881: Part 125 [43] and BS EN 12390: Part 2 [44], which is a common practice in Singapore’s construction sector. Water-cement ratio and water-binder ratio were 0.27 and 0.3, respectively. Cementitious materials consisted of Portland cement and silica fume. Silica fume was used to enhance the cementitious content in the mix for the high-strength requirement. Superplasticizer was incorporated in the mix to maintain a low water/cement ratio required for high strength. Although higher workability has been achieved with increased substitution of sand with CS, superplasticizer use was still necessary for Mix 1 to comply with the design requirements. The coarse aggregate (max. size, 20 mm) used was crushed granite. The fine aggregate was natural sand with a specific gravity of 2.64; CS is heavier, with a specific gravity of 3.66 [31]. All six mixes contained 570 kg of Portland cement, 820 kg of coarse aggregate, 60 kg of silica fume, 4 kg of superplasticizer, and 170 kg of water per cubic meter (m³) of concrete. Only the fine aggregate (sand) content was changed, whereby the sand was replaced by CS at an incremental rate of 20% by weight from 0% to 100%, corresponding to 0 kg to 820 kg of CS per unit volume of the concrete mix. For example, Mix 3 consisted of 492 kg of sand and 328 kg of CS, whereby, 40% of the sand was replaced with CS.

3.3. Methodology: LCA of Concrete Mixes with CS. The LCA methodology is based on the guidelines of International Organization for Standards (ISO) 14040 [45] and is used for the evaluation of the environmental performances of products and processes [46]. In this study, Excel-based GreenConcrete LCA tool, developed by Gursel [3] was utilized to quantify the embodied energy and environmental impacts of washed CS and its alternative use as natural sand in high-strength concrete applications in Singapore. The results were attained through four major steps of LCA methodology, each of which is covered in the following sections.

3.3.1. Scope and Functional Unit. The scope of the LCA study consists of major production processes of concrete constituents (including Portland cement and fine and coarse aggregates, with CS considered as fine aggregate) from a cradle-to-gate perspective, consisting of relevant life-cycle phases of raw materials extraction, transportation, and production processes at the relevant facility where the production occurs. The functional unit through the study is one cubic meter of high-strength concrete normalized with respect to its 28-day compressive strength.

The LCA framework for cement production process in the GreenConcrete LCA tool [3] consists of (i) extraction of raw materials and crushing; (ii) raw meal preparation and homogenization; (iii) pyroprocessing, which includes the preparation of kiln fuels and mixing and calcination of all raw materials; and (iv) finally, milling, grinding, and packaging.

The system boundary for the coarse and fine (sand) aggregates incorporates quarrying, crushing, conveying, and screening processes based on the technologies applied in the supplier country. Calculations are performed to estimate energy use and emissions associated with the electricity use, fuel precombustion, fuel combustion, and processes that occur during fine and coarse aggregates production [3].

The system boundary for washed CS involves the recycling processes of the waste materials to produce a suitable fine filler material (fine aggregate) for concrete. After its transportation from the shipyard to the concrete plant, CS is washed to remove all impurities and is then dried. Figure 3 demonstrates the environmental procedure for recycling and transportation of washed CS.

3.3.2. Life-Cycle Inventory (LCI) of Major Concrete Constituents. Production and processing of major concrete constituents (cement and aggregates), recycling of washed CS as substitute for sand, and concrete batching are analyzed within the cradle-to-gate system boundary. In the analysis, process flow schemes draw well-defined system boundaries, each with one end product, such as Portland cement and fine or coarse aggregate. Supply-chain impacts associated with inputs (e.g., materials, products, electricity, fuels, and water) of varying regional specificity and production/generation technologies add breadth and depth to the LCA analysis. For the electricity-related impact assessment, we considered the percent net electricity generation by fuel type for Singapore.
and its importers. These percentages are presented in Table A.1 and are used in electricity-related LCA calculations to account for the direct and supply-chain impacts of electricity consumption (including impacts of fuels used in electricity generation) during cement, aggregates, and concrete production processes.

Therefore, in addition to direct LCI calculations associated with the consumption of electricity and fuels, the supply-chain LCI of fuels used in the electricity generation, transportation, and production of cement as well as processing of fine and coarse aggregates are considered in an LCA of concrete mixes.

(1) LCI of Portland Cement. Cradle-to-grave inventory data for Portland cement production together with transportation to Singapore’s port was derived on the basis of Singapore’s 2014 cement import data [15]. Singapore imports 56% of its cement from Japan, 17% from Taiwan, 16% from Malaysia, and 11% from China. These numbers may vary slightly based on the market supply-demand and construction activities in Singapore and cement importing countries. Life-cycle inventory (LCI) data for cement production processes of importers and fuel consumption for transportation were calculated with GreenConcrete LCA tool. The prior study by Gursel and Ostertag [47] describes the methodology and related calculations applied for a cradle-to-grave LCI of cement.

Table A.2 in the Appendix provides a snapshot of the LCI details for countries that export cement to Singapore. Global warming potential (GWP in CO₂-eq) per tonne of cement production varies between 1.3 tonne CO₂-eq for China and Taiwan and 1.1 tonne CO₂-eq for Japan and Malaysia. Transportation-related GWP varies considerably due to variations in transportation distances between Singapore and its cement importers. Accordingly, transportation of cement to Singapore causes 70kg of CO₂-eq for China, 100kg CO₂-eq for Japan, 32kg CO₂-eq for Malaysia, and 78kg CO₂-eq for Taiwan. As observed in Table A.2, LCI numbers vary considerably with the changing technologies, national grid mixes, and transportation distances.

(2) LCI of Coarse and Fine Aggregates. The life-cycle inventory (LCI) of quarried raw material (sand, gravel, stone, etc.) calculations is performed to estimate energy use and emissions associated with fine and coarse aggregates production. Both the details of the assumptions and calculations associated with aggregate production (including direct and supply-chain impacts of electricity and fuels consumption) in importing countries can be obtained from Gursel and Ostertag [47].

Results for fine and coarse aggregates were adjusted based on 2014 aggregates import data from the UN’s Comtrade [15]. Singapore imports 45% of natural sand from

<table>
<thead>
<tr>
<th>Materials</th>
<th>Mix 1 (0%) CS</th>
<th>Mix 2 (20%) CS</th>
<th>Mix 3 (40%) CS</th>
<th>Mix 4 (60%) CS</th>
<th>Mix 5 (80%) CS</th>
<th>Mix 6 (100%) CS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ordinary Portland cement (OPC)</td>
<td>570</td>
<td>570</td>
<td>570</td>
<td>570</td>
<td>570</td>
<td>570</td>
</tr>
<tr>
<td>Coarse aggregate</td>
<td>820</td>
<td>820</td>
<td>820</td>
<td>820</td>
<td>820</td>
<td>820</td>
</tr>
<tr>
<td>Sand</td>
<td>820</td>
<td>656</td>
<td>492</td>
<td>328</td>
<td>164</td>
<td>0</td>
</tr>
<tr>
<td>Copper slag (CS)</td>
<td>0</td>
<td>164</td>
<td>328</td>
<td>492</td>
<td>656</td>
<td>820</td>
</tr>
<tr>
<td>Silica fume</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>Water</td>
<td>170</td>
<td>170</td>
<td>170</td>
<td>170</td>
<td>170</td>
<td>170</td>
</tr>
<tr>
<td>Water/cement ratio</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>Water/binder ratio</td>
<td>0.27</td>
<td>0.27</td>
<td>0.27</td>
<td>0.27</td>
<td>0.27</td>
<td>0.27</td>
</tr>
</tbody>
</table>

Table 2: Concrete mix design and proportions of constituents.
Cambodia, 29% from Vietnam, 11% from Myanmar, 9% from Malaysia, and 6% from Philippines. Singapore’s coarse aggregate imports are as follows: 46% from Indonesia, 40% from Malaysia, 8% from China, 4% from Thailand, and 2% from Vietnam. As shown in Table 2, only natural sand is replaced with CS. Similar to cement transportation, aggregate is delivered to Singapore by bulk cargo shipping. Within Singapore and its importers, heavy-duty trucks deliver aggregates from one location to the other, with the final destination being the concrete manufacturing plant.

Tables A.3 and A.4 in the Appendix summarize the LCI results for both fine and coarse aggregates from Singapore’s importers together with the transportation-related LCI. As opposed to cement LCI results, transportation impacts govern in both fine and coarse aggregate results. GWP (in CO$_2$-eq) per tonne of fine aggregate production varies between 1.42 kg CO$_2$-eq for Myanmar, 1.96 kg CO$_2$-eq for Cambodia and Vietnam, 2.49 kg CO$_2$-eq for the Philippines, and 2.68 kg CO$_2$-eq for Malaysia. In contrast, transportation impacts surpass the production-related GWP and vary between 54.4 kg CO$_2$-eq for the Philippines (the longest distance), 47.5 kg CO$_2$-eq for Myanmar, and 32 kg CO$_2$-eq for Malaysia and Vietnam.

Similarly, GWP (in CO$_2$-eq) per tonne of coarse aggregate production varies with the technology and energy sources used in the country of production. It is 2.8 kg CO$_2$-eq for Vietnam, 3.4 kg CO$_2$-eq for Thailand, 3.7 kg CO$_2$-eq for Malaysia, 3.9 kg CO$_2$-eq for China, and 4 kg CO$_2$-eq for Indonesia. Again, transportation impacts are much larger at levels of 32 kg CO$_2$-eq for Malaysia and Vietnam, 41 kg CO$_2$-eq for Indonesia, 49 kg CO$_2$-eq for Thailand, and 72 kg CO$_2$-eq for China and increase proportionally with the distance. Diesel fuel used in the transportation impacts govern the total energy consumption and air emissions in fine and coarse aggregates LCI results (Tables A.3 and A.4).

(3) LCI of Copper Slag (CS). We adopted the LCI of CS processing from the study of Kua [35]. Different from our approach, the focus of the earlier research by Kua [35] was on the LCI of replacing ordinary Portland cement (OPC) with CS, without the consideration of concrete mix design applications in Singapore. To our knowledge, there is no any other study that has analyzed the environmental life-cycle impacts of concrete mixes specifically with CS as fine aggregate replacement. The processing of one kg of washed CS as sand replacement requires 0.078 kWh of electricity, 0.011 kg of heavy fuel oil, and 0.000306 kg of diesel fuel [35]. Electricity-related impacts are calculated on the basis of Singapore’s national grid mix (Table A.1). Based on the quantities of heavy fuel oil, diesel fuel, and electricity used for processing the washed CS, energy use and major emissions associated with fuel and electricity consumption per unit weight of CS were calculated. Results from the calculations are provided in Table A.5.

For comparison purposes, processing of one tonne of natural sand requires 13.7 MJ; the equivalent of fuels for washed CS is 15.7 MJ. The electricity requirement for natural sand processing varies between 28 and 6.4 MJ per tonne of sand, depending on the electricity grid mix of the importing country. Electricity consumption for processing of washed CS corresponds to 9.3 MJ per tonne of slag for Singapore, which is also within the ranges calculated for processing of natural sand LCI results. In regards to GWP, natural sand processing results in 1.4 to 2.7 kg CO$_2$-eq, while processing of washed CS is 1.6 kg CO$_2$-eq per unit weight. Although the difference in processing-related energy use and associated GWP result for natural sand and CS is comparatively small, it is the transportation impacts that results in CS being more favorable over natural sand (Tables A.3 and A.5). For example, transportation-related GWP corresponds to 13 kg CO$_2$-eq for CS that is locally available in Singapore. In contrast, the transportation-related GWP for natural sand is in the range of 32–54 kg CO$_2$-eq per unit weight as it is imported from Singapore’s trading partners.

3.4. Life-Cycle Impact Assessment (LCIA). Impacts considered in the LCIA step can include global warming potential (GWP), marine eutrophication, acidification, PM formation, and photochemical ozone formation (POFP), as well as human toxicity and ecotoxicity; LCI emissions and resources are assigned to each of these impact categories. They are then converted into indicators using impact assessment models (such as ReCiPe). Emissions and resources consumed, as well as different product options, are then cross compared in terms of these indicators [48]. In our analysis, we have adapted the LCIA approach by ReCiPe since it is currently considered as the most compliant and uniform approach from a methodological point of view. The midpoint-oriented method was selected as suggested in ReCiPe guidelines because of the higher level of uncertainty in the regional impact assessment data for both Singapore and its importers [49]. The midpoint-oriented method provides considerably reliable results since there is less assumptions and modeling complexity compared with the damage-oriented (end-point) approach in LCIA [50]. The uncertainty in LCIA characterization models is inevitable as it involves incomplete and location-specific knowledge of the environmental mechanisms that are involved in impact calculations. In ReCiPe, different sources of uncertainty and different choices are grouped into a limited number of perspectives or scenarios that include individualist (I), hierarchist (H), and egalitarian (E) approaches.

The hierarchist (also consensus model), as often encountered in scientific models, is considered to be the default model. It is based on the most common policy principles with regards to time frame and other issues [49]. Therefore, the hierarchist midpoint-oriented model is implemented in the LCIA calculations since impact categorization factors are not yet available for cement and aggregates exporters of Singapore to incorporate the spatial uncertainty.

The effect on climate change was investigated by IPCC, with a time frame of 100 years, to explore the GWP of concrete mixes with washed CS. Table A.6 summarizes the selected LCIA impact characterization factors
(midpoint-oriented and hierarchist approach) as defined by the ReCiPe method.

4. LCA Results and Discussion

Finally, results for embodied energy, GWP, acidification, particulate matter (PM) formation, and photochemical ozone formation (POFP) are compared on the basis of unit volume of concrete mixtures. Human toxicity and ecotoxicity impacts were not considered due to higher level of uncertainty in the determination of these impact categories. Note that only coarse and fine aggregates (natural sand and CS were considered as fine aggregates) and their transportation impacts are reflected in the LCA calculations. Since cement weight remains constant per unit volume of all concrete mix designs, associated impacts from cement production are constant for all concrete mixtures despite the change in natural sand and CS weight proportions per unit volume of specimens. In the second round of calculations, LCA impacts are recalculated by normalizing the earlier results with respect to the 7-day, 28-day and 90-day compressive strengths of concrete mixes to convey the results at a comparable functional unit level.

Results show that environmental impacts from fine aggregates decrease with the increasing substitution rate of natural sand with CS when they are calculated on the basis of unit volume of concrete mixture. By replacing the natural sand in Mix 1 with 40% CS (corresponding to Mix 3) and 100% CS (corresponding to Mix 6) in concrete, respectively, impacts are reduced by

(i) 8% and 40% for embodied energy (Figure 4)
(ii) 12% and 30% for GWP (Figure 5)
(iii) 8% and 41% for acidification (Figure 6)
(iv) 8% and 37% for POFP (Figure 7)
(v) 7% and 35% for PM formation (Figure 8)

Calculations and results were obtained by using the GreenConcrete LCA tool [3]. In summary, overseas transportation was found to be the major source of the environmental impact, while processing of aggregates, including replacement of natural sand with CS, it requires a comparable amount of energy with only slight differences in the environmental impacts.

The results for the normalized impact categories of GWP, embodied energy, acidification, and PM formation are demonstrated in Figures 9–12. Despite the reduction in embodied energy and GWP per unit volume of concrete by replacing natural sand with CS, normalized impacts (i.e. normalized with respect to compressive strength) are almost similar for Mixes 1 (100% sand-0% CS) through 4 (40% sand-60% CS). Therefore, it is recommended that 40–50% of copper slag (by weight) be used as a partial replacement for natural sand, resulting in a concrete mixture with comparable environmental impacts as well as compatible strength and workability properties.

To achieve further reductions in embodied energy and major environmental impacts of concrete consumption, it is necessary to evaluate the effect of changing the ratio of aggregates imports between countries as well as the use of advanced technologies. In their recent study, Gursel and Ostertag [47] indicated that, by importing cement and aggregates from importers in close proximity to Singapore, such as Malaysia, embodied energy and GWP of concrete mixtures were reduced by 11% and 31%, respectively. It is suggested that future LCA studies consider the effects of advanced technologies and alternative materials/fuels on the production of concrete as Singapore’s construction sector is facing significant challenges in meeting economic and population growth.

5. Conclusions and Policy Applications in Singapore

Using washed CS as a natural sand substitute in concrete mixtures is recommended as a potentially sustainable solution to Singapore’s growing concerns over the shortage of sand. CS is a waste material produced in shipyards. Once it loses its original abrasive property, it is then usually shipped to the landfill for disposal. The recycling of washed CS in concrete mixtures as sand replacement would be a noteworthy step in sustainability of concrete production by eliminating the disposal and accumulation of such solid waste. The results from this study showed that normalized impact categories of GWP, embodied energy, acidification, and PM formation are comparable for Mixes 1 (100% sand-0% CS) through 4 (40% sand-60% CS). Therefore, replacement of natural sand with up to 40–50% of CS by weight would result in concrete mixes with comparable environmental impacts as well as desirable strength and workability properties. Additional benefits of using washed CS as a replacement material for fine aggregates are as follows:

(i) Reduce its natural sand imports from neighboring countries and can help conserve the sand islands in the Asia-Pacific region
(ii) Reach its local environmental goals by using locally available industrial wastes or recycled materials to replace sand in concrete mixes
(iii) Reduce global environmental impacts by reducing its dependency on imported materials without sacrificing strength and other design properties (workability and durability such as sulfate attack resistance) of concrete mixes

It is important to note that results from this study are only relevant to Singapore’s environmental, social, and economical constructs. Thus, LCAs for other countries should study making use of the resources, technologies, and strategies that are applicable to their specific needs; that is, recycled aggregates may not be the best solution for all countries, especially when most of the concrete that is being used is high-strength concrete. The approach developed in this study may provide guidance to Singapore’s Building and Construction Authority (BCA) in quantifying major environmental impacts of high-performance concrete mixes with copper slag as well as other alternative materials that
Figure 4: Distribution of embodied energy results for concrete aggregates (cement impacts are excluded), GreenConcrete LCA tool [3].

Figure 5: Distribution of GWP results for concrete aggregates (cement impacts are excluded), GreenConcrete LCA tool [3].

Figure 6: Distribution of acidification results for concrete aggregates (cement impacts are excluded), GreenConcrete LCA tool [3].
Figure 7: Distribution of POFP results for concrete aggregates (cement impacts are excluded), GreenConcrete LCA tool [3].

Figure 8: Distribution of PM formation results for concrete aggregates (cement impacts are excluded), GreenConcrete LCA tool [3].

Figure 9: Normalized GWPs of concrete mixes with respect to their compressive strengths at varying curing ages, GreenConcrete LCA tool [3].
Figure 10: Normalized embodied energy of concrete mixes with respect to their compressive strengths at varying curing ages, GreenConcrete LCA tool [3].

Figure 11: Normalized acidification of concrete mixes with respect to their compressive strengths at varying curing ages, GreenConcrete LCA tool [3].

Figure 12: Normalized PM formation of concrete mixes with respect to their compressive strengths at varying curing ages, GreenConcrete LCA tool [3].
can replace aggregates. As part of future research, environmental and political concerns need to be addressed collectively for the Asia-Pacific region to reach consensus in regards to depletion of natural sand and gravel sources, and investigation of alternative sources to meet the consumption demands of the future should be performed.

Data Availability
The data used to support the findings of this study are available from the corresponding author upon request.

Disclosure
The manuscript was presented before publishing as an abstract in EES 2017 conference. The conference took place in November 9–11, 2017, in Washington, DC, and further information can be found at http://unitedscientificgroup.com/conferences/ees/speakers.

Conflicts of Interest
The authors declare that they have no conflicts of interest.

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Supplementary Materials
Table A.1: net electricity generation by fuel type for Singapore and countries importing materials by percent. Table A.2: LCI data for the cement production in the country of origin and transportation to Singapore (calculated using GreenConcrete LCA tool [3]). Table A.3: LCI data for fine aggregates (sand) production in the country of origin and transportation to Singapore (calculated using GreenConcrete LCA tool [3]). Table A.4: LCI data for coarse aggregate (crushed stone) production in the country of origin and transportation to Singapore (calculated using GreenConcrete LCA tool [3]). Table A.5: LCI data for processing of washed copper slag (CS) at Singapore’s shipyard and transportation to concrete plant (calculated using GreenConcrete LCA tool [3]). Table A.6: selected LCIA impact characterization factors (midpoint-oriented and hierarchist approach) as defined by ReCiPe method [49]. (Supplementary Materials)

References
process on properties of recycled aggregate concrete,” 


