Climate Resilient Construction and Building Materials

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Edited by

Bibhuti Bhusan Das

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3D CONCRETE PRINTING
STEPS TOWARD GREEN BUILDING

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Abstract: Housing is an issue everywhere in the world. Governments across the world are looking for solutions in the building industry to provide housing at a reduced cost in the shortest amount of time. The constraints of conventional construction techniques prevent them from ever being able to mitigate. Another major issue that humanity currently faces is global warming. To stop or address this issue, society must adapt and change its practices to be less damaging to the environment. "Green buildings" would have a significant impact on this issue. Green buildings can better use resources while producing healthier buildings that enhance the environment and human health. On the other hand, new technologies are frequently introduced, and 3D printing is quickly evolving. This technological innovation is rapidly expanding. There are many applications for 3D printing right now, and it continues to grow each year. Even though there are not many 3D-printed liveable structures, this technology can offer dignified homes to the world's least fortunate populations. The construction sector may change due to the application of 3D printing technology with green building design principles. This research emphasises locally obtained materials due to the introduction of 3D printing to the building sector, which reduces the need to transport concrete over large distances and the energy needed to mix concrete.

Keywords: Green building, 3D concrete printing, Sustainable 3D printable material, Global warming, climate change

1. Introduction

The term "eco-friendly" or "ecological" construction refers to building a resource-efficient structure that is helpful to the environment. This sort of construction is referred to as "green building." It is effective in using locally available, renewable resources (Mishra and Roy, 2021), the energy needed to build it, as well as the energy generated while it is in use (Sahoo et al., 2015; Kibert, 2016; Aneesh et al., 2018; Shivaprasad et al., 2019; Snehal et al., 2020a; Snehal and Das, 2020; Shiv et al., 2023). In response to the knowledge that buildings frequently have a very negative impact on our environment and our natural resources, which includes moving materials hundreds or thousands of miles, which increases the energy required to do so, as well as emissions of toxic chemicals from a poorly built building that both produces and traps them, eco-friendly construction has been developed (Das and Kondraivendhan, 2012; Sharath et al., 2018; Snehal et al., 2020b; Sumukh et al., 2021). As 3D printing technology develops, the future of ecologically friendly buildings appears brighter. Using computer-aided design, 3D printing, commonly called additive manufacturing, builds a three-dimensional structure layer by layer. Over the past five years, various impressive buildings have been created using 3D printing, including houses, cabins, offices, bridges, pavilions, large-scale projects, shelters, and more. Any architectural design can be built with the help of 3DCP. It would be helpful in constructing buildings with complex shapes and different orientations that result in buildings that use less energy (Hook, 2017).

The construction sector may benefit from 3D printing technology in the following ways: quickly, cheaply, accurately, and with the least amount of manufacturing waste possible (Snehal and Das, 2018). This research intends to undertake a comprehensive investigation of various aspects of green building construction and 3D printing.

2. Green Building Design Concept

The International Energy Agency (IEA) reports that the production and transportation of concrete account for around 7% of all carbon dioxide emissions. Concrete cannot be reused once it has been created. These findings have prompted the development of standards for green building, certifications, and rating systems to minimize the environmental effect of buildings through sustainable design (WBDG).

2.1. Net Zero Energy Building

The term "net-zero energy building" implies a building annually generating as much energy as it consumes.

The net-zero energy cost building, on the other hand, is a building that incorporates renewable energy and energy-saving measures into its business model (Kyoto).

2.2 Sustainable design

Three worldwide accepted pillars of sustainability are social concern, environmental protection, and economic development. The best combination of sustainability is shown in Figure 1.

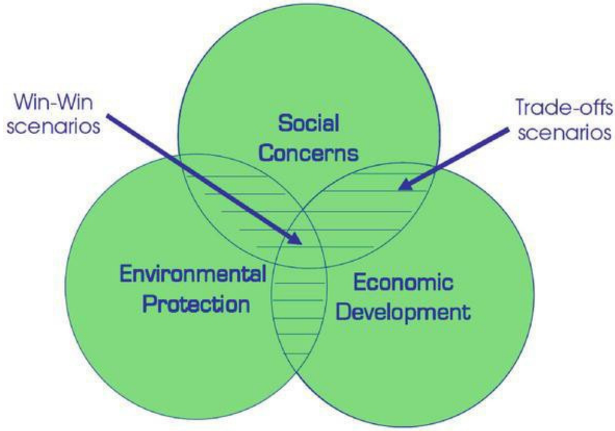

Figure 1: Best combination for sustainable design

2.3 Various energy efficiency measures

In summer, the east-west direction receives maximum solar radiation, so the long face of buildings oriented in the north-south direction is most energy-efficient as the cooling cost is less. In winter, a north- south direction is also preferred, as the south orientation receives maximum sunlight. Various energy efficiency measures and energy-efficient buildings are shown in Figures 2 and 3.

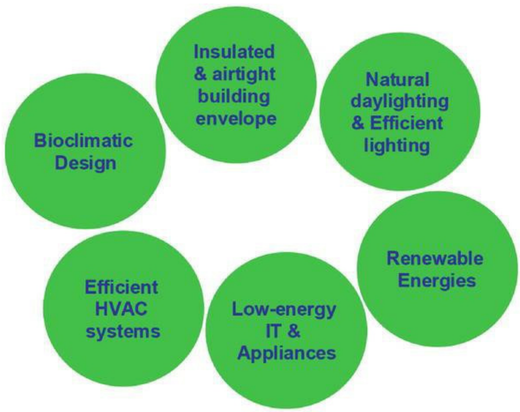

Figure 2: Energy-efficiency measures

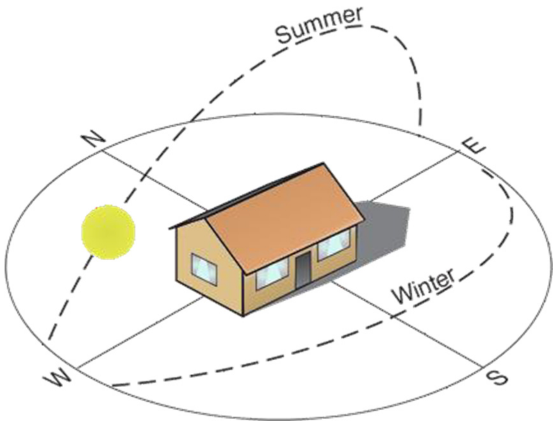

Figure 3: Orientation of energy-efficient building

The foundation of climate-responsive construction is how a building's orientation and structure control the surrounding environment for the benefit and well-being of people. The following climatic factors are considered in climate-responsive building design because they directly impact indoor thermal comfort and energy use in buildings (Thangaraj, 2013).

- Humidity
- Air temperature
- Prevailing wind direction and speed
- Longwave radiation between other buildings, the surrounding environment, and the sky also plays a significant role in building performance
- The solar path and the quantity of solar energy

2.4 Steps to Build Eco-Friendly Construction

Smart design is the first step towards eco-friendly building. You may conserve the environment and save money by exercising strategic thinking and using appropriate materials and technologies early (Hook, 2017). Figure 4 illustrates the ten steps for creating eco-friendly buildings.

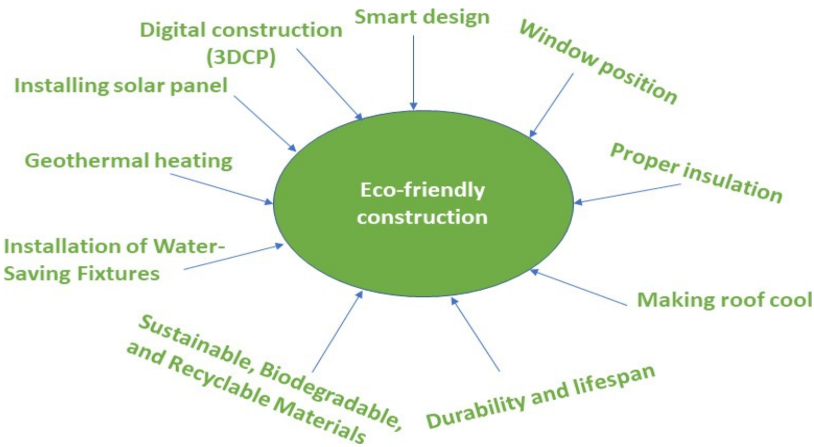

Figure 4: Steps involved in eco-friendly construction

- **Smart design-** smaller structures are less energy-intensive and cost less to maintain. Making the best possible use of the given space is a key component of smart design. It forces designers to think differently about freedom and the orientation of infrastructure.

- **Window position-** The ambience of a space may be significantly altered by something as straightforward as the positioning of windows. The best window placements to benefit from sunlight and prevailing winds may be determined through innovative technologies.

- **Proper Insulation-** Insulation is a different aspect to consider while building an ecologically friendly building. A room with enough insulation stays cool in the summer and warm in the winter, requiring less frequent use of the cooling and heating systems.

- **Cool roof-** In countries with a tropical climate, like Australia, a building exposed to the sun may allow heat to be trapped in the roofs, progressively warming the inside. Green roofs are indeed a creative solution to this issue. Making a structure cooler via heat-reduction strategies like reflecting roof paint, tiles, roof coverings, and grass planting would conserve the resources and energy that would have been utilised to cool it.

- **Assess Durability and Lifespan of Foundations-** Life expectancy is a factor that is growing more significant in the design and construction industries. Long-lasting materials like stone, brick, and concrete are better for the environment when demolished and disposed of. Additions, repairs, and renovations may increase a structure's lifespan, especially if made of sturdy materials.

- **Sustainable, Biodegradable, and Recyclable Materials-** Recycling old materials is an easy method to cut costs and minimise the ecological footprint of buildings. Plastic, glass, and timber from recycled sources are safer than those from fresh sources. Environmentally friendly materials are frequently produced more cheaply with fewer emissions.

- **Install Water-Saving Fixtures-** Water wastage may be easily reduced by installing plumbing fittings that decrease the flow of faucets, showerheads, and toilets. By calculating how much water clients would save in the long run, you may persuade them to purchase ecologically friendly products.

- **Think About Geothermal Heating-** To heat homes or workplaces, geothermal systems utilize temperatures from under the ground. Underground pipes connect a heat pump, which uses them to heat or cool the home. The technology, which is still in its infancy, uses minimal power to run, saving homeowners money and energy.

- **Installing solar panels-** Sun radiation is transformed into energy by solar power. Solar panel installation is pricey up front, but it will ultimately save you much money and energy. However, we must take the environment and the placement of solar panels into account in order to utilise solar energy. Using estimation tools, you can determine how much energy you can save and accumulate.

- **Investigate Innovative Approaches to Construction Such as 3D Printing**- As 3D printing technology develops, the future of ecologically friendly buildings seems to be looking up. A Chinese startup utilised the technology to manufacture ten concrete homes made of recyclable materials within 24 hours. The carbon footprint of these technologically advanced designs was far lesser than that of traditional buildings, making them less costly to maintain and producing less trash.

3. Features of an ecological building

3.1 Sustainable and Eco-friendly Materials

The use of various industrial wastes as sustainable and eco-friendly 3D-printable materials is discussed in this section.

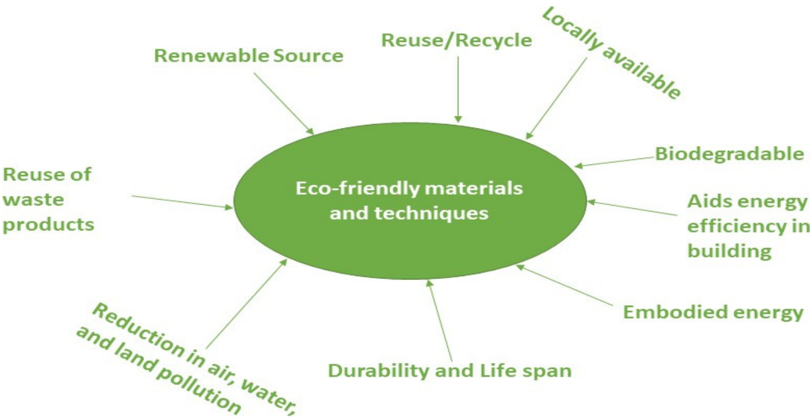

Figure 5: Eco-friendly materials and techniques

A significant issue on a global scale is the disposal of fly ash (FA) waste from power plant facilities. It was discovered that the combination with a higher FA concentration demonstrated more remarkable flowability and less drying shrinkage than the mixture with a lower FA level (Dalinaidu et al., 2007; Snehal et al., 2022). Fly ash can decrease drying shrinkage, which is a problem for concrete 3D- printed components because there is no formwork (Dey et al., 2022). According to Panda and Tan (2019), viscosity and static yield stress were reduced when class F fly ash concentration was increased in an OPC- based combination with a water-to-binder ratio (w/b) of 0.45. Mixtures for 3D printing are more extrudable as viscosity decreases.

Moreover, admixtures like nano clay that increased mix crystallisation strength and shear-yield stress helped to improve buildability.

Various types of slags are produced while manufacturing steel and iron in blast or other furnaces (Goudar et al., 2019; Farsanna et al., 2020). The blast boiler slag often produces crystalline granular particles when it is abruptly quenched with water while still in molten condition. These particles are then ground to create GGBS. A typical SCM is a slag with surface areas of 400 to 600 m^2/kg and grain sizes of less than 45 μm. Buildability was improved because of the angular particle interlocking caused by large-volume slag. The buildability of the printable material is influenced by green strength, which was significantly improved by particle packing. Phase separation during the extrusion of the mixture containing 50 wt.% slag was explored by Rahul et al. (2020), who also emphasised the beneficial role of additives in reducing phase separation. High-volume slag mixes composed of 70% slag and 30% OPC were created by Qian et al. (2021). Dai et al. (2021) improved the operational performance of 3D printing materials by substituting steel slag for natural fine aggregate. The capacity of the printing mortar, which contains 25% slag, to create an actual 3-dimensional item has been demonstrated. Slag usage enhances the mechanical strength of printable materials, according to research by Dai et al. (2021).

Silica fume (SF) forms as a result of the smelting procedure used to create ferrosilicon alloys and elemental silicon (ACI 116R). Micro-silica, commonly known as SF, is a primarily amorphous form of SiO2 that comprises very small, spherical SiO2 particles with an average size of 0.1-0.3 μm (Panesar, 2019). Panda and Tan (2019) employed 2.5 and 5% silica fumes (by mass) to substitute fly ash to improve buildability. According to experimental data, the introduction of 2.5% SF in the mixture design increased the structural build-up rate and yield stress. Moreover, it was discovered that the SF-modified mixes had good viscosity recovery, which made them the perfect thixotropic material for concrete 3D printing.

Mine tailings are one of the additional resources that may be utilised in place of fine aggregates. Mining wastes known as mine tailings are frequently crystalline calcium aluminosilicates with minimal reactivity (Sharath et al., 2019). Silica fume, fly ash, and blast-furnace slag are some examples of typical SCMs, albeit they might not always be accessible for long-term use (Das and Pandey, 2011; Das et al., 2012; Sahoo et al., 2017; Scrivener et al., 2018; Kudachimath et al., 2019; Snehal et al., 2021a). To continue using sustainable cementitious materials, it appears to be essential to find substitute SCMs (Snehal and Das, 2018; Kumar et al., 2020; Snehal et al., 2021b; Barbhuiya and Das, 2022; Snehal and Das, 2022). Limestone calcined clay stands out as a potential raw material that is incredibly plentiful globally compared to typical SCMs (Scrivener et al., 2018).

Limestone powder is frequently used as a filling component in the binder. According to Jiao et al. (2017), the physical properties of the particles, such as their surface roughness and fineness, are the main determinants of how limestone powder affects rheology. A suitable proportion of limestone with a particle size similar to or larger than OPC can be included in the mix to improve the workability of fresh cement- based materials (Vance et al., 2013). Because the texture of the limestone particles provides more nucleation sites, replacing a tiny portion of Portland cement with limestone might fasten the hydration of early-stage materials (Berodie and Scrivener, 2014).

The 3DCP might gain a lot from substituting calcined clay for OPC. The quantity of easily accessible clay deposits may be the most significant factor. Technically speaking, kaolinitic clay is most abundant in subtropical and tropical regions, such as India and Southeast Asia (Scrivener, 2014; Scrivener et al., 2018). Another benefit is that burning calcined kaolinitic clay occurs at a temperature of 700–850 °C, which is significantly lower than the temperature required to produce OPC clinker, which is 1250–1450°C (Scrivener et al., 2018).

Table 1: Effect of different SCMs on the properties of the 3D printable mixture

Sl. No.	Materials	Properties	References
1.	**Fly ash**	• Flowability ↑ • Extrudability ↑ • Shape retention ↑ • Buildability ↓	Dey et al., 2022; Panda and Tan, 2019
2.	**GGBS**	• Particle packing ↑ • Buildability ↑	Rahul et al., 2020; Qian et al., 2021; Dai et al., 2021
3.	**Silica fume**	• Buildability ↑ • Yield stress ↑ • Shape retention ↑ • Particle packing ↑	Panda and Tan, 2019
4.	**Limestone**	• Early-age hydration ↑ • Workability ↑	Jiao et al., 2017; Vance et al., 2013; Berodie and Scrivener, 2014
5.	**Calcined clay**	• CO2 Emission ↓ • Workability ↓	Scrivener, 2014; Scrivener et al., 2018

6.	**Calcium Sulfoaluminate Cement (CSA)**	• CO_2 Emission ↓ • Buildability ↑ • Volume Expansion ↑ • Open time ↑ with the addition of admixtures • Setting time ↑ with the addition of admixtures • Plastic viscosity ↑	Khalil et al., 2017; Mohan et al., 2021

It can be seen from Table 1 that adding fly ash to the mix improved its rheological properties but decreased its buildability (Dey et al., 2022; Panda and Tan, 2019). However, the inclusion of silica fumes can enhance buildability (Panda and Tan, 2019). To promote eco-friendly construction, GGBS can be used as a substitute for Portland cement (Goudar et al., 2020). This substitution can lead to a significant decrease in carbon dioxide emissions, with up to 80% replacement of ordinary Portland cement being possible. According to Zhou et al. (2012), a 30% substitution of GGBS yielded the highest compressive strength value. The inclusion of calcined clay in the mix decreased its workability and reduced carbon emissions (Scrivener, 2014; Scrivener et al., 2018). Furthermore, Calcium sulfoaluminate cement also played a role in reducing CO_2 emissions (Khalil et al., 2017; Mohan et al., 2021).

3.2 Other Features of Ecological Buildings

The other features of an ecological building might include the following points, as shown in Figure 6.

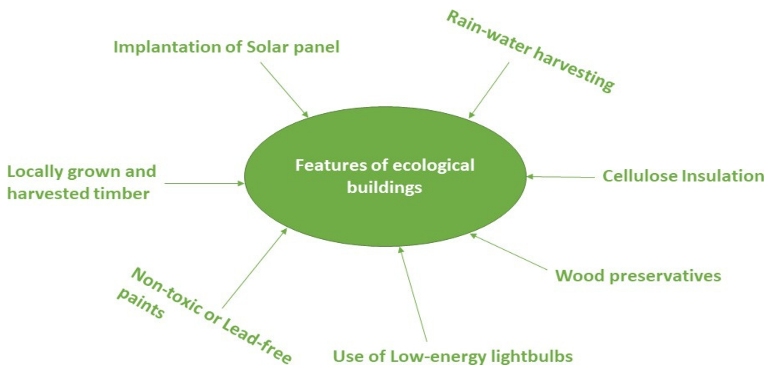

Figure 6: Ecological building features

4. Green Building using 3D printing technology

Green building construction may include highly complex design elements such as non-prismatic beams, columns, and other structural elements made from locally available materials. This can be done easily with 3D printing because it only involves machine work. The concrete walls, partitions, and building envelopes of the house can all be printed on the printer. All that remains for the contractor to do is paint the house, wire it, put it on the roof, and insulate it. Pace, cheaper labour, optimum precision, better integration of functions, and minimal waste during production are some of the potential benefits of 3D printing for the construction industry.

The technology is intended to be a long-term replacement for traditional approaches that produce high carbon dioxide emissions. Soil, fly Ash, geopolymer, and other sustainable materials with low carbon footprints can be used for 3D printing. A new approach to building that makes use of materials derived from nature is envisioned by printing structures out of the type of soil that may be found in any garden. By using such materials, it would be possible to create custom dwellings that are suited to the requirements of the area's climate. Locally produced goods will lessen the need to export concrete over vast distances, thus reducing the structures' environmental impact. If they can increase the earth's capability to support loads, it will determine whether they can substitute concrete with soil (*The Guardian*, 2020).

5. Eco-cost comparison of two alternatives (3D printed building vs conventional building)

Eco-costs are a metric for expressing a product's environmental impact based on the cost of avoiding the impact. It is the expense of reducing emissions and material degradation in the world to a degree that is consistent with the planet's carrying capacity. Eco-cost is a single environmental burden metric focused on Life Cycle Analysis. It is based on the principle of "marginal prevention costs," or the costs needed to reduce the environmental burden to a degree that is sustainable.

More eco-cost involved in manufacturing a product means that the product is mainly responsible for the environmental burden.

All the relevant data regarding house construction was collected for both 3D-printed houses and conventionally-built houses. The house was assumed to have a floor area of 60 m^2. The house was terraced. It was assumed that a material once used in the construction was dumped in the environment and was never used again.

Since 3D printing in construction is still in its early stages, more is needed to know about its environmental consequences. The buildings considered in this project have a "cradle to gate" life cycle phase. Due to a lack of documentation, the operational and demolition stages of 3D-printed houses are ignored, as they are currently uninhabitable. Furthermore, recent research has shown that the demolition process of a building has a lower environmental effect than the construction and service phases.

For this project, the design of the blueprint of the structures is not taken into consideration since there is no documentation about the design stage; the 3D printer is carried to the construction site in pieces; utilities (wiring, piping, ventilation, etc.) for the housing functional were not taken into consideration; and for traditional construction, 10% of materials were added during the modelling to make up for the absence of knowledge about the design stage (Dey et al., 2022). The steps involved in the life cycle stage are shown in Figure 7. The data collected for the comparison of 3D printed and conventional houses are shown in Tables 2 and 3, respectively.

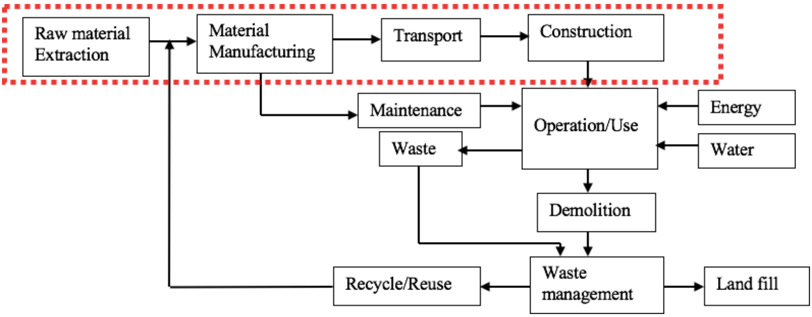

Figure 7: System boundary and life cycle stages in buildings

Table 2: The data collected for 3D-printed buildings

Materials	Unit	Building (unit)	Foundation (unit)	Roof (unit)	Total Quantity (unit)
Cement (Blast Furnace)	kg	25699.8	11160	9674.05	46533.85
Blast Furnace Slags	Kg	2867.05	1245	1079.23	5191.28
Sand	100 Kg	428.676	186.15	161.365	776.191
Glass Fibre	Kg	48	21	18	87
Fuel for Transportation (Diesel)	Kg	8394.93			8394.93
Transport of printer	Ton. km	500			500
Transport of materials	Ton. Km	50			50
Linoleum floor tiles	Kg	102.12			102.12
Timber(oak) floorboards	m^3	331			331
Hardwood timber	m3	331			331
Electricity	100 MJ	28.63	12.43	10.8	51.86

Table 3: The data collected for conventionally-built buildings

Materials	Unit	Building (unit)	Foundation (unit)	Roof (unit)	Total Quantity (unit)
Brick	Kg	30002	10956		40958
Cement	Kg	2280.86	207.43	308.35	2796.64
Sand	100 Kg	57.02	5.18	7.71	69.91
Concrete Block	Kg	6716	12906.85		19622.85
Concrete Slab	Kg	7097.14			7097.14
Gravel	100 Kg	33.12			33.12
Tiles	Kg			1991	1991
Plasterboard (Gypsum)	Kg	3088			3088
Softwood Timber (Cedar)	m3	1362			1362
Timber(oak) floorboards	m3	331			331

The laminated floor (particleboard outdoor)	m3	331			331
Transport of materials	Ton. Km	3611.82	1487.61	67.91	5167.34
Electricity	100 MJ	111.686	46.26	2.205	160.151

Data related to eco-cost was taken from the IdematLightLCA Android Application, and relevant unit conversions were performed. TU Delft develops the application and has data for the Europe region. Also, the paper from which data regarding the construction of buildings was taken provided Europe-based information. The data was analysed using an Excel spreadsheet, and the following results were obtained. The eco-cost of buildings built by 3D printing technology was 24970.93 €.

The eco-cost of buildings built by conventional methods was found to be 73204.07€.

Percentage contribution of eco-cost in 3D printed buildings by cement, blast furnace slags, fuel, oak timber, and hardwood timber is found to be 29.82 %, 2.5%, 18.83%, 23.7%, and 23.7%, respectively.

Percentage contribution of eco-cost in buildings constructed by conventional methods by brick, cement, softwood timber (cedar), timber (oak), and laminated floor is found to be 8.95%, 1.03%, 36.47%, 8.09%, and 42.64 %, respectively.

Based on the above results, it can be concluded that conventional construction methods put around three times more burden on the environment than 3D printing technology. Also, the economic cost of the buildings can be further reduced by using green building technology.

Conclusions

- The battle against climate change is raging across the globe. Governments are now concerned about using resources more efficiently than ever before. The green building revolution aims to tackle these concerns through the principles of ecological construction. Combined with the 3D printing technique, the construction process can be made more environmentally friendly because the 3D printing technique is more resource-efficient than the conventional building methods.

- Sustainable and renewable energy sources are used in green buildings, which can further reduce the building's net energy consumption.

- Based on the eco-cost analysis that was carried out, it can be concluded that conventional construction methods put around three times more burden on the environment than construction based on 3D printing technology.

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Optimization of High Strength Concrete (M70) with Different Proportions of Mineral Admixtures – An Experimental Study

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Abstract. Concrete having a strength of more than 65 N/mm^2 is known as high-strength concrete (HSC). Generally, mineral admixtures, superplasticizers, and a low water-cement ratio are necessary for achieving HSC. Ordinary Portland cement (OPC) is the main constituent used to make concrete. It is responsible for the setting and hardening of the concrete mixture. However, it is the source of greenhouse gas emissions and contributes significantly to the construction industry's carbon footprint. The use of mineral admixtures, such as alccofine (AF), fly ash (FA), metakaolin (MK), and silica fume (SF), has several benefits, including improved workability, increased resistance to cracking and erosion, and reduced heat of hydration. In addition, mineral admixtures can significantly lower the carbon footprint of concrete production as they are by-products of other industrial processes and are often readily available. In the present study, a laboratory investigation was conducted to evaluate the mechanical properties of HSC of grade M-70