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Literature Survey for Comparative Analysis of the Life Cycle Assessment for Concrete and Steel as Construction Materials

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Abstract: Concrete and steel are extensively utilized construction materials with an ever-increasing demand. The construction sector alone consumes approximately 75% of the total raw materials, resulting in significant strain on natural resources and considerable environmental impact. Moreover, construction materials contribute substantially to global CO2 emissions. Steel and in-situ concrete are dominant materials in commercial construction, making their production and usage highly influential in environmental terms due to the sheer quantity involved. Furthermore, the escalating energy costs and potential future shortages have heightened the importance of considering both embodied energy (energy consumed during production) and operational energy (energy utilized over the projected lifespan) for construction materials. Consequently, builders, designers, and building owners are increasingly emphasizing these energy aspects.A prevailing global trend, including in India, is to adopt eco-friendly designs. Consequently, the concrete and steel industries have made substantial efforts in recent years to position their materials as optimal solutions for sustainable building design. Given that sustainable practices necessitate minimizing natural resource consumption, reducing air emissions, and optimizing embodied energy, this study aims to compare and quantify these factors to evaluate the disparities between concrete and steel frame structures in terms of their construction requirements.

Keywords: Construction materials, Concrete, Steel, Life cycle assessment, Sustainable building design, Environmental impact.

1. INTRODUCTION

Steel and reinforced cast-in-place concrete are the prevailing building materials in the global commercial construction industry. These materials have been widely utilized in the built environment since the early 1900s, and their distinct properties regarding strength, stiffness, density, and constructability set them apart. Steel offers notable advantages in terms of strength and stiffness, making it ideal for structures requiring large spans or tall heights. Its relatively low density also facilitates easier transportation and installation. On the other hand, reinforced cast-in-place concrete boasts exceptional durability and fire resistance, making it suitable for structures subjected to harsh environments. Additionally, concrete provides valuable thermal mass and sound insulation properties.However, these materials come with their respective drawbacks. Steel is prone to corrosion and requires protective coatings as well as regular maintenance. It also tends to be more expensive compared to concrete. On the other hand, concrete has a slower construction process and necessitates formwork for shaping. Its higher density may also impact transportation logistics and require robust foundations.In summary, steel and reinforced cast-in-place concrete exhibit significant differences in their characteristics, influencing their suitability for various construction applications. Understanding these divergent attributes is crucial for making informed decisions in commercial construction projects.Table 1 provides a concise comparison between steel and concrete, highlighting their respective positive and negative attributes. This table offers a brief overview of the characteristics of these two materials in terms of their advantages and disadvantages.

Particular	Characteristics
Steel	+ High strength to weight ratio +Tensile and compressive strength +Ductility +Accurate connection settings
	- Fire-proofing required - Expensive rigid connections (weld)
Concrete	+Formable; molded to any required shape +Durable +Fire resistant +Rigid connections
	- Compressive strength only - Labor-intensive

Table 1: Concrete and Steel Characteristics for Construction.Source: (Madsen, 2005)

2. LIFE CYCLE ASSESSMENT METHOD

While not a recent discipline, industrial ecology is gaining prominence as an essential research area for addressing contemporary environmental challenges, alongside environmental management and sustainable design. Within the field of industrial ecology, various analysis methods are employed, and one such method is Life Cycle Assessment (LCA). Developed in the 1990s by the Society of Environmental Toxicology and Chemistry (SETAC) and later standardized by the International Standards Organization (ISO), LCA serves as a valuable tool for evaluating the environmental impacts of a product system. The utilization of LCA methodology is particularly fitting for the present research study, which aims to compare two materials.

3. DEFINED ENVIRONMENTAL IMPACTS

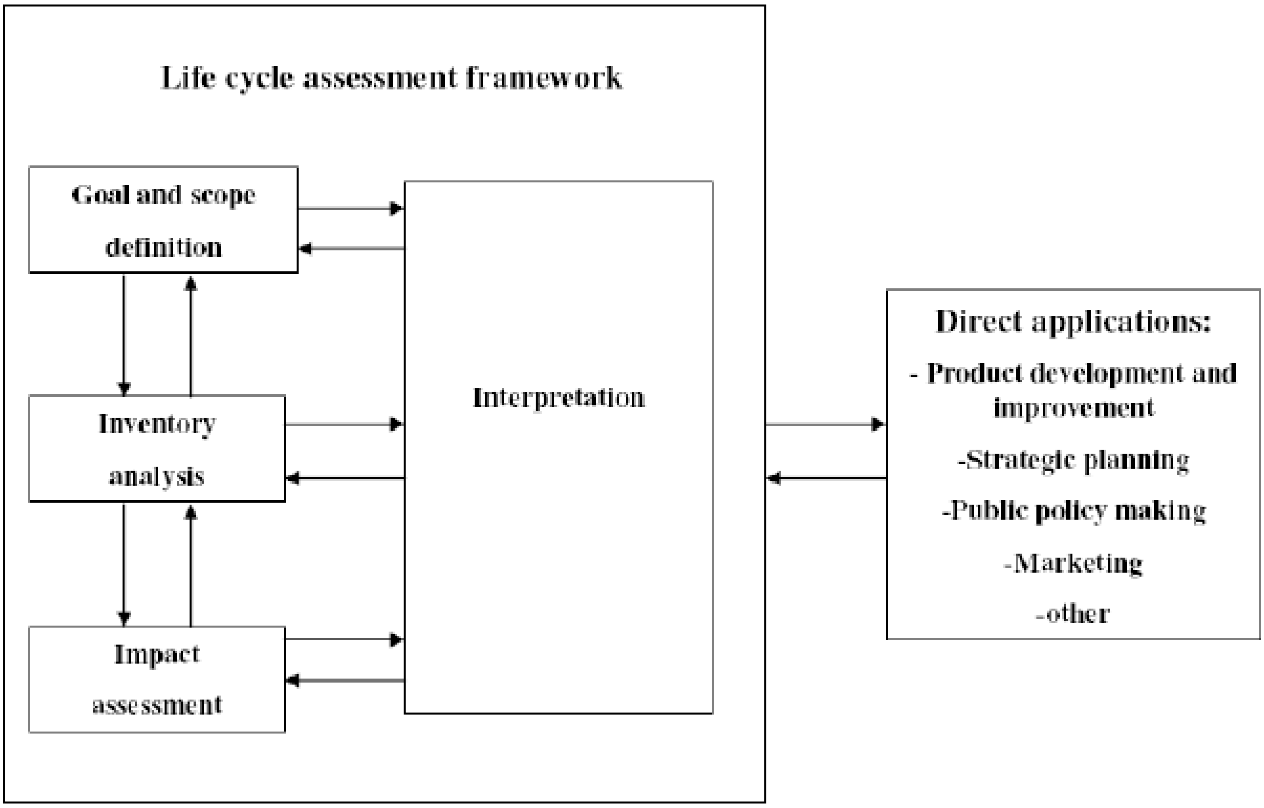
These environmental factors are the focus of investigation in this study, as they play a significant role in assessing the overall environmental impact of the materials under examination.This study addresses several key environmental concerns, including:

- Acidification Potential
- Aquatic Eutrophication Potential
- Global Warming Potential
- Ozone Depletion Potential
- Smog Potential
- Total Primary Energy
- Non-Renewable Energy
- Fossil Fuel Consumption

4. LIFE CYCLE ASSESSMENT (LCA)

Life Cycle Assessment (LCA) is a valuable tool utilized within the field of environmental management. It enables the assessment of potential environmental impacts throughout the entire life cycle of a system or product under examination. This comprehensive approach takes into account the possible impacts associated with each stage of the life cycle. LCA encompasses four main stages: goal definition, inventory analysis, impact assessment, and interpretation.The holistic nature of LCA makes it applicable in various contexts and serves multiple purposes. It is commonly employed in environmental management practices, including risk assessment, environmental performance evaluation, environmental auditing, and environmental impact assessment. LCA provides insights into the complete life cycle of a product or service, from the acquisition of raw materials to manufacturing, distribution, usage, potential recycling or reuse, and final disposal.However, it is important to acknowledge the limitations of LCA when drawing conclusions from LCA studies. While LCA offers numerous advantages, such as its comprehensive scope and ability to assess environmental impacts, there are inherent constraints to consider. These limitations should be taken into account to ensure accurate interpretations and conclusions are drawn from an LCA study.

Figure1: Stage of an LCA, Source: International Organization for Standardization (2006)



5. LITERATURE SURVEY

The practice of conducting life cycle assessments (LCAs) for construction materials is not a recent development. Due to the widespread use of materials like concrete and steel on a global scale, understanding their environmental impacts has been a longstanding area of interest. Nevertheless, when it comes to commercial structures, research efforts have been fragmented and not consistently beneficial or applicable.

Nele et al. (2014) Completely Recyclable Concrete (CRC) is specifically engineered to be recycled within cement production, resulting in reduced environmental impact associated with concrete and cement manufacturing. To assess the environmental benefits of CRC, a comprehensive life cycle assessment (LCA) was conducted.The findings of the LCA indicated that the environmental impact of concrete production is strongly influenced by its binder content, primarily cement, and also fly ash when economic allocation is considered. Additionally, the recycling potential of concrete is significantly affected by transportation requirements, which may be higher for CRC due to longer distances to cement plants compared to concrete recycling facilities.The key environmental advantage of CRC recycling lies in its potential to mitigate global warming. By utilizing CRC instead of traditional cement raw meal for clinker production, a certain amount of CO2-free CaO is incorporated, resulting in a reduction in CO2 emissions.When examining the complete life cycle of CRC compared to traditional concrete, it was determined that a reduction of 66% to 70% in global warming potential is achievable by designing high-strength CRC with a low clinker content. For normal-strength CRC with a higher clinker content, reductions of 7% to 35% can be attained if an adequate service life is achieved. However, for other impact categories such as abiotic depletion, acidification, eutrophication, ozone layer depletion, photo-oxidant formation, human toxicity, and ecotoxicity, only the performance of high-strength CRC with low clinker content could compensate for the additional transportation requirements associated with the recycling process.

Saheedet al.(2015) This study aimed to assess the impact of material specifications on the life cycle environmental performance of buildings using BIM-enhanced LCA methodology. It underscores the significance of LCA as a comprehensive approach for evaluating the environmental impact of buildings throughout their entire life cycle, from inception to disposal. Furthermore, the study explored the application of ISO 14040, the internationally standardized LCA methodology for products, in the context of whole buildings.The findings of the study revealed that ISO 14040 can be adapted to assess whole buildings in a similar manner to product-based assessments. This enables the determination of the relative importance of building components and life cycle stages, as well as facilitating comparisons between different building types and specifications through the use of what-if scenarios and variability analysis. By employing BIM-enhanced LCA methodology, the study demonstrates the feasibility of utilizing LCA as a tool to support informed decision-making and sustainability assessments in the building industry.

Lu et al.(2017) This study conducted a life cycle comparison of four alternative options for structural beams in the building construction sector. It examined engineered LVL (Laminated Veneer Lumber) beams made from hardwood forestry mid-thinning and final harvest, as well as traditional options of steel and concrete beams.

The results of the study indicated that LVL beams from mid-rotation thinning performed significantly better in terms of Global Warming Potential (GWP). This was primarily attributed to the low energy intensity and utilization of low-value materials in the manufacturing process of LVL beams. Furthermore, substituting biomass fuel for fossil fuel during manufacturing resulted in a substantial reduction in greenhouse gas (GHG) emissions.Concrete beams were found to have the highest GWP among the options considered, primarily due to the energy-intensive materials used and their heavy weight, which increased energy consumption during manufacturing and transportation. Steel beams performed slightly better than concrete beams, primarily due to their lighter weight, resulting in reduced energy and material consumption, as well as transportation emissions. The recycling of steel also contributed to significant GHG emission reduction.Two scenarios were evaluated for LVL beams, and the study concluded that LVL beams sourced from thinned hardwood logs had lower environmental impacts compared to beams from mature hardwood logs. This was mainly attributed to the avoided emissions during the plantation stage. Additionally, while the embedded energy in thinned wood LVL beams was only marginally lower than that of steel, it was significantly lower than that of concrete. However, LVL beams from mature hardwood logs exhibited much higher embedded energy compared to the options of thinned wood LVL beams and steel beams.

Biswas et al.(2017) In the pursuit of green infrastructure design, life cycle assessment (LCA) has played a vital role by providing an objective and consistent approach to evaluating the environmental impacts of construction materials and assemblies. In line with this objective, the first-ever LCA study following the Gulf Green Mark - Environmental Product Declaration - Product Category Role (GGM-EPD PCR) was conducted. The study focused on assessing the environmental performance of precast and ready-mix concrete, utilizing data from a concrete manufacturer in Qatar.This pioneering methodology holds the potential for application to similar construction materials and other sectors within the Gulf States, enabling the mitigation of environmental impacts associated with the rapidly expanding construction industries in the region. Preliminary findings indicate that incorporating recycled steel and utilizing electricity generated from solar radiation in the production of concrete materials and concrete itself can further reduce the environmental impacts of these products in Qatar.

Maria et al.(2018) The objective of this paper is to evaluate the environmental advantages and disadvantages associated with the utilization of steel residue for the creation of a new binder in construction materials. Specifically, the potential of argon oxygen decarburisation (AOD) slag, a type of stainless steel slag, to serve as a binder in construction materials is explored. Activation methods such as alkali activation and carbonation are examined to activate the binding properties of AOD slag. Presently, AOD slag is predominantly recycled as low-quality aggregate, but this study investigates its potential for higher-value applications.To assess the environmental performance of utilizing AOD slag in construction blocks, three types of blocks, referred to as SSS-blocks, were developed using alkali activation and carbonation processes. Data on the production of these blocks was collected and analyzed through a life cycle assessment (LCA) study. The environmental impacts of SSS-block production were compared with those of traditional paver ordinary Portland cement (OPC) concrete.The LCA results revealed that SSS-block production through alkali activation and carbonation has the potential to mitigate certain environmental impacts associated with OPC-concrete. However, the analysis also identified some challenges. In the alkali activation process, the production of alkali activators emerged as a significant bottleneck, impacting the environmental performance of the process. On the other hand, the use of electricity and pure CO2 streams in the carbonation process was found to have a favorable effect on the overall environmental performance.In summary, the study highlights the potential environmental benefits of utilizing AOD slag in construction materials, specifically through alkali activation and carbonation processes. However, it also emphasizes the need to address challenges related to alkali activator production and optimize electricity and CO2 usage in order to enhance the environmental performance of the entire process.

Mohd. et al. (2020). The aim of this study is to compare the environmental impacts and costs of steel and concrete Prefabricated Prefinished Volumetric Construction (PPVC) systems using Life Cycle Assessment (LCA) and Life Cycle Cost (LCC) methods. The analysis considers the entire life cycle of these systems, from their initial stages to their end-of-life.The findings indicate that steel PPVCs require higher electricity usage compared to concrete PPVCs across all environmental categories. However, concrete PPVCs have a higher emission rate. In terms of non-renewable energy measures, steel outperforms concrete by approximately 37%, while it performs better by 38% in respiratory inorganics, 43% in land occupation, and 40% in mineral extraction. On the other hand, concrete performs 54% better on average in terms of greenhouse gas (GHG) emissions.Although steel incurs higher costs during the construction stage, it proves to be more cost-effective in the long run. This is attributed to the recovery, recycling, and reuse of materials, allowing steel PPVC to cost 4% less than concrete PPVC. Overall, steel PPVCs demonstrate better performance in terms of both cost and environmental factors (excluding GHG emissions).In summary, this study highlights that steel PPVCs exhibit superior performance compared to concrete PPVCs in terms of cost and several environmental factors. However, concrete PPVCs have an advantage in reducing GHG emissions. The results provide valuable insights for decision-making in the selection of PPVC systems.

Rakhmawatiet al.(2020) The findings of the concrete Life Cycle Assessment (LCA) research indicate that the casting process of concrete plates has a significant impact on the environment, particularly in terms of global warming. This is primarily due to several factors, including the carbon emissions associated with the main material used in ready-mix, namely cement.

Additionally, air pollution generated by trucks during transportation to the project site and the use of pump trucks for concrete slab implementation also contribute to the environmental impact. Overall, the process of casting concrete plates emerges as the major contributor to the environmental impact, highlighting the importance of addressing these factors to reduce carbon emissions and air pollution in construction practices.

Victor et al. (2021) This study presents a life cycle assessment (LCA) and comparison of four different bridge deck alternatives with varying span lengths, aiming to determine the most sustainable solutions. The analysis utilizes the ReCiPe method and the Ecoinvent 3.3 database to assess the environmental impacts of each alternative throughout their life cycles. The life cycle is divided into four phases: manufacturing, construction, use and maintenance, and end of life, while considering associated uncertainties. The results are presented using both midpoint and endpoint approaches. The findings reveal that for span lengths below 17 m, the prestressed concrete solid slab is the optimal alternative. In the span length range of 17 to 25 m, where the box-girder solution is not used, the best choice is the prestressed concrete lightened slab. For span lengths between 25 and 40 m, the ideal solution depends on the percentage of recycled structural steel. If the percentage exceeds 90%, then the composite box-girder bridge deck emerges as the most favorable alternative.

Oladazimiet al.(2021) To assess the sustainability of buildings in Tehran, Iran, two conventional construction frames, steel frame and concrete frame, were chosen for analysis. The study employed three conventional approaches: life cycle assessment (LCA) to evaluate environmental impacts, life cycle cost (LCC) to assess economic factors, and social life cycle assessment (SLCA) to examine social impacts. The key findings can be summarized as follows: The LCA results indicated that the concrete frame resulted in approximately 38% more environmental pollution compared to the steel frame. In terms of total building costs evaluated through LCC using the present value (PV) method, the steel frame was around $152,000 USD more expensive than the concrete frame. The quantified results of the social dimension using the SLCA method revealed that concrete and steel buildings scored 0.199 and 0.189, respectively, suggesting that concrete slightly outperformed steel in terms of social performance based on expert opinions.

Hegeiret al.(2022) This study aims to compare the environmental impact of timber, steel, and reinforced concrete in industrial buildings using life cycle assessment (LCA). The analysis focuses on the cradle-to-gate stage, including transportation to the construction site, due to data limitations. Only the quantities of the main structural system are considered, and portal frames with variable spans are designed to meet comparable load carrying capacities. The foundation of all frames utilizes reinforced concrete. The comparative study reveals that timber exhibits a significantly better environmental impact compared to reinforced concrete and steel, primarily attributed to the carbon stored in wood. Furthermore, the study shows that reinforced concrete and steel alternatives have similar environmental impacts. These findings align with previous research conducted on residential buildings.

Islam et al.(2022) This study conducted a life cycle analysis of anaerobic bio-digesters constructed from various materials to evaluate their suitability for solid waste management and their ability to meet the demand for clean energy for cooking and electricity generation, while prioritizing sustainability in the design. The materials considered for construction were brick, concrete, steel, and plastic. The analysis included sequential assessments of Life Cycle Analysis (LCA), Life Cycle Cost Analysis (LCCA), and social impact assessment. The LCA utilized the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI). The findings revealed that using plastic as the material for the digester, with a lifespan of ten years, was advantageous compared to brick, concrete, or steel. Plastic demonstrated favorable attributes such as recyclability and ease of construction. The environmental impact of the plastic digester was approximately 50% lower than that of an equal-volume steel digester. Furthermore, the cost of gas per unit volume was lowest for the plastic digester at the end of its design life. In comparison, the brick, steel, and plastic digesters were 11%, 18%, and 23% less expensive, respectively, than the concrete digester. The social impact assessment indicated that the plastic digester was well-received in the local community.

Sbahiehet al.(2023) The objective of this paper is to conduct a life cycle assessment (LCA) to evaluate the environmental impacts of glass fiber-reinforced polymer (GFRP) bars, carbon fiber-reinforced polymer (CFRP) bars, and steel bars. Additionally, another LCA was performed to compare steel-reinforced beams using desalinated fresh water with GFRP/CFRP-reinforced beams using seawater in the concrete mixture. The findings indicate that GFRP bars outperformed steel bars in 10 out of 14 categories, while CFRP bars performed worse than steel bars in 10 categories. The SGFRP bars yielded results between steel and GFRP bars, performing better than steel bars in 10 categories. Furthermore, the GFRP beams exhibited superior environmental performance to steel beams in 9 categories, while CFRP beams performed better than steel beams in 8 categories. These improvements can be attributed to the reduced reinforcement ratio due to the high tensile strength of CFRP and GFRP bars compared to steel bars.

6. SUMMARY

The purpose of this literature survey is to provide a comparative analysis of the life cycle assessment (LCA) studies conducted on concrete and steel as construction materials. The paper summarizes and examines a range of research articles that have investigated the environmental impacts of these two materials throughout their life cycle.The survey begins by highlighting the significance of LCA in assessing the environmental performance of construction materials and its role in sustainable building design. It emphasizes the importance of considering the entire life cycle, from raw material extraction to end-of-life disposal, in order to obtain a comprehensive understanding of the environmental impacts.The survey then presents an overview of various LCA studies conducted on concrete and steel, focusing on their environmental indicators such as carbon emissions, energy consumption, and resource depletion. It discusses the methodologies used in these studies, including system boundaries, data sources, and impact assessment methods, to ensure comparability and consistency.The findings from the reviewed studies are synthesized, revealing both similarities and differences in the environmental performance of concrete and steel. The survey highlights that concrete production is associated with significant carbon emissions due to the high energy requirements of cement manufacturing. On the other hand, steel production has a substantial impact on resource depletion and energy consumption during extraction and processing.Overall, the survey concludes that both concrete and steel have environmental implications, and their relative sustainability depends on various factors such as production methods, material efficiency, and recycling capabilities. It emphasizes the need for further research and development to reduce the environmental footprint of these materials and identifies potential areas for improvement.In summary, this literature survey provides a comprehensive analysis of LCA studies comparing the environmental impacts of concrete and steel as construction materials. It offers valuable insights into the sustainability aspects of these materials and sets the foundation for future research and decision-making in the construction industry.

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