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High strength concrete in high-rise reinforced concrete buildings: A sustainable solution to reduce energy consumption and carbon emissions

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Abstract. Reinforced concrete is an important construction material that is of great research value in industry and science. Today, it is one of the most widely used materials in high-rise buildings around the world. However, at the same time, this kind of construction production activity has a non-negligible impact on the earth's environment, mainly in terms of its consumption of environmental resources and carbon dioxide emissions. Therefore, this paper focuses on how to reduce the burden of high-rise reinforced concrete buildings on the environment and achieve sustainable development. Through reading and analyzing the literature, it could be inferred that the use of high strength concrete reduces the volume of structural components as well as making the building more impermeable, thus reducing the amount of material that needs to be manufactured during the life cycle of the building, which can efficiently cut carbon emissions and energy consumption in high-rise buildings.

Keywords: high-strength concrete; energy conservation; reinforced concrete; high-rise buildings.

1. Introduction

In recent decades, the number of high-rise buildings has been increasing rapidly as the world's population continues to grow and urban land resources become increasingly scarce. A high-rise building is often classified as one with 14 or more floors (or one with a height of more than 50 m) by The Council on Tall Buildings and Urban Habitat (CTBUH).

Reinforced concrete is an important material widely used in high-rise buildings, with an annual consumption of nearly 30 billion tonnes in the world [1]. It consists of cement, aggregates, fines, and steel reinforcement and has numerous superior properties.

Firstly, reinforced concrete plays an important role in structural design. It constructs high-rise buildings that can withstand a variety of static and dynamic loads with excellent tensile and compressive properties, ensuring the structural stability and safety of the building. Secondly, the plasticity of reinforced concrete material also gives it an important advantage in building design. By pouring and moulding reinforced concrete during the construction phase, it enables architects and designers to create unique architectural styles and meet different needs and functions. In addition, reinforced concrete materials are relatively easy to obtain and manipulate during production and construction. Raw materials

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such as cement and aggregates are widely available, and the production process is sophisticated enough to allow for mass production [2].

However, notwithstanding the benefits listed above, the negative environmental implications of high-rise reinforced concrete buildings must also be considered. The construction industry has a massive environmental impact, accounting for roughly 30% of global greenhouse gas emissions and 40% of energy consumption [3], with reinforced concrete production accounting for 5% or more of global carbon emissions [4]. These factors will exacerbate the challenges of global warming, resource depletion, and pollution.

This paper assesses the environmental implications of high-rise building development across their full life cycle, including construction, usage and maintenance, and removal, in terms of environmental resource consumption and carbon dioxide emissions. It considers whether using high-strength concrete is a viable strategy to lessen the environmental impact of tall structures. It strives to improve the sustainability of high-rise building design and accomplish resource conservation. This research also examines the environmental implications of tall building development throughout their life cycle, including resource consumption and CO_2 emissions during construction, usage and maintenance, and removal. It considers whether using high-strength concrete is a viable strategy to lessen the environmental impact of tall structures. It aims to enhance the sustainability of high-rise building design and achieve conservation of environmental resources.

2. Life cycle of building

2.1. Steps

The construction phase, the usage and maintenance phase, and the demolition phase are the three stages of a building's life cycle. The data collected and processed during these phases can be used to quantify the building's environmental resource consumption and carbon dioxide emissions.

The life cycle construction phase is separated into three parts: material manufacturing, transportation, and on-site construction. The material production phase refers to the process of collecting raw materials to producing building materials for use in the building's working stages, and the amount of different types of materials utilised influences the carbon and energy consumption of this process. The transport step refers to the process of transporting the materials to the building site, where data on the mode of transport, distance travelled, and fuel and electricity consumption of the transport equipment are examined and recorded. The construction phase is divided into three parts: building work, public work, and facility work.

When a building is put into use, the annual amount of electricity and oil used for heating, lighting, gas energy, etc., is usually taken into account. When a building needs to be maintained or restored, information on the amount of building materials used for replacement and restoration, as well as information on the use of oil and electricity in the process, are needed to calculate the building's energy consumption and carbon emissions.

The demolition and abandonment phase refers to the dismantling and disposal of a building when it reaches the end of its life cycle or needs to be dismantled for other reasons. The energy consumption and carbon emissions of the equipment used to dismantle the building in its process and the vehicles adopted to transport the waste make up the load on the environment caused by this process [5, 6].

2.2. Analysis methods

In order to assess and calculate the environmental loads over the life cycle of a building, a number of inter-industry methods have been investigated and used to address different study environments.

In a 2011 study of energy consumption and carbon emissions over the life cycle of a high-rise building, inter-industry relations analysis was mainly used to derive energy consumption and carbon emissions. For example, the carbon emissions and energy consumption in the material production phase can be calculated using the following expressions (1) and (2):

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$$E_{C-M} = \sum M_{ij} \times COST_m \times U_{M;E} \quad (1)$$

$$CO_{2C-M} = \sum M_{ij} \times COST_m \times U_{M;CO_2} \quad (2)$$

$E_{C\text{-}M}$ (MJ/m^2) : energy consumption of material production step
M_{ij} ($Unit/m^2$) : the amount of construction material (j) used for the construction type (i)
$COST_m$ (Won/Unit) : the cost of construction material (m)
$U_{M,E}$ (Mj/Won) : the basic unit of energy consumption for construction material (m)
$CO_{2C\text{-}M}$ ($kg\text{-}CO_2/m^2$) : CO_2 emission of material production step
$U_{M,CO2}$ ($kg\text{-}CO_2$/Won) : the basic unit of CO_2 emission for construction material (m).[7]

Using the energy simulation tool Autodesk Ecotect Analysis, which is compatible with some BIM applications, is another technique to determine the environmental pressures brought on during the life cycle of a structure. Numerous studies have demonstrated the accuracy of Ecotect's statistics, particularly when estimating energy use and carbon emissions during a building's use phase. In addition to offering thermal, lighting, and acoustic studies, Ecotect also assesses a building's material qualities and simulates local weather patterns [8]. For instance, in 2013 this technique was applied to determine the energy usage and life cycle carbon emissions of a university building [9].

In addition to this, there are other assessment methods, such as interviews with demolition companies or industry experts, where data can be collected to estimate the carbon emissions and energy consumption of a certain part of a building's lifecycle [7].

3. Application of high-strength concrete in high-rise buildings

3.1. Evaluation

Specialized concrete known as "high strength concrete" has a higher compressive strength than regular concrete. To obtain higher strength levels, it is accomplished by using particular ingredients and procedures in the concrete mix ratio. High strength concrete typically has a compressive strength exceeding 40 MPa, whereas normal concrete typically has a compressive strength between 20 and 30 MPa [10].

The use of high-strength concrete in construction will reduce the cross-section of some structural elements, thus reducing the amount of reinforcement and concrete used in these structural elements. As shown in the previous expressions (1) and (2), the reduction in the amount of building materials utilized will lead to a decrease in energy consumption and carbon emissions in the material production step. At the same time, the smaller cross-section size and fewer components of high-strength concrete elements means faster construction and a more simplified construction process, which will result in a reduction of carbon emissions and consumption of environmental resources in the on-site construction step. In addition, the reduction in the structural volume of the building will improve space utilisation.

On the other hand, one of the causes of building damage is the carbonation of reinforced concrete structures. Carbonation is the penetration of carbon dioxide into the concrete, which reacts with the hydration products of the cement contained therein, resulting in a decrease in the alkalinity of the concrete and a decrease in its pH value. The steel reinforcement in reinforced concrete corrodes as a result of this process, which reduces the strength and longevity of the concrete structure [11]. High strength concrete increases the service life of the building because it has a lower water-cement ratio and improved impermeability. Therefore, buildings with high strength concrete do not require maintenance costs for the duration of their service life as compared to buildings with normal concrete.

In summary, by reducing the amount of material used and extending the service life of buildings, high strength concrete contributes to the sustainability of the construction industry and reduces resource consumption and environmental impact.

3.2. Limitations

However, it must be remembered that there is ongoing debate over whether using high-strength concrete is always advantageous to construction.

Firstly, although high-strength concrete has a higher compressive strength, it also has a relatively low ductility. This makes high-strength concrete more susceptible to brittle damage when subjected to extreme loads, such as earthquakes.

Secondly, the production and construction process of high-strength concrete requires higher technical requirements and precision to ensure its quality and performance. This will lead to higher costs, including raw material costs, construction costs, and inspection and testing costs. Stricter quality control and construction techniques are also the essential conditions for the use of high-strength concrete, and any quality problems in the production or construction process may have a significant impact on the safety and reliability of the final structure [10].

Most importantly, high-strength concrete is more important at the production stage, as it requires larger quantities of cement as a binder, and the process of cement production is energy-intensive and CO_2 emitting. Because of this, even though using high-strength concrete will reduce the volume of structural components, resulting in a reduction in the amount of material, the energy savings and carbon emission reductions in this process are not always sufficient to make up for the increase in carbon dioxide emissions caused by the production of high-strength concrete [12]. The environmental performance of high-strength concrete will be contrasted and studied in this research based on the information supplied in the case study in order to further determine whether using high-strength concrete in high-rise structures is a successful method of decreasing environmental loads.

4. Case study

In order to better understand the efficiency of high-strength concrete in decreasing carbon emissions and energy consumption through empirical data, three reinforced concrete high-rise buildings were analyzed for their environmental performance over a 100-year cycle in a 2011 study.

All three structures are flat blocks made of reinforced concrete with a combined floor space of 14,424 square meters and 35 stories above ground.

Both Cases 1 and 2 are currently standing structures—regular apartment buildings made of reinforced concrete with an estimated service life of 50 years—with the exception that Case 1 will be torn down and rebuilt twice over the course of the 100-year study cycle. In Case 2, after 50 years of use, the building is maintained and repaired to last until 100 years, which means that the maintenance work is only carried out once in the 100-year cycle. In Case 3, a high-strength concrete building was used with an estimated service life of 100 years, during which time no new reinforced concrete had to be manufactured for the maintenance and rehabilitation of the building. In the construction phase of the building life cycle, the material production step requires the highest amount of material in Case 1, which results in higher energy consumption and carbon emissions than Cases 2 and 3. The transport and on-site construction step are considered to have twice the energy consumption and carbon emissions of Case 1 than Case 2 and 3, due to the fact that Case 1 requires two new buildings to be constructed. In conclusion, it can be calculated that the energy consumption of the high-strength concrete building (Case 3) in the construction phase decreased by 51.89% and 3.79%, and the CO_2 emissions decreased by 52.06% and 4.12% compared to Cases 1 and 2, respectively.

As shown in Table 1, here is no difference in energy consumption or carbon emissions among the three buildings in the use phase. In the maintenance step, Case 2 had more reinforced concrete used to repair the deteriorated structure due to carbonation than Cases 1 and 3, and therefore the CO_2 emissions from the manufacture of this reinforced concrete should be taken into account (the CO_2 generated in the transport and construction steps was considered negligible in this calculation). During the demolition step, Case 1 still consumes twice as much energy and emits twice as much carbon as Cases 2 and 3 due to the fact that the construction has to be carried out twice during the 100-year cycle.

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Table 1. Life cycle energy consumption and CO_2 emission.

	LCE(MJ/m^2)			$LCCO_2$($kg\text{-}CO_2/m^2$)_		
	Case 1	Case 2	Case 3	Case 1	Case 2	Case 3
Production	9608	4804	4611	833	416	397
Transportation	209	105	105	15	7	7
Construction	400	200	200	78	39	39
Use	24250	24250	24250	1981	1981	1981
Maintenance	0	695	0	0	66	0
Removal	2	1	1	0	0	0
Disposal	148	74	74	11	5	5
Total	34618	30129	29241	2917	2515	2430

Ultimately, Case 3 of the high-strength concrete building showed a reduction in CO_2 emissions of 16.70 percent and 3.37 percent, respectively, and energy consumption of 15.53 percent and 2.95 percent, respectively, compared to Cases 1 and 2.

5. Conclusion

This essay discusses ways to lessen the environmental burden high-rise reinforced concrete structures place on the planet. Despite having many benefits as a building material, reinforced concrete's mass manufacture and use still have a negative influence on the environment. Measurements of energy use and carbon dioxide emissions over the course of a building's life cycle can be used to evaluate the environmental impact of high-rise reinforced concrete structures. Numerous studies have recommended the use of high strength concrete as a practical means of lowering carbon emissions and energy use. The use of high-strength concrete in high-rise structures can reduce the quantity of material needed for the manufacturing of reinforced concrete by reducing the volume of structural parts, according to the data provided in the case study. At the same time, due to the better impermeability of high-strength concrete, it can extend the life of the building without the need to produce new reinforced concrete for maintenance and repair. These two advantages result in lower carbon emissions and energy consumption over the life of the building.

However, there are problems with high-strength concrete, such as the need to use more cement to manufacture it. Therefore, it is still required to assess whether high-strength concrete is a useful strategy to lessen its environmental impact based on its particular environmental location and usage needs in the design and planning of future high-rise buildings. Finally, it is important to note that the production of high-rise buildings should be designed, constructed, maintained, and dismantled in a way that reduces the environmental impact of the process, and always follows the principles of sustainable development and the construction of environmentally sound and sustainable "green" buildings.

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