Proceedings of the International Conference on Industrial Engineering and Operations Management

Publisher: IEOM Society International, USA DOI: 10.46254/NA10.20250345
Published: June 17, 2025

Evaluating the Use of Steel Slag and Rice Husk Ash as Replacements of Aggregate in Concrete: A Sustainable Next-Gen Concrete

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Abstract

Concrete serves as the fundamental element for construction. The use of traditional constituent materials, including binders, coarse aggregates, and fine aggregates sourced from natural resources, is gradually declining. Binder materials, primarily cement, consist mainly of carbon compounds, leading to global carbon emissions. To resolve this issue, we must concentrate on alternative materials that generate low carbon emissions and do not deplete our natural resources. Steel slag, a byproduct of the steel industry, and rice husk ash, a waste product from rice mills, can be utilized in the concrete industry as a partial substitute for binder, coarse aggregate, or fine aggregate. This study examined the life cycle evaluation of steel slag and rice husk ash as binder replacements and analyzed their mechanical properties based on the research of other authors. Besides, life cycle assessment (LCA) results show the impact of the carbon footprint for both concrete. The LCA analysis shows that rice husk ash-modified concrete has lesser effects on environmental parameters such as acidification, ozone, and eutrophication than steel slug-modified concrete.

Keywords
Concrete, Steel Slag, Hice Husk Ash, Life Cycle Assessment, Sustainability.

1.Introduction
Concrete is a fundamental material for the construction industry. It mainly consists of coarse aggregate, fine aggregate, binder such as cement, and water. The binder, primarily composed of Ordinary Portland Cement (OPC), is responsible for 6-8% of total anthropogenic CO_2 emissions, which is significant in global warming (Feiz et al. 2015). The calcination process in manufacturing Ordinary Portland Cement (OPC) is the primary contributor to CO_2 emissions (Worrell et al. 2001). This production accounts for 74-81% of the carbon footprint in concrete (Schepper et al.2014). Researchers and academics are actively focused on how to prevent carbonation in concrete. Exhibiting excellent cementitious characteristics industrial byproducts, such as Steel Slag (SS) from the steel sector, may provide a viable option (Wang et al. 2013). Conversely, rice husk ash (RHA) from rice milling is also a viable alternative to ordinary

Portland cement (OPC). This study evaluated and compared the life cycle assessments of SS concrete and RHA concrete to determine which is more sustainable and evaluated other mechanical properties.

1.1 Objectives

The main goal of this study is to explore the environmental impacts of steel slag (SS) and rice husk ash (RHA) as partial replacement of binder materials. Nowadays, ordinary Portland cement (OPC) mainly contains 80-90 % clinker (Kabir et al., 2020), which is the main ingredient of the binder material. Based on the "Cement Technology Roadmap to 2050'' clinker produces 5% of global anthropogenic CO_2 emissions (WBCSD and IEA, 2009). By utilizing industrial waste as a replacement for binder material, researchers seek to reduce carbon emissions from the cement industry. A comprehensive life cycle assessment (LCA) is used to assess the footprint of the carbonation. Mechanical properties are also evaluated to ensure structural integrity.

2. Literature Review

Research indicates that a 15% substitution of steel slag facilitates 10-15% enhancement in the relative compressive strength of concrete (Wang et al. 2013). Using steel slag increases compressive strength; the study lacks clarity regarding the proportions used. Furthermore, according to their life cycle evaluation, they gave no graphical data illustrating the amount of carbonation (Mocharla et al. 2022). Further research by (Václavík et al. 2020) was undertaken; however, it did not address carbonation, although it evaluated eutrophication and other factors. Moreover, several writers have employed various software for LCA study; nonetheless, a research gap persists in using "Athena" software for this purpose (Li et al. 2021). This technique diminishes mining activities, fosters circular economic systems, and decreases carbon emissions by fifty percent (Manso et al.2019). Likewise, concrete including rice husk ash exhibits enhanced compressive strength compared to standard concrete when rice husk ash constitutes 10% of the mix. This section (Krishna et al. 2016) presents their optimal strength. However, they did not conduct any life cycle evaluations in their study, which is a significant limitation.Furthermore, the utilization of rice husk ash as a substitute for cement diminishes early-age strength, while it achieves maximum strength subsequently; nevertheless, the study did not specify the percentage of rice husk ash replacement, nor was a life cycle analysis performed (Madandoust et al. 2011). Furthermore, its siliceous composition exhibits resistance to natural degradation, potentially resulting in a significant environmental burden (Zerbino et al. 2011). Consequently, examining their studies through a life cycle evaluation is essential.

3. Methods

Two distinct mix designs for SS concrete and RHA concrete are utilized, sourced from (Wang et al. 2013) and Krishna et al. 2016). (Wang et al.2013) examined percentage replacements of 0%, 15%, and 30%, whereas (Krishna et al.,2016) analyzed replacements ranging from 0% to 20% in 5% increments. The objective strength for SS concrete was 47 MPa with varying water-cement ratios; however, this research considers a 0.50 w/c ratio. (Krishna et al. 2016) evaluated 30 MPa. Rather than employing a 0.5 water-cement ratio utilized for SS concrete, a 0.55 water-cement ratio is adopted for RHA.

4. Data Collection

Data collection is a critical component of research. This study collected a lot of data, including material qualities, quantities of aggregates, water, binder, and other ingredients. Other physical and mechanical parameters, including fineness modulus, moisture content, and specific gravity, were also documented for the mix design. The findings provided a basis for further investigation of environmental and mechanical parameters.

4.1 Raw Materials

Ordinary Portland Cement (OPC) is used as the binding ingredient for SS and RHA concrete. Oxygen furnace steel slag is utilized for stainless steel concrete, whereas locally accessible rice husk ash is employed for rice husk ash concrete. Additionally, local sources are utilized for both coarse and fine aggregates. Table 1 presents the differences in chemical characteristics between SS and RHA (Wang et al. 2013; Krishna et al. 2016). The analysis indicates a notable CaO, Fe_2O_3, and MnO concentration in the steel slag. Consequently, it undoubtedly generates a substantial carbon footprint. Conversely, RHA mainly comprises SiO_2. Although it lacks significant quantities of other elements (such as MgO, Fe_2O_3, Al_2O_3, etc.) contributing to carbon emissions, RHA is more sustainable than SS.

Table 1. Chemical properties comparison between SS & RHA

SS & RHA Properties (%)	Difference (%)
CaO	38.07
SiO_2	64.39
MgO	7.49
Fe_2O_3	25.33
MnO	1.94
Al_2O_3	5.23

4.2 Mix Design

Using growing replacement rates, concrete mix designs using steel slag and rice husk ash exhibit appropriate component ratios that emphasize material performance and sustainability. Cement concentrations in steel slag mixes are gradually lowered from 350 kg/m³ (0% replacement) to 298 kg/m³ (15% replacement) and 245 kg/m³ (30% replacement). As the slag percentage increases, the cement content decreases proportionally (171 to 147 kg /m³), indicating reduced need for water or mixing modifications to maintain workability. To facilitate volumetric swap, fine and coarse aggregate quantities range from 821 kg/m³ to 831 kg/m³ in the former and from 1088 kg/m³ to 1102 kg/m³ in the latter.

Additionally, the admixture dose is increased from 1.9 to 2.4 kg/m³ to guarantee adequate slump at high slag levels. All replacement levels in RHA mix designs maintain stable fine aggregate (572.74 kg/m³), coarse aggregate (1189.5 kg/m³), and water content (191.60 kg/m³), but cement content falls from 348.36 kg/m³ to 278.7 kg/m³ from 0% to 20% RHA series' constant water content increases the water-cement ratio, which is acceptable considering RHA's excellent pozzolanic characteristics and paste matrix improvement. Changes in mix proportions suggest a significant decrease in Portland cement usage, which accounts for 8% of worldwide CO_2 emissions. Concrete mixes that partially replace cement with steel slag (an industrial by-product) (Silgado et al. 2024) and RHA (an agricultural by-product) (J et al. 2024) reuse these waste materials and reduce their environmental impact, following the circular economy and sustainable construction principles. Steel slag as an additional cementitious material increases concrete's long-term strength and durability at sufficient replacement rates without drastic effects. At the same time, RHA's high silica content improves the pore structure and the durability of hardened concrete.

Figure 1. Typical Composition of Concrete

These mix designs showed increased steel slag and RHA substitution, which reduced cement and water consumption and promoted the use of alternative materials, emphasizing the balance between environmental sustainability and concrete performance in the composite. Figure 1 outlines the volumetric proportion of the optimized concrete mix used in the research under investigation as found during data collection. The central mass constitutes a coarse aggregate, a cement, and a fine aggregate, which also forms the majority of the matrix. Water in the chemical admixture is controlled at reduced but controlled amounts to get the desired workability and setting properties. RHA and SS are incorporated as additional components in small quantities without compromising the mixture's ability to efficiently achieve industrial and agricultural wastes while maximizing the fresh and toughened components.

Table 2. Mix Design of SS Concrete

Replacement %	Steel Slag (Kg/m^3)	Cement (Kg/m^3)	Fine Aggregate (Kg/m^3)	Coarse Aggregate (Kg/m^3)	Water (Kg/m^3)	Admixture (Kg/m^3)
0	0	350	821	1088	171	1.9
15	52	298	824	1092	164	2.1
30	105	245	831	1102	147	2.4

Table 3. Mix Design of RHA Concrete

Replacement %	RHA (Kg/m^3)	Cement (Kg/m^3)	Fine Aggregate (Kg/m^3)	Coarse Aggregate (Kg/m^3)	Water (Kg/m^3)
0	0	348.36	572.74	1189.5	191.60
5	17.42	330.94	572.74	1189.5	191.60
10	34.83	313.52	572.74	1189.5	191.60
15	52.2	296.11	572.74	1189.5	191.60
20	69.6	278.7	572.74	1189.5	191.60

5. Results & Discussions

Life-cycle assessment and performance testing demonstrate that substituting cement with steel slag and rice husk ash saves the environment considerably in terms of reduction in carbon emission, embodied energy, and acidification potential, with no negative impact on their mechanical properties or improvement. Steel slag mixes improve early strength and reduce water demand. In contrast, RHA mixes improve pore structure and durability but require a slight increase in the water-binder ratio to achieve workability. Suitable admixture dose and curing methods ensure satisfactory fresh-state consistency and hardened-state performance in either series. Findings suggest that adding industrial and agricultural by-products to the cementitious formulations may achieve sustainability and concrete quality equilibrium when optimized.

5.1 Sankey Body Diagram

This study aims to analyze the life cycle evaluation of two kinds of concrete and identify their carbon footprints. Additionally, mechanical qualities were also assessed in this investigation. A Sankey diagram was produced to quantify the materials for this research, illustrating the total amount of materials necessary for each form of concrete. Figure 2 illustrates 3,282.0 kg/m³ of coarse aggregate necessary for concrete with a Steel Slag Replacement Percentage of 0 (SSRP). Likewise, the quantity is indicated for all other ingredients. This result suggests that the amount of steel slag is relatively less than that of the binder ingredient. Conversely, Figure 3 illustrates the entire quantity of material necessary for Rice Husk Ash Percentage Replacement (RHAPR)-0 concrete. All materials are measured in kg/m³. The increased substitution of RHA necessitates a greater quantity of materials than SS concrete. RHA concrete requires around 6000 kg/m3 of coarse material, nearly double that of SS concrete. A similar distinction is observed with garbage as well. Meanwhile, the fine aggregate remains consistent mainly for both types of concrete.

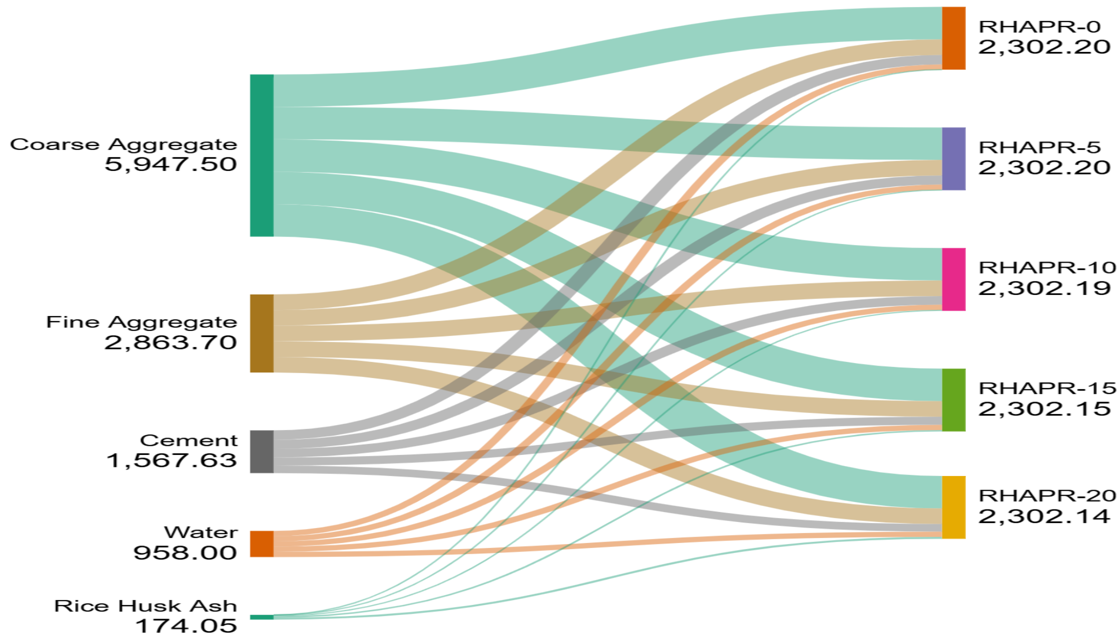

Figure 2. Sankey body diagram for RHA concrete.

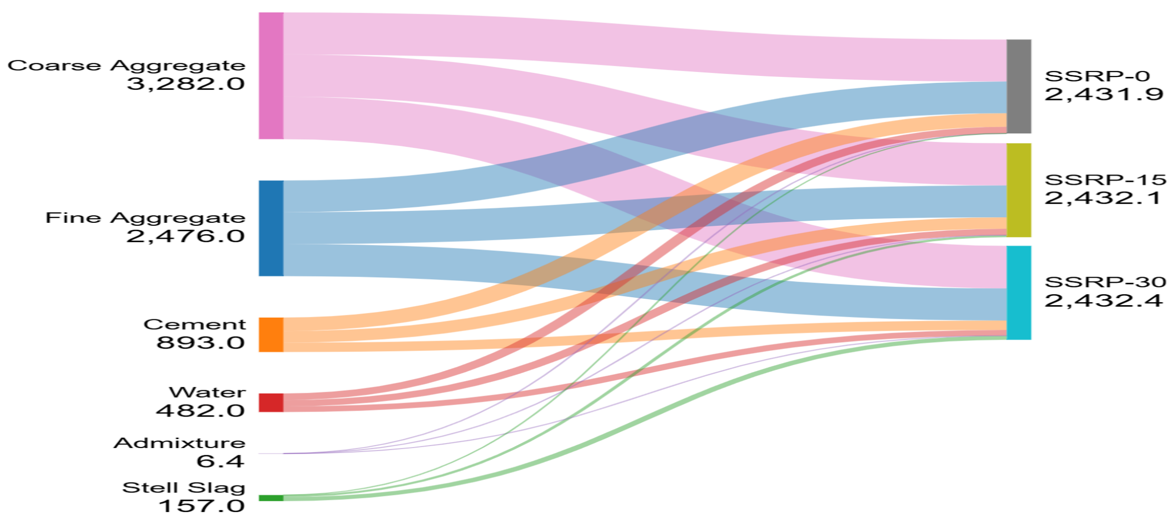

Figure 3. Sankey body diagram for SS concrete.

5.2 Life Cycle Assessment

It is essential to undertake a life cycle evaluation of goods due to the use of waste materials from the industry. Furthermore, it is necessary to analyze LCA using various applications. There remains a gap in identifying the precise evaluation. Researchers performed a review, yet certain restrictions persist. Some did not specify the program name (Kua 2015), while others omitted additional parameters such as acidification, eutrophication, and ozone depletion (Prusinski et al., 2014). To solve this limitation, the "ATHENA" program is employed to do the Life Cycle Assessment (LCA) specifically within the building construction sector of SS and RHA concrete.

These numbers demonstrate that a higher carbon content in steel slag has a greater environmental impact than RHA. RHA is primarily an organic substance with lower carbon content and contains elements such as Mn, Mg, and Fe, in contrast to SS. Figure 4 indicates that the CO_2 emissions from SS concrete amount to 79,900 kg, whereas those from RHA are 44,000 kg. Likewise, the parameters of acidification and eutrophication are 300 kg and 78 kg, respectively.

In RHA, all other metrics, including acidification, eutrophication, and ozone depletion, are lower than SS concretes. This demonstrates that, per sustainability principles, RHA concrete is more appropriate than SS concrete.

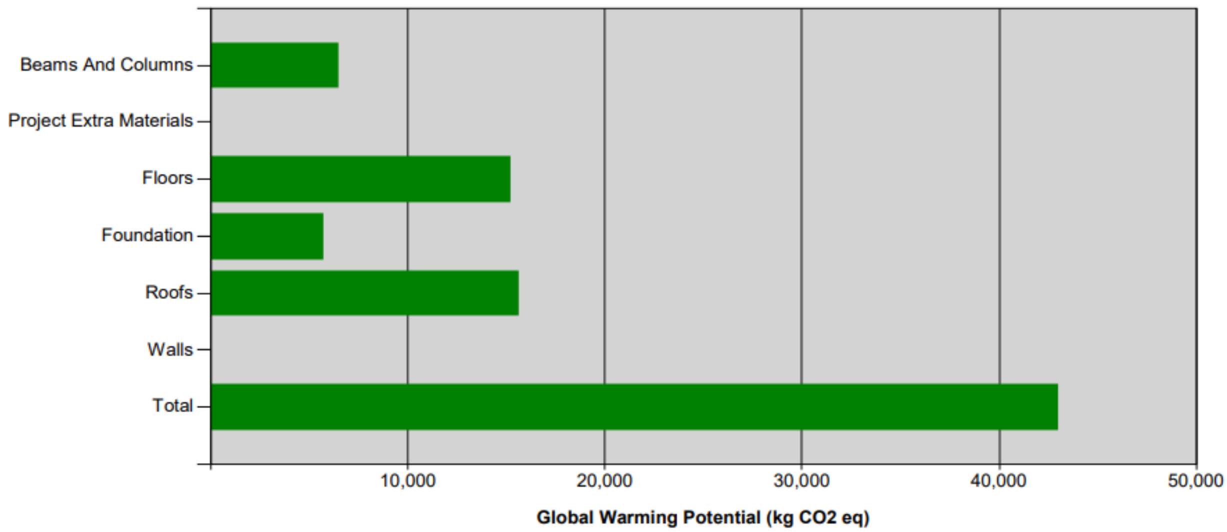

Figure 4. Global warming for RHA concrete

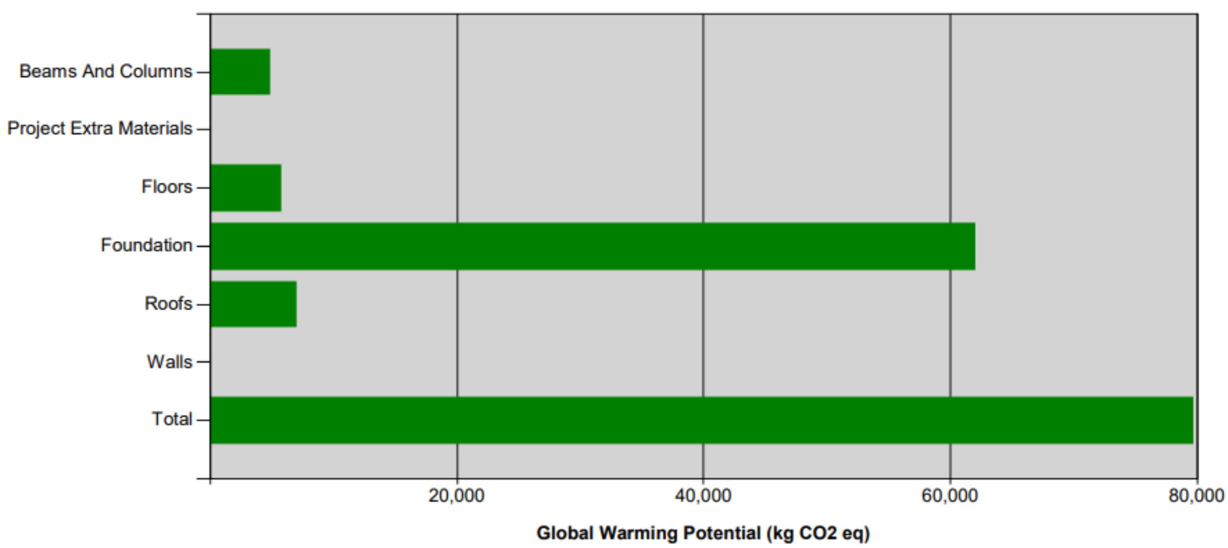

Figure 5. Global warming for SS concrete

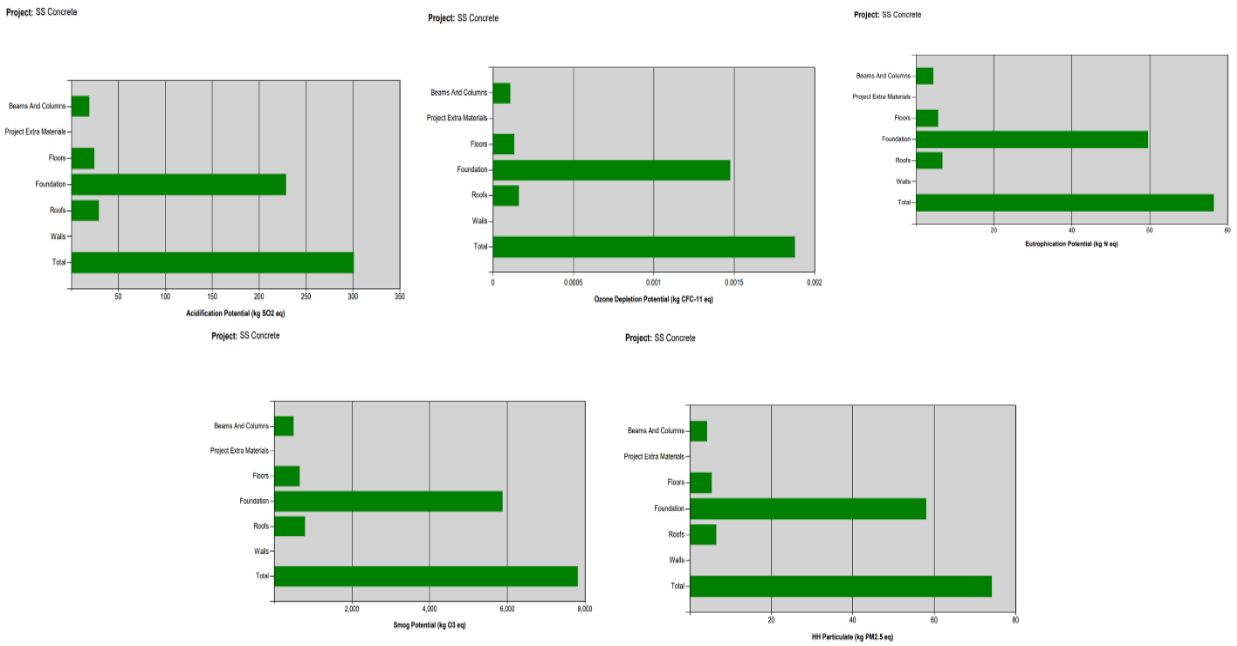

Figure 6. Acidification, Ozone, Eutrophication & Particulate analysis for SS concrete

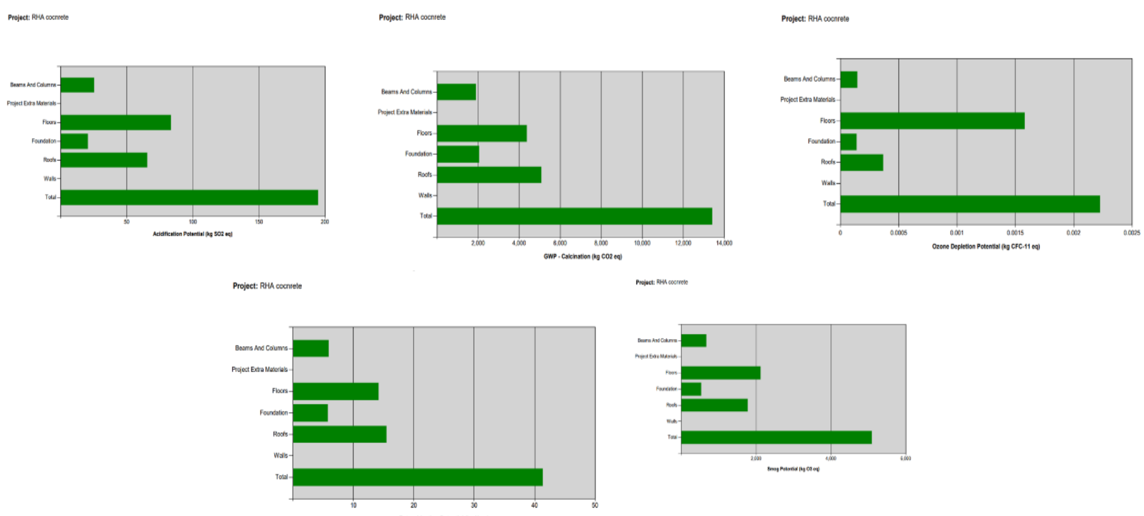

Figure 7. Acidification, Ozone, Eutrophication & Particulate analysis for RHA concrete

5.3 Compressive Strength

Two distinct goal strengths were established for each concrete type, and each concrete achieved its desired strength (Wang et al.2013 & Krishna et al. 2016). They utilized a standard percentage replacement of 10% for both SS and RHA, allowing for a comparative strength analysis. Figure 8 compares strength development in RHA and SS concrete at various curing ages. Concrete achieves 90% of its strength at 28 days (Kabir et al. 2012), as seen in the picture, where RHA attained 91.62% of its desired strength and SS reached 94.03% of its goal strength.

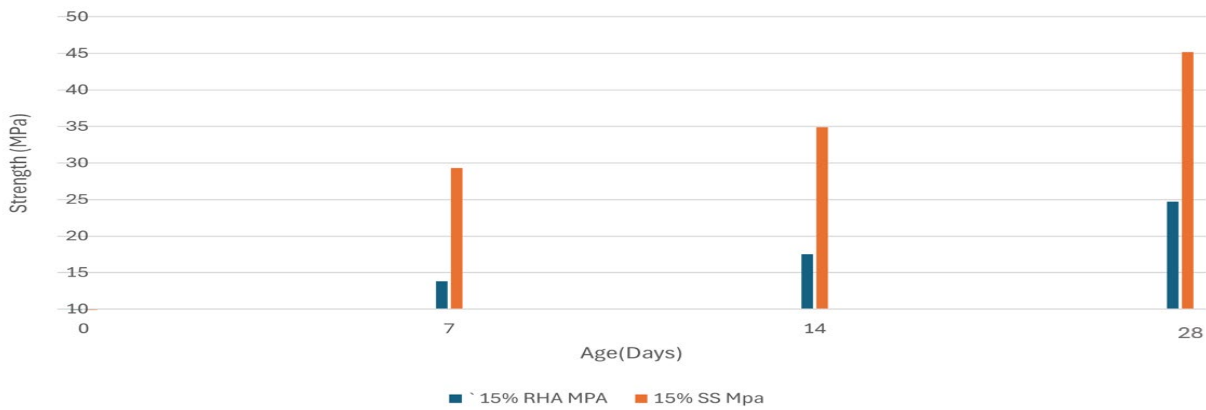

Figure 8. Compressive strength with common percent replacement

6. Conclusion

In summary, it can be stated that, due to sustainability and environmental considerations, RHA concrete is a more acceptable alternative than SS concrete. Due to its reduced carbon footprint in manufacture, it may be optimal for the next generation; nonetheless, in terms of mechanical qualities, SS concrete is advisable. There remains a research vacuum in determining the optimal percentage of replacement and in employing Life Cycle Assessment (LCA) according to global standard guidelines for evaluation. The life cycle assessment analysis indicates that steel slag produces nearly twice the amount of carbon dioxide as rice husk ash generates. In addition, other results like acidification, eutrophication, and ozone depletion are also higher in steel slag than in rice husk ash, which proves that rice husk ash is better than steel slag for sustainable use. Additional research may be necessary to address these concerns.

References

De Schepper, M., Van den Heede, P., Van Driessche, I. and De Belie, N., Life cycle assessment of completely recyclable concrete, *Materials*, vol. 7, no. 8, pp. 6010–6027, 2014.

Feiz, R., Ammenberg, J., Baas, L., Eklund, M., Helgstrand, A. and Marshall, R., Improving the CO_2 performance of cement, part I: Utilizing life-cycle assessment and key performance indicators to assess development within the cement industry, *Journal of Cleaner Production*, vol. 98, pp. 272–281, 2015.

Kabir, H., Hasan, M. M. and Rahman, M. S., Review of clinker content and CO_2 emissions of ordinary Portland cement, *International Journal of Sustainable Built Environment*, vol. 9, no. 1, pp. 12–24, 2020.

Krishna, R. V., Ranjbar, M. M. and Moghadam, H. A., Optimal rice husk ash level for compressive strength of concrete, *Materials and Structures*, vol. 49, no. 5, art. 177, 2016.

Madandoust, R., Ranjbar, M. M., Moghadam, H. A. and Mousavi, S. Y., Mechanical properties and durability assessment of rice husk ash concrete, *Biosystems Engineering*, vol. 110, no. 2, pp. 144–152, 2011.

Manso, J. M., Rodríguez-Leal, L. and Terrones-Saeta, J. J., Circular economy strategies for concrete production, *Journal of Cleaner Production*, vol. 214, pp. 441–450, 2019.

Mocharla, D., Kumar, R. and Singh, A., Performance and life-cycle assessment of high-volume fly ash concrete mixes containing steel slag sand, *Construction and Building Materials*, vol. 345, art. 128135, 2022.

Wang, Q., Yang, J. and Yan, P. Y., Cementitious properties of super-fine steel slag, Powder Technology, vol. 245, pp. 35–39, 2013.

Václavík, V., Ondová, M., Dvorský, T., Eštoková, A., Fabiánová, M. and Gola, L., Sustainability potential evaluation of concrete with steel slag aggregates by the LCA method, Sustainability, vol. 12, no. 23, art. 9873, 2020.

WBCSD and IEA, Cement Technology Roadmap to 2050, *World Business Council for Sustainable Development & International Energy Agency*, Paris, 2009.

Worrell, E., Price, L., Martin, N., Hendriks, C. and Meida, L. O., Carbon dioxide emissions from the global cement industry, *Annual Review of Energy and the Environment*, vol. 26, no. 1, pp. 303–329, 2001.

Zerbino, R., Giaccio, G. and Isaia, G. C., Durability and environmental impact of rice husk ash-based concrete, *Construction and Building Materials*, vol. 25, no. 5, pp. 2231–2240, 2011.

Li, L., T.-C. Ling, and S.-Y. Pan. Environmental Benefit Assessment of Steel Slag Utilization and Carbonation: A Systematic Review. *Science of The Total Environment*, Vol. 806, 2022, p. 150280.

Zerbino, R., Giaccio, G., & Isaia, G. C. (2011). Durability and environmental impact of rice husk ash-based concrete. *Construction and Building Materials*, 25(5), 2231–2240.

Ro, J. W., Cunningham, P. R., Miller, S. A., Kendall, A., & Harvey, J. (2024). Technical, economic, and environmental feasibility of rice hull ash from electricity generation as a mineral additive to concrete. *Scientific Reports*, 14, 9158.

Suárez Silgado, S. S., Calderón Valdiviezo, L., & Betancourt Quiroga, C., Life cycle analysis and economic evaluation of cement and concrete mixes with rice husk ash: application to the Colombian context, *Materiales de Construcción*, vol. 74, no. 353, e335, Jan.–Mar. 2024.

Biographies

Naim-Ur Rahman is a graduate civil engineering student at Arkansas State University in Jonesboro, Arkansas, pursuing his M.Sc. and working as a Graduate Teaching Assistant. He graduated first in his class from Bangladesh Army International University of Science and Technology with a bachelor's degree in civil engineering (CGPA 3.80/4.00). His undergraduate thesis examined replacing coarse concrete with processed e-waste to promote sustainable building. Naim's strengths are AutoCAD, ETABS, SAFE, Microsoft Office, GraphPad Prism, and Photoshop. He directed beam and column grid layouts, concrete quality monitoring, and field worker-university communication during a three-month internship at BAIUST's permanent campus. He organized sustainable engineering lectures and contests as the BAIUST Civil Engineering Club vice-president. At a UNESCO meeting on "Eco Civilization and Peace." Naim represented his school. His research is on big infrastructure structural design, material reuse, and changed concrete.

Arpan Das is a graduate teaching assistant in the Department of Civil Engineering at Arkansas State University. He is an experienced civil engineer and infrastructure specialist with over twelve years of expertise in highway design, asphalt overlay, transportation modeling, and construction supervision. He earned his B.Sc. in Civil Engineering from Khulna University of Engineering & Technology (KUET), Bangladesh 2011.

Dr. Zahid Hossain joined as a faculty member of Arkansas State University (A-State) in 2012 and serves as a Professor of Civil Engineering. His research interests include energy conservation, recycling, nano- and bio-modifications, and intelligent system design of geotechnical and transportation materials for pavement applications. He is also a faculty member of an interdisciplinary research team at the Centre for Efficient and Sustainable Use of Resources. Dr. Hossain focuses on developing and characterizing innovative geotechnical (stabilized subgrades and aggregates) and asphalt pavement materials and green technologies that will safeguard the environment and facilitate building longer-lasting pavements. Furthermore, Dr. Hossain is interested in constitutive modeling, data mining and visualization, neural network modeling, lean construction, and molecular dynamics simulation of pavement materials. Dr. Hossain also holds a "Green Belt" Lean and Six/Sigma certification from the University of Oklahoma.