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Sustainable multi-story building design utilizing recycled marble and ceramic waste

Ruchit Parekh [1,*], Leslie Norford [2] and James Hughes [3]

[1] *Department of Engineering, Hofstra University, New York, USA.*

[2] *Department of Sustainable Energy Engineering, University of Illinois Urbana-Champaign, USA.*

[3] *Department of Energy and Sustainability, University of California, Los Angeles (UCLA), USA.*

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Abstract

This study explores the design of a multi-story structure utilizing recycled waste materials. Locally produced materials from recycled sources were used for making concrete and bricks. The design of a 10-story building was carried out using ETABS software. In the process, 10% of the cement in the concrete was replaced with waste marble powder (WMP), while the bricks were made by replacing 12% of clay with waste ceramic powder and 15% with waste brick powder. The materials were developed in a laboratory, adhering to ASTM standards, and their properties were input into the software for analysis and design. The results were compared to a structure made with traditional materials. The analysis showed that using recycled materials led to the conservation of 164 tons of cement and 475 cubic meters of fertile clay while maintaining the required stability standards as per building codes. The design also prevented the release of 148 tons of carbon dioxide into the atmosphere and reduced the energy demands associated with cement production. Additionally, the building utilizing waste materials was found to be Rs. 5.8 million more economical than one made with conventional materials.

Keywords: High-rise Buildings; Recycling; Waste Marble; Waste Ceramic; Environmental Sustainability; Cost Efficiency

1. Introduction

In contemporary construction practices, concrete remains a fundamental material in civil engineering. It consists of three key components: cement, sand, and coarse aggregates. However, cement production is a major source of carbon dioxide emissions, significantly contributing to global warming. The manufacturing process, which requires heating to 1400°C, relies on burning fossil fuels, further depleting these non-renewable resources. Therefore, reducing cement usage is essential for promoting sustainable and environmentally friendly construction.

Marble, a commonly used material, is a metamorphic rock derived from limestone. Research by Majeed et al. explored the impact of using waste marble powder (WMP) in concrete. Their findings revealed that replacing up to 10% of cement with WMP enhanced both compressive and tensile strengths, thanks to the pozzolanic and cementitious properties of marble. Memon et al. studied the effect of substituting marble dust for cement in fresh and hardened concrete, showing improvements in compressive strength but reduced workability.

Özkılıç et al. investigated the performance of concrete when cement was partially replaced with 10-40% waste marble powder. They recommended a 10% replacement based on both mechanical and sustainability factors. In another study, Khitab et al. evaluated the use of waste brick powder (WBP) and waste ceramic powder (WCP) as alternatives to clay in brick production. Their research demonstrated that bricks with 15% WBP and 12% WCP had comparable density to those made entirely of clay, with increased porosity, offering better weather resistance and insulation. Although

* Corresponding author: Ruchit Parekh

compressive strength was slightly reduced, it remained within acceptable limits for second-class bricks. Additionally, bricks with these replacements exhibited a 27% reduction in initial water absorption and no efflorescence. The incorporation of WBP in brick production saved 27% of fertile clay, contributing to eco-friendly construction practices.

This study focuses on the design and structural analysis of a reinforced concrete (RCC) high-rise building. The concrete mix used in the design includes a 10% replacement of cement with waste marble powder (WMP). Additionally, the partition walls are made from red bricks where 27% of the fertile clay has been substituted with a combination of 10% waste ceramic powder (WCP) and 12% waste brick powder (WBP). The objective was to develop a sustainable building using materials that had been previously researched and produced by the team. The environmental and cost benefits of using these locally sourced, recycled materials were evaluated by comparing the newly designed RCC structure to a conventional building. This research aligns with the United Nations' sustainable development goals by emphasizing waste reduction and resource utilization. The chosen test case was a 10-story building, and the design and analysis were conducted using ETABS software. The results showcase the advantages of green building, specifically in terms of reducing greenhouse gas emissions, conserving natural resources, and lowering energy consumption and costs.

2. Research Methodology

2.1. Dimensions of the Proposed Building:

The design for the high-rise building is illustrated in Figure 1, with dimensions measuring 37 meters by 36.57 meters and a total height of 32 meters, including the ground floor. In the design, four shear walls were incorporated in accordance with ASCE 7-17 guidelines. As depicted in Figure 2, one shear wall was placed along each of the longer sides, while two central shear walls were located along the shorter side. The building was designed to withstand dead loads, live loads, wind forces, and seismic activity, in compliance with the Universal Building Code 97.

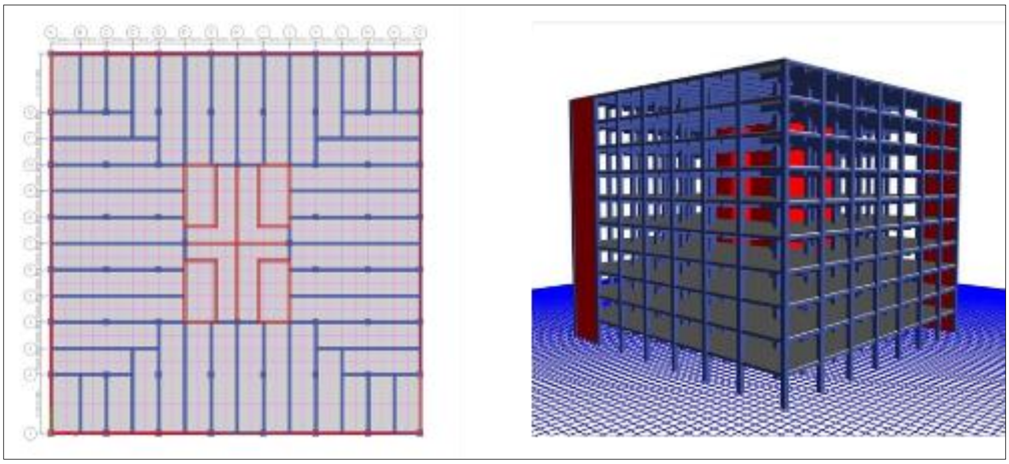

Figure 1 Proposed Building

2.2. Design and Analysis

Table 1 Data Analysis

Materials	Compressive Strength (MPa)	Density (kg/m³)	Poisson’s Ratio	Modulus of Elasticity (GPa)
Conventional concrete	25	2385	0.2	23.5
10% WMP in Concrete	32	2410	0.2	26.6
Conventional brick	9.31	2162	0.2	12.4
15% WBP + 12% WCP in Bricks	9	1400	0.2	14.1

The proposed structure was modeled using ETABS, with material properties from previous research applied to various building components such as slabs, columns, beams, and walls. The specific material properties used in the design are listed in Table 1, which were derived from earlier studies conducted by the research team.

3. Results

Following the design of the model in ETABS, the dimensions of the components for the green building, including slabs, beams, columns, and walls across all stories, are presented in Table 2.

Table 2 Dimensions obtained from design

Components	Width (mm)	Depth (mm)
Slabs	-	175
Beams	300	750
	300	300
Columns	560	560
Shear Walls	300	-
Perimeter Walls	228	-

After completing the model analysis, the parameters were verified in accordance with ACI-318-14 [10] using ETABS, confirming the building's stability. Key limit state parameters are summarized in Table 3.

Table 3 Analysis Parameters

Display Type	Load	Max. (X-direction)	Max. (Y-direction)	Max. Limit
Story Drift (Unit less)	Earthquake	0.000141	0.0000136	0.0015
Max. story Displacement (mm)	Earthquake	3.63	3.66	30
Overturning Moments (KN-m)	Earthquake	558434	-480000	Depends on foundation soil

Story drift is a parameter that indicates the relative movement between one floor and the floor directly above it. As per Indian Standards IS 1893 (Part 1) [11], the maximum allowable story drift is 0.004, while Appendix C of ASCE 7 specifies a range between 0.005 and 0.0015 [7]. The story displacements in this analysis are well within these limits [12]. A comparison of sustainability-related parameters between a conventional building and the green building design is presented in Table 4.

Table 4 Sustainability Parameters

Parameters	Conventional Building	Green Building	Savings	Cost Effectiveness (Millions of Rs.)
Cement (tons)	1088	924	164	4.75
Carbon Dioxide (tons) [13]	979	813	148	-
Electricity (kWh)[14]	119704	101597	18167	0.73
Clay (m^3)	1762	1287	475	0.332
Structure weight (MN)	169.22	141.8	27.4	-
Total saving in Rs. Million				5.812

The use of environmentally friendly materials, tested in laboratory settings, offers an eco-conscious solution. This approach not only reduces cement usage but also cuts down on related greenhouse gas emissions. Furthermore, lower energy consumption is achieved due to the reduced cement manufacturing process. The inclusion of 27% waste in brick production significantly conserves fertile clay, which can be preserved for agricultural purposes such as growing crops, vegetables, and fruits.

Table 5 Cost Parameters

Parameters	Conventional Building	Green Building	Savings	Cost Effectiveness (Millions of Rs.)
Cement (tons)	1088	924	164	4.75
Carbon Dioxide (tons) [13]	979	813	148	-
Electricity (kWh)[14]	119704	101597	18167	0.73
Clay (m^3)	1762	1287	475	0.332
Structure weight (MN)	169.22	141.8	27.4	-
Total saving in Rs. Million				5.812

4. Conclusion

This study focused on designing a 10-story RCC building utilizing green materials developed in the laboratory. Based on the simulations, the following conclusions were made:

- The building design resulted in saving 164 tons of cement and 475 cubic meters of fertile clay.
- The reduction in cement use led to a decrease of 513 tons of CO2 emissions and saved 18.2 MWh of energy.
- The green design ensured a cost saving of 5.8 million PKRs.
- The structure using waste materials is 16% lighter compared to one built with conventional materials.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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