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Research Article

Carbon Emission Assessment of 3D Printing Concrete Mixtures

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Abstract
In this study, carbon emission and energy consumption values of seventeen 3D printable concrete mixtures were investigated. The carbon emission assessment of the mixtures was evaluated according to the use and amount of cement, fly ash, silica fume, limestone aggregate, recycled concrete aggregate, polypropylene fiber and water reducing admixture. Carbon emission assessment was made by using various embodied carbon and embodied energy values obtained from studies in the literature. As a result, a reduction in CO2 emission values of the mixtures was measured with the use of silica fume. Also, it was determined that with increasing use of polypropylene fiber, CO2 emission values increased by 3.6% (by 0.2%), 7% (by 0.4%) and 10.8% (by 0.6%). It was understood that the use of recycled concrete aggregate causes a decrease in the carbon emission values of the mixtures. It was determined that the energy consumption values of 3D printable concrete mixtures have a similar trend as their carbon emission values.

Key Words: Carbon Emissions, Energy Consumption, 3D Printable Concrete, Recycled Concrete Aggregate, Silica Fume, Fly Ash, Polypropylene Fiber, Water Reducing Admixture

Introduction

Global population growth and the acceleration of urbanization have increased the need for urban infrastructure and therefore the demand for building materials to critical levels [1]. This situation, in particular, makes the environmental impacts of the construction sector even more evident. In fact, it was reported that 36% of global greenhouse gas emissions originate from building and infrastructure construction [2]. In this context, it is clear that the choice of building materials plays a decisive role in the carbon footprint.

The complex life cycle of cement, pozzolanic materials, aggregates and chemical admixtures used in concrete production makes it difficult to calculate carbon emissions. Therefore, the concept of "embodied carbon" is widely used in the literature to express the total carbon emissions that occur in the process from raw material acquisition to the production stage of a material [3]. Similarly, embodied energy describes the primary energy consumed throughout the life cycle of the material [4]. Hammond and Jones limited this concept to the "Cradle-to-Gate" approach and addressed the energy consumption of the product from the factory to the point of exit [5].

Compared to traditional construction methods, 3D printing technology significantly reduces carbon emissions by providing material optimization, waste reduction and energy efficiency [6-8]. This study aims to provide critical data for sustainable material selection by comparatively analyzing the embodied carbon and energy values of the components of 3D printable concrete mixtures.

Materials and Methods

In this study, the carbon emission and energy consumption values of 17 different 3D printable concrete mixtures were examined in detail. The materials and their proportions used in the composition of the mixtures are shown in Table 1. These mixtures were evaluated according to the amount of cement, fly ash, silica fume, aggregate type (limestone and recycled concrete aggregate-RCA), polypropylene fiber and water-reducing admixture.

Mixture	Cement (kg/m^3)	Fly Ash (kg/m^3)	Silica Fume (kg/m^3)	Limestone Aggregate (kg/m^3)	RCA (kg/m^3)	Water (kg/m^3)	Polypropylene Fiber (kg/m^3)	Water Reducing Admixture ($kg\ m^3$)
1	450	300	0	1134.6	0	280	0	8.5
2	450	300	0	1134.1	0	280	0	8.7
3	450	300	0	1133.4	0	280	0	9
4	450	330	0	1074.6	0	280	0	8.5
5	450	350	0	1034.5	0	280	0	8.5
6	450	350	0	1029.4	0	280	3.6	8.5
7	450	350	0	1024.2	0	280	7.1	8.5
8	450	350	0	1019.1	0	280	10.7	8.5
9	450	350	0	1029.4	0	280	3.6	8.5
10	450	350	0	1024.2	0	280	7.1	8.5
11	450	350	0	1019.1	0	280	10.7	8.5
12	450	350	0	1029.4	0	280	3.6	8.5
13	450	350	0	1024.2	0	280	7.1	8.5
14	450	350	0	1019.1	0	280	10.7	8.5
15	450	350	0	0	993.4	280	7.1	3
16	423	350	27	0	981.1	280	7.1	4
17	409.5	350	40.5	0	973.8	280	7.1	5

Table 1: Mixing ratios of 3D printable concrete

In calculating carbon emission and energy consumption values, embodied carbon (kg CO_2/kg) and embodied energy (MJ/kg) values per unit weight of each component were taken into account. These calculations, using the lowest and highest values in the literature (Table 2), were carried out according to the methodology given in Equation 1. Thus, the carbon emission and energy consumption values of the mixtures were obtained.

$$CO_2=\sum^{n}_{i=1} (W_i \times CO_{2i-e}) \qquad [1]$$

Where,

CO_2 is the total embodied CO_2 value of 1 m^3 of concrete. Its unit is $kgCO_2/m^3$.

n, is the total raw material in the mixture.

W_i is the total amount of material (in kg) required to produce 1 m^3 of concrete.

CO_{2i-e} is the equivalent CO_2 value of material (in kg CO_2/kg)

Mixing Component	Embodied Carbon ($kgCO_2/kg$)		Embodied energy (MJ/kg)	
	Minimum value	Maximum Value	Minimum value	Maximum Value
Cement	0.804[a]	0.94[b]	4.6[c]	6.15[d]
Fly Ash	0.008[e]	0.027[f]	0[b]	0.1[g]
Silica Fume	0.014[h]	0.024[a]	0.036[i]	0.1[h]
Limestone Aggregate	0.0026[j]	0.017[a]	0.018[k]	0.17[g]
RCA	0.002[e]	0.013[l]	0.066[m]	0.076[k]
Water	0[c]	0.001[e]	0[g]	0.2[c]
Polypropylene Fiber	3.43[n]	5.03[c]	79.8534[o]	94.4[c]
Water Reducing Admixture	0.0000052[f]	2.388[a]	0.0058[m]	18.3[g]
[a]Thilakarathna et al., [b]Hu et al., [c]Hammond and Jones, [d]Goggins et al., [e]Gan et al., [f]Flower et al., [g]Adesina et al., [h]Kuruşcu et al., [i]Murthy et al., [j]Yang et al., [k]Kurda et al., [l]Yazdanbakhsh et al., [m]Sobuz et al., [n]Korol et al., [o]Galan-Marin et al., [9-22].				

Table 2: Embodied CO_2 emission and embodied energy factors used in the study

Experimental Results and Discussion

Embodied carbon dioxide refers to the total amount of carbon dioxide released throughout the production processes of a material, from raw material production to the final product [3]. Carbon emission and energy consumption values of the mixtures analyzed in the study are presented comparatively in Figure 1 and Figure 2, respectively, based on 1 m^3 of concrete. The findings support the emphasis made by Kaya et al. [4]. Cement stands out as the most dominant emission source, accounting for 92-98% of the total CO^2 emissions in the mixture. This result is consistent with the high embodied carbon values of cement (0.804–0.94 kg CO_2/kg) in Table 2. Specifically, how the use of cement substitutes can reduce these emissions is one of the focuses of the study.

Keeping the amount of cement constant throughout the mixtures examined within the scope of the study made the effect of cement on carbon emissions more evident, especially in mixtures number 16 and 17 containing silica fume. Experimental results show that these mixtures containing 6% and 9% silica fume reduce CO_2 emissions by 4-7% compared to mixture number 15, which uses the same aggregate type but does not contain silica fume. This reduction can be explained by two main properties of silica fume: first, the additional energy requirement in its production is minimal since it is an industrial product; second, it has a much lower embedded carbon value compared to cement [3]. The study by Wang et al. also supports these findings, revealing that the use of silica fume as a partial replacement material for cement significantly alleviates the environmental impacts of concrete production [23].

Experimental findings reveal that the lowest carbon emission value among the mixtures examined was observed in mixture number 17, which has the lowest cement content and was produced entirely using RCA. The performance of this mixture can be explained due to two critical factors: (1) minimization of the cement amount and (2) lower embedded carbon content of RCA compared to natural aggregates (Table 2). In contrast, the highest emission values were measured in blends 8, 11 and 14 containing 0.6% polypropylene fiber. This is explained by the relatively high embodied carbon values of polypropylene fibers (3.43-5.03 kg CO_2/kg).

Analysis revealed that mixtures 1-5 did not show any significant difference in CO_2 emission values. This similarity is mainly due to the fact that variations in the mixture components are limited to only minimal changes in the amount of fly ash (in the range of 300-350 kg/m³) and the water-reducing admixture dosage (8.5-9 kg/m³). The data presented in Table 2 show that the embodied carbon values for these two components are at quite low levels (in the range of 0.008-0.027 kg CO_2/kg for fly ash and 0.0000052-2.388 kg CO_2/kg for water-reducing admixture). These low emission factors resulted in final CO_2 emission values remaining within a narrow band (419-420 kg CO_2/m³) despite composition differences between the mixtures. In particular, the fact that fly ash has an embodied carbon content approximately 30-100 times lower than cement played a decisive role in stabilizing emission values in these mixtures.

When examining mixtures containing fiber, it was found that there was a significant increase in CO_2 emissions as the use of polypropylene fiber increased. A 3.6% increase was observed in mixtures containing 0.2% fiber, a 7% increase in mixtures containing 0.4% fiber, and a 10.8% increase in mixtures containing 0.6% fiber. The main reason for this significant difference is that polypropylene fibers have a much higher emissions potential than other components, with an embodied carbon value of 3.43-5.03 kg CO_2/kg. This value is calculated to be 4-6 times higher than cement and 127-628 times higher than fly ash. These findings clearly demonstrate that the amount of fibers used should be carefully optimized to improve mechanical performance and that fiber selection is a critical parameter in sustainable concrete design.

The effects of using RCA on carbon emissions were evaluated by comparing it with mixture number 10, which has the same fiber length and ratio but contains limestone aggregate. The analyses revealed that mixture number 15 containing 100% RCA provided a 2% reduction in CO^2 emissions compared to mixture number 10. This limited reduction suggests that the environmental advantages of RCA should be carefully evaluated. As noted by Bostanci et al. this modest decrease in the carbon footprint of RCA is mainly due to the fact that the recycling process itself (extraction, processing and transportation stages) produces additional emissions [24]. Also, the significantly lower amount of water-reducing admixture in mixtures containing RCA can be considered as a secondary factor contributing to this slight reduction in emissions.

Experimental findings revealed a parallel relationship between embodied energy and carbon emissions. As noted by Kaya et al. these two parameters are closely related [4]. As can be seen in Figure 2, the embodied energy values of mixtures 1-5 showed a variation of 6%. This is primarily due to the increase in fly ash content (300-350 kg/m³). Of particular note is the impact of polypropylene fiber use on energy consumption: an energy increase of 5% was observed for blends containing 0.2% fiber, 10% for those containing 0.4% fiber, and 16% for those containing 0.6% fiber. This increase is due to the higher energy requirements of fiber production processes. In contrast, the use of RCA resulted in a 7% decrease in embodied energy values. This can be explained by the more energy-intensive extraction and processing of natural aggregates.

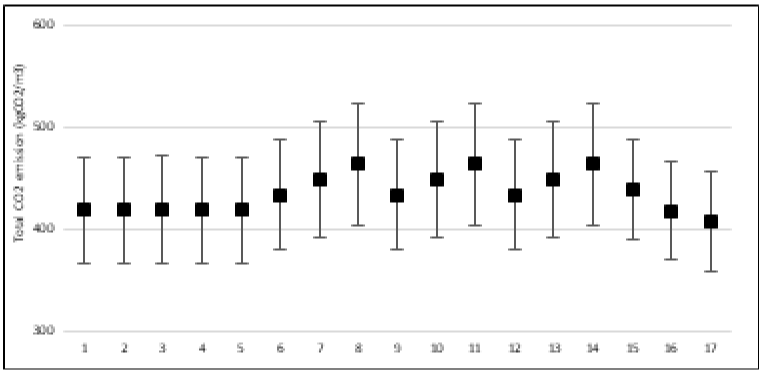

Figure 1: Carbon emission values of the mixtures

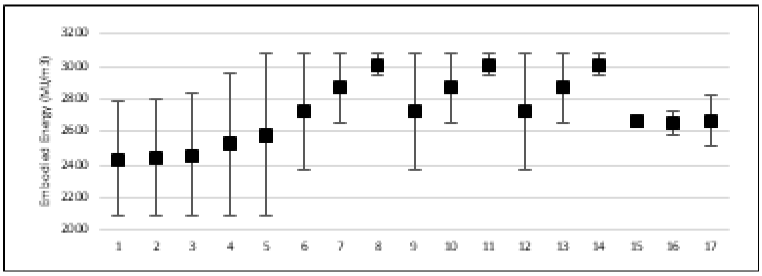

Figure 2: Embodied energy values of mixtures

Conclusion

As a result of the materials used and the analyses performed, the following results were obtained;

• It was determined that substituting 6-9% silica fume for cement reduces CO_2 emissions of mixtures by 4-7%.

• Polypropylene fibers have been found to have a significant impact on the carbon footprint of mixtures. Increases in CO_2 emissions were observed with increases of 3.6% (0.2% fiber), 7% (0.4% fiber), and 10.8% (0.6% fiber) as fiber content increased.

• When the environmental impacts of using recycled concrete aggregate were evaluated, it was calculated that mixes containing 100% RCA provided a 2% reduction in CO_2 emissions compared to mixes with traditional limestone aggregate.

• It was determined that the embodied energy and carbon emission values of the mixtures show parallel trends.

• Overall, the results obtained in this study demonstrate that the sustainability of concrete produced with 3D printing technology can be significantly improved through careful selection and optimization of the constituent materials. In particular, the use of alternative binders instead of cement and the utilization of recycled aggregates hold promise for developing green building materials.

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References

1. Rossi, C., Reitemeyer, F., Heidrich, O., & Rybski, D. (2024). Comparison of embodied carbon of 3D-printed vs. conventionally built houses. Findings.
2. UNEP. 2021. “Global Status Report for Buildings and Construction: Towards a Zero-emission, Efficient and Resilient Buildings and Construction Sector.” 2021.
3. Hashim, A. A., Al-Mosawi, A. I., & Abdulsada, S. A. (2025). Investigating the mechanical properties, durability, microstructure, and embodied CO2 emissions of silica fume-infused sustainable concrete. International Journal of Applied Ceramic Technology, e15136.
4. Kaya, E., Ciza, B., Yalçınkaya, Ç., Felekoğlu, B., Yazıcı, H., & Çopuroğlu, O. (2025). A comparative study on the effectiveness of fly ash and blast furnace slag as partial cement substitution in 3D printable concrete. Journal of Building Engineering, 112841.
5. Hammond, G., & Jones, C. (2008). Inventory of carbon & energy: ICE (Vol. 5). Bath, UK: Sustainable Energy Research Team, Department of Mechanical Engineering, University of Bath.
6. Raghu Nath Dharmalingam, V., Santhosh Kumar, A., Kachari, J., Dungrani, M., & Hashemi, A. (2024). Sustainable 3D Printing for Construction: Cement Choices, Structural Components, and Real-World Insights.
7. Şahin, H. G., Mardani, A., & Mardani, N. (2024). Performance requirements and optimum mix proportion of high-volume fly ash 3D printable concrete. Buildings, 14(7), 2069.
8. Şahin, H. G., Kaya, Y., Akgümüş, F. E., Mardani, N., Mardani, A., Assaad, J., & Hamad, B. (2025). Degradation of mechanical properties of 3D fiber reinforced printed concrete mixtures exposed to elevated temperatures. Case Studies in Construction Materials, 22, e04506.
9. Thilakarathna, P. S. M., Seo, S., Baduge, K. K., Lee, H., Mendis, P., & Foliente, G. (2020). Embodied carbon analysis and benchmarking emissions of high and ultra-high strength concrete using machine learning algorithms. Journal of Cleaner Production, 262, 121281.
10. Hu, W., Zhang, D., Ftwi, E., Ellis, B. R., & Li, V. C. (2023). Development of sustainable low carbon Engineered Cementitious Composites with waste polyethylene fiber, sisal fiber and carbonation curing. Resources, Conservation and Recycling, 197, 107096.
11. Goggins, J., Keane, T., & Kelly, A. (2010). The assessment of embodied energy in typical reinforced concrete building structures in Ireland. Energy and Buildings, 42(5), 735-744.
12. Gan, V. J., Cheng, J. C., & Lo, I. M. (2019). A comprehensive approach to mitigation of embodied carbon in reinforced concrete buildings. Journal of Cleaner Production, 229, 582-597.
13. Flower, D. J., & Sanjayan, J. G. (2007). Greenhouse gas emissions due to concrete manufacture. The international Journal of life cycle assessment, 12(5), 282-288.
14. Adesina, A. (2020). Performance and sustainability overview of alkali-activated self-compacting concrete. Waste Disposal & Sustainable Energy, 2(3), 165-175.
15. Kuruşcu, A. O., & Girgin, Z. C. (2014). Efficiency of structural materials in sustainable design. Journal of Civil Engineering and Architecture, October, 8(10), 1260-1265.
16. Murthy, A. R., & Iyer, N. R. (2014). Assessment of embodied energy in the production of ultra-high-performance concrete (UHPC). International Journal of Students Research in Technology & Management, 2(3), 113-120.
17. Yang, K. H., Song, J. K., & Song, K. I. (2013). Assessment of CO2 reduction of alkali-activated concrete. Journal of Cleaner Production, 39, 265-272.
18. Kurda, R., Silvestre, J. D., de Brito, J., & Ahmed, H. (2018). Optimizing recycled concrete containing high volume of fly ash in terms of the embodied energy and chloride ion

resistance. Journal of Cleaner Production, 194, 735-750.
19. Yazdanbakhsh, A., Bank, L. C., Baez, T., & Wernick, I. (2018). Comparative LCA of concrete with natural and recycled coarse aggregate in the New York City area. The International Journal of Life Cycle Assessment, 23(6), 1163-1173.
20. Sobuz, M. H. R., Datta, S. D., Akid, A. S. M., Tam, V. W., Islam, S., Rana, M. J., ... & Sutan, N. M. (2024). Evaluating the effects of recycled concrete aggregate size and concentration on properties of high-strength sustainable concrete. Journal of King Saud University-Engineering Sciences, 36(3), 216-227.
21. Korol, J., Hejna, A., Burchart-Korol, D., & Wachowicz, J. (2020). Comparative analysis of carbon, ecological, and water footprints of polypropylene-based composites filled with cotton, jute and kenaf fibers. Materials, 13(16), 3541.
22. Galan-Marin, C., Rivera-Gomez, C., & Garcia-Martinez, A. (2016). Use of natural-fiber bio-composites in construction versus traditional solutions: Operational and embodied energy assessment. Materials, 9(6), 465.
23. Wang, Y. S., Cho, H. K., & Wang, X. Y. (2022). Mixture optimization of sustainable concrete with silica fume considering CO2 emissions and cost. Buildings, 12(10), 1580.
24. Bostanci, S. C., Limbachiya, M., & Kew, H. (2018). Use of recycled aggregates for low carbon and cost-effective concrete construction. Journal of Cleaner Production, 189, 176-196.

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