Recycled Materials in Design and Construction; Perception of "Most Sustainable" in the Built Environment

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction

The average person spends most of their life indoors, emphasizing the importance of buildings and construction in society. With this need of new infrastructures come environmental impacts from all steps of the design and construction process. Sustainable practices should be enacted to choose more environmentally-conserved materials suited for the project, recycling materials that could be used in buildings or other applications, and reduce the amount of waste generated from these projects. Concrete, steel, and timber are the main structural materials used around the world. (DEI Creative in Seattle, 2023) With the increasing production of the previously stated materials to support the need for structures, there should be more discussions on how civil engineers contribute to the built environment while reducing their carbon footprint and waste. There have been many advances in sustainability research in support of the use of timber structures and re-using concrete and steel elements from collapsed or ancient structures. (Kumar et al., 2024) This critical development demands more attention from the industry and especially from the next generation of civil engineers and material scientists.

Civil engineers design for the serviceability of the structure and comfort of the user. An ideal design enhances the usability of the space, creating an enjoyable and comfortable space, without impacting the environment. New methods of sustainability must be quickly enacted within our existing practices, classrooms, workforce, and everyday lives to ensure a future built environment. Design professionals should begin to investigate the influential effects of perceived sustainable material and choose the material that is best for the project to achieve all five categories of the sustainability instrument: quality, functionality, user appeal, resourcefulness, and purchasability. What are the factors of consideration to develop a sustainable design without compromising the structural integrity or environmental concerns of future generations? It is the role of the structural engineer to consider all relevant factors to find a balance of biophilic solutions and sustainable materials that work to create a structurally-sound and healthy product. This research paper will dive into the current need for sustainability, the research of technical properties of recycled steel and concrete aggregates, and the perspectives of upcoming practicing engineers on sustainability in the design and construction industry.

Background

In June of 2022, a French company named Holcim produced the world's first fully recycled concrete building called "Recygénie". Holcim deploys circular construction in their projects and recycles over 30 million tons of materials every year, making them one of the world's largest recyclers. At the company's plant, they produced 100% recycled clinker, the primary component of cement, developed from construction and demolition waste and recycled wastewater and rainwater. (Holcim, 2022) This circular design and construction thinking marks an essential step forward for the research and development of sustainable high-strength building materials. Of the total global steel demand, construction accounts for 50%, meaning half of the steel production is for the sole purpose of construction. Additionally, the industry consumes 50% of raw materials and 50% of all non-renewable resources used, further diminishing the resources left for future generations. In terms of water consumption, the building and construction industry accounts for 33%. Furthermore, out of the total materials delivered to a construction site, ~15% is wasted. This accumulation of waste on site is possibly due to transporting damage, damage due to weather, engineering and construction mistakes, overbuying, and vandalism. (Harby, 2024) While construction and demolition waste totals up to nearly 7 million tons, there should be more done within circular construction to avoid the errors listed in the previous sentence.

Recygénie should set a new standard for the elimination of waste on the project site, and turning previous waste into high-strength resources.

Carbon emissions released from construction projects accounts for 15% of all greenhouse gas emissions world-wide. The buildings sector combined with the construction sector are responsible for 36% of global energy consumption and ~40% of total CO_2 emissions (International Energy Agency, 2019). As these engineers reflect on construction practices and materials for large-scale projects, there are much more sustainable options that could be enforced and widely used that would limit the amount of resources and energy used, waste produced, and carbon emissions released. Compared to other construction professionals, an engineer's technical expertise is more impactful for financial, constructability, operational, social, and environmental decisions due to their trusted background knowledge and mathematical calculations to support their claims (Chaudhary, Muhammad & Piracha, 2013). Thus, structural engineers have an integral role of advocating for sustainable, low-energy projects as well as understanding sustainable design elements and their effects of carbon emissions, cost efficiency, and user's comfort.

There are several green building rating systems with LEED (Leadership in Energy and Environmental Design) being the most widely used. LEED certification is a "globally recognized symbol of sustainability achievement" that provides a foundation for healthy, highly efficient, and cost-saving green buildings, with environmental, social, and governance benefits. (USGBC). The top goals of LEED include shifting design to promoting sustainable and regenerative material cycles, protecting and restoring water resources, and enhancing quality of life, biodiversity, human health and climate change. Earlier versions of LEED awarded individual credit for the use of materials that documented a "high percentage of recycled content, a regional origin or a high bio-based content." (Cross, 2015) that ultimately decided what level of LEED certification the project would receive (Certified, Silver, Gold, or Platinum). While the required documentation for LEED certification is increasing, there has not been a decline in LEED-certified structures, meaning that many construction projects will continue to seek a green certification. Currently, there is an increasing number of sustainable building designs resulting in a projection in the number of codes, standards, and rating systems evaluating these designs and construction methods. ASHRAE 189.1 Standard for High-Performance Buildings and the International Green Construction Code (IgCC) have requirements for recycled content, point of origin, and Environmental Product Declarations (EPDs). (AISC, 2023) As many clients and Architecture, Engineering, and Construction (AEC) teams seek to attain LEED certification for their structures, biophilic elements and recycled material use may be the answer to the following six broad categories: site selection and urban connectivity, water conservation, energy efficiency, building material efficiency, indoor air quality and occupant comfort, and innovation and exemplary performance.

Methodology

Multiple definitions of sustainability have been used to measure sustainable practice in construction and design. This paper will use the sustainability instrument described in "Measuring Sustainability Perceptions of Construction Materials". The sustainability instruction has five main factors: quality, functionality, user appeal, resourcefulness, and purchasability. The quality factors require the product to satisfy the requirements of the project through a prolonged time. For the product to be functional, the product must be useful and appeal to the user. The resourcefulness factor embodies the sustainable characteristics and extensive use of the materials. Lastly, purchasability depicts the product's ability to bring in purchases and serve as an attraction. (Florez, Castro, & Irizarry, 2013)

With this need of new infrastructure come environmental impacts from all steps of the design and construction process. Sustainable practices should be enacted to choose more sustainable materials suited for the project, recycling materials that could be used in buildings or other applications, and reduce the amount of waste generated from these projects. To analyze the current state of sustainable efforts in the industry and the thoughts of engineers, a number of research methods will be utilized. Literature reviews will be conducted to review information scholars already developed related to the topic and how advanced research is within this topic of interest. Topics of recycled concrete aggregates and steel and biophilic elements would be explored to understand the technical concepts behind these research topics and a comparison would be held on the properties and methods between recycled versus new material. Case studies of specific sustainable buildings will be studied to determine the social, environmental, and economical benefits the infrastructure brings to the environment and community around them. Interviews with upcoming civil engineers will further represent the perception of sustainability in the current industry and if structural engineers play a key role in making this change. Using this combination of research methods would allow perceptions of sustainability from various sources and roles of engineers: practicing engineers, engineers dedicated to researching sustainable material to determine if there is potential for change in the industry, and upcoming engineers. This wide variety of engineers with different backgrounds will provide a holistic view of the topic of sustainable design and construction and the changes that need to be enacted.

Literature Review

Recycled Structural Steel

The strong durability and recyclability of steel make it essential in the modern sustainable construction world. Steel is 100% recyclable, and its durability is the root of its simple reusability. The recycling process is simple- due to its magnetic properties, the steel can be separated from solid waste and diverted from waste streams resulting in typically 60-80 million tons of scrap steel recycled per year in North America. (The American Iron and Steel Institute, 2020) Unlike other framing materials, steel structures can be disassembled at one location for reinstallation and reuse at another location. To provide a standard for energy and electricity conserved from recycled steel, the American Iron and Steel Institute provided the following information: "Even recycling one steel food can conserve enough energy to light a 10-watt LED light bulb for more than 24 hours. Through recycling, the steel industry saves enough energy to supply the annual electricity needs of more than 18 million homes. A single ton of steel recycled conserves 2,500 pounds of iron ore, 1,400 pounds of coal, and 120 pounds of limestone." In addition to the environmental benefits, steel recycling can supply more than 531,000 jobs and generate more than $110 billion in economic activity. (The American Iron and Steel Institute, 2020) The several thousand gallons of water used to quench the hot steel, which serves as a cooling and strengthening mechanism, is recycled into a closed-loop system for future use.

The steel industry is the largest recycler of waste by mass in the United States with efficient water usage rates and low carbon emissions. Unlike older steel mills, current-day mills are highly automated to minimize emissions to the neighboring communities they are located within. The circular flow of steel does not reduce any of its metallurgical properties, with the quality and properties of recycled steel being identical to the ones of virgin steel. Steel has proven multiple times to be more resilient than other building materials in terms of strength (~50,000 psi in both tension and compression), elasticity (29,000 psi), durability, non-combustibility, and resistance to decomposition. (AISC, 2017) Reduction of structural material and minimization of fabrication operations can lead to more sustainable use of steel for greater efficiency. Having early involvement with the steel fabricator and engineer can provide optimizations for the structure without using additional steel through using higher strength metals and taking advantage of the structural framing load path and material attributes. The use of domestic steel produced from adequate environmental controls and through the use of an electric arc furnace. If the material is from an electric arc furnace (EAF) mill the recycled content will be in the 90% to 100% range. If it is from a basic oxygen furnace (BOF) mill the recycled content will be near 25%. (AISC, 2017)

Recycled Concrete Materials

Common recycled C&D materials used in structural and infrastructure applications include recycled concrete aggregates (RCA), recycled masonry aggregates (RMA), mixed recycled aggregates (MRA), and reclaimed asphalt pavement (RAP). Recycled aggregates can be used in pavement applications in substitute for virgin materials. To be suitable for structural use, the recycled aggregate must hold suitable shear strength, drainage, chemical resistance to environmental or chemical degradation agents, anti-freeze-thaw characteristics, and good hydraulic behavior to ensure appropriate durability. (Pereira, P. M., & Vieira, 2022) Materials that are more durable are more resistant to deterioration and require minimal maintenance, thus having a lower impact on the environment, as it contributes to resource conservation and waste reduction. Additionally, waste reduction and efficient use of concrete materials can be implemented throughout the process of construction and deconstruction. Precast structures produce less waste due to its controlled and specific construction process. To efficiently maximize the amount and value of recycled aggregates, a proper sorting and selection process must be carried out. Selective demolition is an option, where the separation and sorting of building materials are conducted within the deconstruction process. (Pereira, P. M., & Vieira, 2022)

Coarse recycled aggregate (CRA) is attained by crushing concrete that has reached its end-of-service life, composed mainly of natural stone, and attached mortar. Mostly coarse aggregates are considered for recycled aggregates, due to their high cohesion, water absorption, risk of contamination, and low workability. CRA typically has lower densities and workability and increased porosity than natural aggregates, due to the less dense and more permeable attached motor. The interfacial transition zones of the CRA are weaker and have limited mechanical properties. The average moisture content of MRA, RCA, and RMA is 10% above, while RAP has a smaller ratio close to that of virgin aggregates. Pure CRA concrete displays a 10-37% decrease in compressive strength at 28 days, compared to coarse natural aggregates. Thus, it requires about 5% more cement to attain the same strength, compromising the cost-effectiveness and sustainability of CRA. (Tamayo, Pacheco, Thomas, Brito, & Rico, 2019) After 28 days, there is a relative increase in compressive strength due to the hydration of the unhydrated grain. The use of CRA reduces fatigue limit and life, consequently, limiting the recycling cycles to three before more new natural aggregates are needed.

To recover some of the lost mechanical and physical properties, additional pre-processing procedures were proposed including additional crushing stages to eliminate the attached mortar and make the aggregates less porous, the use of Thermo-mechanical processes, and the use of steel slag- a by-product of the steelmaking industry. The use of electric arc furnace slag (EAFS) improves compressive strength by 50% and induces a higher elastic modulus, greater durability, and lower permeability. The quality of material produced by the CRA and EAFS seems to be more sustainable than the common CRA as it saves additional natural resources and waste production. (Tamayo, Pacheco, Thomas, Brito, & Rico, 2019) This production of recycled concrete accounts for a reduction as high as 35% in CO2 emissions. Its improved mechanical and durability properties allow the material to be used for a multitude of applications: foundations, plain concrete walls, or structures where a high self-weight is important.

Discussion/Results

To aim for sustainable design and construction without compromising the structural integrity of a project, the scope and use of the project are the most important factors to consider. It is essential to involve engineers, architects, and material fabrications early in the design process to determine the optimal material needed and its quantities. Design professionals are expected to investigate the influential effects of perceived sustainable material and choose the material that is best for the project to achieve all five categories of the sustainability instrument- quality, functionality, user appeal, resourcefulness, and purchasability. Due to the high percentages of waste accumulation from the construction industry and lack of resource preservation, alternatives such as recycled steel and concrete aggregates are ideal substitutes. Through the study of their properties, the materials exhibit properties comparable to those of virgin materials and would serve as a sustainable alternative with the verification by structural calculations and the judgment of a licensed structural engineer.

The recyclability and properties of building materials should not be compared with one another, “a ton of concrete is not the same as a ton of steel or a ton of wood” (AISC, 2023). To accurately compare two materials, the framing structure, location, orientation, size, function, and load capacity must be of similar fit. For example, one may say that wood is more sustainable than steel or concrete and choose it as the primary building material for a large-scale project, but due to the weak strength of timber and lumber, greater quantities are needed compared to steel or concrete. Thus, increasing the number of materials such as water, electricity, labor, etc. needed to create this “sustainable” building. This example shows the frequent wrongful thinking and selection of construction materials based on misleading information that results in increasing rather than decreasing the environmental mark of the building. Therefore, although each material has varying levels of sustainability, not one can be said to be better, the engineer’s goal should be to select the most applicable material that fits the design and then continue to optimize the use of materials environmentally. To gain the maximum benefit of a sustainable building, the engineer must choose the appropriate material for the project and gain proper and accurate information and properties on the material.

During an interview with several undergraduate civil engineering students at the University of Virginia, many have stated their motivation for choosing civil engineering was to help communities in a tangible way and to build physical products in the world. When asked if they think the construction and design industry can currently be labeled as sustainable, one student stated “Definitely not. Construction is destruction” While others agreed that engineers and construction managers are making slow progress, the industry is still “more sustainable than not sustainable”. Additionally, it has been agreed that there are more incentives for sustainability now than in the past, however, more efforts should be made to achieve the title of sustainable. The UVa students also believe that while structural engineers can and should influence the sustainability of a project with materials selection, the owners and architects make most of the final decisions and the role does not fall upon the engineer. The last question asked to the undergraduates was "What do you think is the most important way to improve sustainability in construction and design currently?" The responses include changing specifications that require sustainable materials, product requirements, performance and execution standards.

Conclusion

The responsibilities of a civil engineer include designing buildings for not only the community but also for the environment. To design the most sustainable building, the engineer must evaluate the material based on all five of these factors and align the choice with the project's specifications. Although each material has varying levels of sustainability, not one can be said to be better, the engineer's goal should be to select the most applicable material that fits the design and then continue to optimize the use of materials environmentally. The architects and engineers at Holcim are a global leader and excellent example of sustainable construction and should be a testimony of the benefits of sustainable durable materials. To gain the maximum benefit of a sustainable building, the engineer must choose the appropriate material for the project and gain proper and accurate information and properties on the material. The suitability of structural components for reuse depends solely on the calculations and judgment of structural engineers.

Bibliography

DEI Creative in Seattle, W. (2023, May 2). 11 – structure: Steel, Concrete + Wood. LMN Architects. https://lmnarchitects.com/lmn-research/11-structure-steel-concrete-wood#:~:text=Concrete%2C%20steel%2C%20and%20wood%20are,is%20from%20the%20built%20environment).

Kumar, S., Saravanan, J., Yew, M. K., & Kabeer, S. A. (2024). Advancements in sustainable construction materials: Innovations, applications, and environmental impact. Advancements in Sustainable Construction Materials: Innovations, Applications, and Environmental Impact. https://www.frontiersin.org/research-topics/60007/advancements-in-sustainable-construction-materials-innovations-applications-and-environmental-impact/overview

A world first: Holcim produces 100% recycled clinker. Holcim. (2022, August 4). https://www.holcim.com/who-we-are/our-stories/recycled-clinker

Harby, A. (2024, January 10). Sustainable construction: Facts & figures. CityChangers.org – Home Base for Urban Shapers. https://citychangers.org/construction-facts-and-figures/

IEA (2019), Global Status Report for Buildings and Construction 2019, IEA,

Paris,
https://www.iea.org/reports/global-status-report-for-buildings-and-construction-2019, Licence: CC BY 4.0

Chaudhary, Muhammad & Piracha, Awais. (2013). Examining the role of structural engineers in green building ratings and sustainable development. Australian Journal of Structural Engineering. 14. 10.7158/S12-019.2013.14.3.

American Iron and Steel Institute. (n.d.). Sustainability in Steel Recycling. https://www.steel.org/wp-content/uploads/2020/09/Steel-Sustains-in-Recyclability-Fact-Sheet.pdf

John Cross, SUSTAINABILITY 2015: WHAT'S NEW WITH STEEL AND SUSTAINABILITY? Plenty. https://www.aisc.org/globalassets/modernsteel/archives/2015/03/n6.pdf

Florez, L., Castro, D., & Irizarry, J. (2013). Measuring sustainability perceptions of construction materials. Construction Innovation, 13(2), 217–234. https://doi.org/10.1108/14714171311322174

American Iron and Steel Institute. (2020). Sustainability in steel recycling. https://www.steel.org/wp-content/uploads/2020/09/Steel-Sustains-in-Recyclability-Fact-Sheet.pdf

More than recycled content - AISC. (2017).

https://www.aisc.org/globalassets/aisc/publications/white-papers/more-than-recycled-content.pdf

Pereira, P. M., & Vieira, C. S. (2022). A literature review on the use of recycled construction and demolition materials in unbound pavement applications. Sustainability, 14(21), 13918. https://doi.org/10.3390/su142113918

Pablo Tamayo, Joao Pacheco, Carlos Thomas, Jorge de Brito, & Jokin Rico (2019). Mechanical and Durability Properties of Concrete with Coarse Recycled Aggregate Produced with Electric Arc Furnace Slag Concrete. Applied Sciences, 10(1), 216.