Original Research Article

Study on mechanical properties and carbon sequestration capacity of carbon sequestration concrete based on TOPSIS

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Abstract: To address the dual challenges of construction waste recycling and carbon sequestration in the concrete industry, this study employs the TOPSIS method to conduct a comprehensive comparative analysis of the mechanical properties and carbon sequestration capacity between carbon-sequestering concrete and conventional concrete. It systematically investigates the impact of carbon-sequestering concrete on the mechanical performance and carbon sequestration capability of CO_2-cured concrete. As global climate change intensifies, the traditional concrete industry—Primarily reliant on cement-based materials—Faces unprecedented environmental pressures due to its massive carbon emissions. Carbon-sequestering concrete (CSC)[1],an innovative technology that actively absorbs and sequesters carbon dioxide, is recognized as a critical pathway to achieving carbon neutrality in the concrete sector. However, while sequestering carbon, CSC often exhibits changes in mechanical properties such as compressive strength, flexural strength, and elastic modulus, posing challenges for engineering applications. The core issue in this field is how to scientifically, comprehensively, and objectively evaluate the overall performance of carbon-sequestering concrete[2], thereby maximizing its carbon sequestration benefits while ensuring structural safety. To address the aforementioned issues, this study proposes a multi-attribute decision-making evaluation method based on TOPSIS (Technique for Order Preference by Similarity to Ideal Solution). The method aims to establish a comprehensive evaluation system that simultaneously considers both the mechanical properties and carbon sequestration capacity of carbon-sequestering concrete, thereby providing theoretical foundations and decision-making support for resolving the trade-off and optimization of "performance-benefit" in carbon-sequestering concrete. First, this study systematically investigates the carbon sequestration mechanism and mechanical property influencing factors of carbon-sequestering concrete, establishing an 8-item comprehensive evaluation system comprising 5 mechanical performance indicators (compressive strength, flexural strength, elastic modulus, impermeability, and dry shrinkage rate) and 3 carbon sequestration capability indicators (carbon sequestration rate, carbon sequestration per unit volume, and carbon sequestration efficiency). Second, to address the limitations of the TOPSIS method in handling dimensional and magnitude differences among evaluation indicators, the Entropy Weight Method[3] is introduced to determine objective weights for each indicator, thereby eliminating subjective influences on evaluation results. Finally, a case study demonstrates the application process of the developed comprehensive evaluation model, with comparative analysis and ranking of the overall performance of carbon-sequestering concrete with different mix proportions. The research findings demonstrate that the entropy-weighted TOPSIS-based comprehensive evaluation model developed in this study effectively quantifies the performance of carbon sequestration concrete. This model not only provides researchers and engineers with a scientific and objective evaluation tool, but also serves as a critical reference for optimizing concrete mix proportions, regulating performance, and making engineering application decisions[4-6]. The study lays a theoretical foundation for the sustainable development of carbon sequestration concrete and provides robust support for its application in green infrastructure projects.

Keywords: carbon sequestration concrete; TOPSIS; entropy weight method; mechanical properties; carbon sequestration capacity; comprehensive evaluation

1. Introduction

1.1. Research background and significance

Cement-based materials, particularly concrete, are the most widely used man-made materials globally, with annual consumption exceeding 40 billion tons. However, during traditional cement production, limestone ($CaCO_3$) decomposes at high temperatures, releasing substantial amounts of carbon dioxide (CO_2) in a process known as "process emissions," which accounts for approximately 5% to 8% of global anthropogenic CO_2emissions. Consequently[7], the concrete industry stands as a major contributor to greenhouse gas emissions, making its green transition and the achievement of "carbon peaking and carbon neutrality" goals an urgent priority.

Against this backdrop, carbon-sequestering concrete (CSC) has emerged as a groundbreaking low-carbon building material. The core concept involves using concrete as a "carbon sink" to actively absorb $CO_2$from the environment during the hardening process, converting it into stable carbonate minerals for permanent storage. This approach not only reduces carbon emissions from cement production but also utilizes industrial waste materials like fly ash and slag as raw materials, further minimizing the carbon footprint throughout the product's lifecycle.

However, the introduction of carbon sequestration concrete comes at a cost. The carbon sequestration reaction is a complex chemical process involving the transformation of cement hydration products and the evolution of pore structure. These changes inevitably affect the mechanical properties of concrete, such as delayed early strength development or reduced long-term strength. The key bottleneck in advancing carbon sequestration concrete from laboratory to engineering practice lies in how to maximize its carbon sequestration capacity while ensuring it meets the mechanical requirements of engineering design and construction (particularly compressive strength).

Therefore, it is of great theoretical and practical significance to establish a scientific, comprehensive and objective evaluation system to quantify and compare the comprehensive performance of different carbon sequestration concrete schemes, which can guide the mix design, performance regulation and engineering application decision of carbon sequestration concrete.

1.2. Current research status at home and abroad

1.2.1. Research progress of carbon sequestration concrete

The research on carbon sequestration concrete mainly focuses on the carbon sequestration mechanism, influencing factors, performance characterization and long-term durability.

Carbon fixation mechanism: The carbon fixation reaction mainly involves the interaction between cement hydration products (such as calcium hydroxide and C-S-H gel) and CO_2. The reaction rate is influenced by factors including ambient humidity, CO_2 concentration, temperature, concrete age, and microstructure.

Influencing factors: A large number of studies have shown that the incorporation of active admixtures such as fly ash and slag can significantly promote carbon sequestration reactions, but their effects on mechanical properties depend on the dosage and activity. Additionally, admixtures (e.g., air-entraining agents, water-reducing agents) and curing conditions also play a crucial role in the overall performance of carbon-sequestering concrete.

Characterization: The microstructure of carbon-seeding concrete was analyzed by XRD and SEM[8-10], and the macroscopic properties of carbon-seeding concrete, such as compressive strength, flexural strength and permeability, were tested.

1.2.2. Application of multi-attribute decision making

The Multi-Attribute Decision Making (MADM) approach is widely used in engineering[11], economics, and management to address decision-making challenges involving multiple conflicting objectives or metrics. In materials science, the TOPSIS method has gained prominence for its simplicity, computational efficiency, and intuitive results, making it a go-to tool for concrete mix optimization and material performance evaluation. However, traditional TOPSIS methods often rely on subjective weighting when determining indicator weights, which can be influenced by evaluators' personal biases and lack objectivity.

1.2.3. Existing issues and research gaps

The current research primarily faces the following issues:

(1) Single evaluation dimension: Most studies either focus on carbon sequestration performance or mechanical properties, lacking systematic and comprehensive evaluation of both aspects.

(2) Subjectivity in weight determination: In the evaluation model, the weight of indicators is mostly determined by subjective methods such as expert scoring, which fails to fully reflect the dispersion degree and information entropy of the indicator data itself.

(3) Lack of universal evaluation model: The comprehensive evaluation model for the performance-benefit synergistic optimization of carbon sequestration concrete is not yet mature, making it difficult to conduct scientific comparisons among different mix ratios of carbon sequestration concrete.

Therefore, this paper aims to construct a TOPSIS comprehensive evaluation model based on objective empowerment[12], in order to provide a new idea and method for the performance evaluation and decision-making of carbon sequestration concrete.

1.3. Research content and technical approach

1.3.1. Research content

The main research contents of this paper include:

(1) Analysis of factors affecting the performance of carbon-sequestering concrete[13]: A systematic analysis of the key factors influencing the mechanical properties and carbon-sequestering capacity of carbon-sequestering concrete.

(2) The evaluation index system is constructed, which includes the comprehensive evaluation index system of mechanical properties and carbon sequestration capacity.

(3) The construction of entropy-weighted TOPSIS model: The entropy-weighting method is introduced to determine the index weight, and the comprehensive evaluation model of carbon sequestration concrete based on entropy-weighted TOPSIS is established.

(4) Case analysis and verification: Through case analysis, the validity and practicability of the model are verified, and the different schemes are sorted and compared.

2. Properties of carbon sequestration concrete and its evaluation index system

2.1. Carbon sequestration mechanism of carbon sequestration concrete

The carbon fixation process in carbon-fixing concrete fundamentally involves the carbonation reaction between cement hydration products and CO_2. The primary chemical reaction equations are as follows:

(1) Carbonation of calcium hydroxide ($Ca(OH)_2$):

$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$

(2) Carbonation of calcium silicate hydrate (C-S-H gel):

$C_3S\cdot 3CaO\cdot 2SiO_2\cdot 3H_2O + 3CO_2 \rightarrow 3CaCO_3 + 2SiO_2 + 6H_2O$

The calcium carbonate ($CaCO_3$) produced by the reaction fills the voids within the concrete, improves its microstructure, and sequesters CO_2 from the environment, thereby achieving carbon sequestration.

2.2. Factors affecting mechanical properties

The mechanical properties of carbon-sequestering concrete are affected by many factors:

Cement usage: Cement is the main source of strength, but its increased use will increase carbon emissions.

Mineral admixtures: fly ash, slag and so on can participate in the carbon fixation reaction, but their early strength contribution is limited, and excessive admixtures may lead to strength reduction.

Water-cement ratio: Water-cement ratio is the key parameter that affects the strength and density of concrete.

The results showed that the rate and extent of carbon sequestration were mainly affected by the humidity and CO_2 concentration[14].

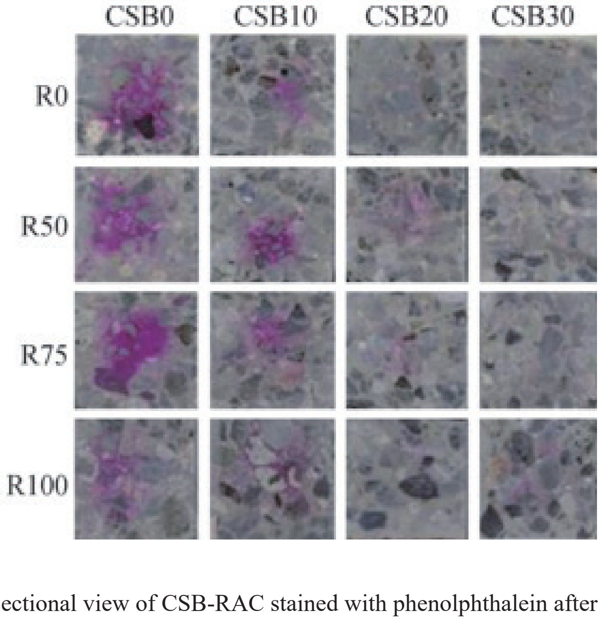

Figure 1. Cross-sectional view of CSB-RAC stained with phenolphthalein after 28 days of carbonization.

2.3. Factors affecting carbon sequestration capacity

Carbon sequestration capacity is mainly affected by the following factors:

Environmental CO_2 concentration: Higher concentrations result in faster carbon sequestration rates (see **Figure 1**).

The environmental humidity: moderate humidity is beneficial to the carbon fixation reaction, but too high or too low humidity will inhibit the reaction.

Carbon sequestration is a long-term process, and the amount of carbon sequestration usually increases with the age of the plant.

Material composition: Materials containing more $Ca(OH)_2$ and C-S-H gel have greater carbon sequestration potential.

2.4. Construction of evaluation index system

To comprehensively evaluate the performance of carbon sequestration concrete, this study establishes an evaluation system comprising eight indicators, as detailed in **Table 1**.

Table 1. Comprehensive evaluation index system of carbon sequestration concrete.

Class	Order Number	Evaluating Indicator	Symbol	Unit	Index Property	Indicator Description
Mechanical Property	1	cubical compressive strength	f_c	MPa	benefit type	The core index of concrete bearing capacity.
	2	rupture strength	f_t	MPa	benefit type	It is an important index to reflect the bending and tensile capacity of concrete.
	3	modulus of elasticity	E	GPa	benefit type	The index reflects the deformation characteristics of concrete.
	4	impermeability	P	water resistance grade	benefit type	It reflects the concrete's resistance to seepage and is closely related to its durability.
	5	dry shrinkage rate	ε_{sh}	%	cost type	Excessive shrinkage is likely to cause cracking and reduce durability.
Carbon Sequestration Capacity	6	carbon sequestration rate	C_r	%	benefit type	The percentage of carbon sequestration to the theoretical maximum carbon sequestration.
	7	carbon sequestration per unit volume	C_v	kg/m³	benefit type	It directly reflects the carbon sequestration capacity of concrete.
	8	carbon sequestration efficiency	C_e	kg/(m³·d)	benefit type	It reflects the carbon sequestration rate of concrete per unit time.

3. Comprehensive evaluation model of carbon sequestration concrete based on entropy weight TOPSIS

3.1. TOPSIS method principle

The core idea of the TOPSIS method is to rank a finite number of evaluation objects based on their relative closeness to the ideal solution. The steps are as follows:

(1) Constructing the decision matrix: With n evaluation objects (carbon sequestration concrete schemes) and m evaluation indicators, the initial decision matrix X is constructed.

(2) Standardization: The decision matrix X is standardized to eliminate the influence of dimension, and the standardized decision matrix R is obtained.

(3) Weight determination: Establish the weight vector $W = [w_1, w_2, ..., w_m]$ for each evaluation metric.

(4) Construct the weighted decision matrix: Multiply the normalized decision matrix R with the weight vector W to obtain the weighted decision matrix V.

(5) Determine the ideal solution and negative ideal solution: Based on the properties of the indicators, identify the positive ideal solution A^+ (for benefit-oriented indicators, the maximum value is taken; for cost-oriented indicators, the minimum value is taken) and the negative ideal solution A^- (for benefit-oriented indicators, the minimum value is taken; for cost-oriented indicators, the maximum value is taken).

(6) Calculate the relative closeness: Calculate the distance of each evaluation object to the positive ideal solution and the negative ideal solution, and calculate the ratio of the distance to the negative ideal solution to the sum of the two, which is the relative closeness C_i.

(7) Ranking and Decision: All evaluation objects are ranked from highest to lowest based on C_i values,

where a higher C_i value indicates better overall performance of the scheme.

3.2. Principle of entropy-weight method

Entropy weighting is an objective weighting method based on the degree of dispersion of index data. The smaller the information entropy, the greater the information provided by the index[15], and its weight should be larger. The calculation steps of entropy weighting are as follows:

(1) Calculate the proportion P_{ij} of the i-th scheme indicator value under the j-th indicator.

(2) Calculate the entropy value e_j for the j-th indicator.

(3) Calculate the difference coefficient g_j for the j-th indicator.

(4) Calculate the weight w_j for the j-th indicator.

3.3. Entropy-weighted TOPSIS model construction process

The specific process of the entropy-weighted TOPSIS comprehensive evaluation model constructed in this paper is as follows:

(1) Data collection: The measured data of eight evaluation indexes of n different carbon sequestration concrete mixtures were collected to construct the initial decision matrix X.

(2) Data standardization: The decision matrix X is standardized to obtain the normalized decision matrix R.

(3) Entropy-weight calculation: Entropy-weight method is used to calculate the standardized data, and the objective weight vector W of each evaluation index is determined.

(4) Weighted decision matrix: Multiply the normalized decision matrix R with the weight vector W to obtain the weighted decision matrix V.

(5) Find the ideal solution: Based on the weighted decision matrix V, calculate the positive ideal solution A^+ and the negative ideal solution A^- respectively.

(6) Calculate relative proximity: Calculate the distance from each scheme to A^+ and A^-, and compute its relative proximity C_i.

(7) Result analysis: The carbon sequestration concrete scheme is ranked according to the C_i value, and the optimal scheme is obtained by analyzing the weight of each index.

4. Case analysis and discussion

4.1. Experimental design and data collection

To validate the proposed model, we fabricated four carbon-sequestering concrete specimens with varying mix proportions, as detailed in **Table 2**. All specimens underwent standard curing for 28 days, followed by 30 days of CO_2curing (5% concentration, 70% humidity), after which their performance parameters were measured.

Table 2. Basic material composition of carbon sequestration concrete specimens.

Sample Number	Cement (kg/m³)	Fly Ash (kg/m³)	Slag (kg/m³)	Water-cement Ratio	Curing Condition
CSC-A	350	100	50	0.45	standard curing for 28 days + CO_2 curing for 30 days
CSC-B	300	150	50	0.45	standard curing for 28 days + CO_2 curing for 30 days
CSC-C	300	100	100	0.45	standard curing for 28 days + CO_2 curing for 30 days
CSC-D	250	150	100	0.45	standard curing for 28 days + CO_2 curing for 30 days

4.2. Data standardization and weight calculation

The experimental data were input into the model, first standardized, then the entropy weight method was used to calculate the weight of each index. The calculation results are shown in **Table 3**.

Table 3. Weighting of indicators by entropy method.

Order Number	Evaluating Indicator	Weight (w_j)
1	Cube compressive strength (f_c)	0.185
2	flexural strength (f_t)	0.120
3	modulus of elasticity (E)	0.105
4	impermeability (P)	0.095
5	Shrinkage rate (ε_sh)	0.075
6	Carbon sequestration rate (Cr)	0.150
7	Carbon sequestration per unit volume (C_v)	0.130
8	Carbon sequestration efficiency (Ce)	0.140

As shown in **Table 3**, the weights of cube compressive strength, carbon sequestration rate and carbon sequestration per unit volume are relatively high, which indicates that the bearing capacity and carbon sequestration capacity of concrete play a dominant role in the comprehensive evaluation.

4.3. TOPSIS comprehensive evaluation results and analysis

Based on the weights and experimental data, the relative closeness C_i of each scheme was calculated using the TOPSIS method, as shown in **Table 4**.

Table 4. TOPSIS comprehensive evaluation results of carbon sequestration concrete schemes.

Scheme	Relative Closeness (C_i)	Sort
CSC-A	0.682	1
CSC-B	0.598	2
CSC-C	0.512	3
CSC-D	0.431	4

interpretation of result:

(1) CSC-A solution emerges as the optimal choice: It ranks first in comprehensive evaluation. The high cement content (350 kg/m³) ensures its superior mechanical properties. Although its carbon sequestration capacity is not the strongest, it demonstrates the best performance when considering the balance between "performance and cost-effectiveness".

(2) Comparison between CSC-B and CSC-C: CSC-B (primarily fly ash) demonstrates slight superiority over CSC-C (primarily slag). The volcanic ash effect and micro-aggregate effect of fly ash may better facilitate early strength development, whereas slag's activity activation typically requires extended duration or elevated temperature.

(3) The CSC-D formulation underperforms: Despite its highest total admixture content and greatest carbon sequestration potential, its minimal cement usage results in a significant decline in mechanical properties (particularly compressive strength). In the comprehensive evaluation, its "cost" (mechanical properties) is excessively high, leading to the lowest overall performance ranking.

The results clearly reveal that the trade-off between performance and benefit must be made in the design of carbon sequestration concrete[16]. It is not advisable to pursue high carbon sequestration rate at the expense of mechanical properties.

5. Conclusion and prospects

5.1. Main conclusions

(1) This paper constructs a comprehensive evaluation system with 8 indexes to solve the problem that the mechanical properties and carbon sequestration capacity of carbon sequestration concrete are difficult to coordinate.

(2) The multi-attribute decision-making model based on entropy weight TOPSIS is proposed. The model uses entropy weight method to objectively determine the index weight, which can effectively avoid the deviation caused by subjective weighting.

(3) The effectiveness and practicability of the model are verified by example analysis. The results show that the model can make a scientific and objective comprehensive evaluation and ranking of the carbon sequestration concrete with different proportion.

(4) The model analysis reveals the trade-off between performance and benefit in the design of carbon sequestration concrete, which provides a decision-making basis for engineering practice.

5.2. Research perspectives

(1) Long-term performance study: The evaluation data in this paper are mainly based on the curing age of 28 days + 30 days[3]. The long-term mechanical properties, durability and carbon fixation stability of carbon fixation concrete need to be tracked on a longer time scale.

(2) Model Optimization and Extension: Future research could explore incorporating alternative objective weighting methods (e.g., CRITIC or Principal Component Analysis) for comparative analysis, or integrating hybrid approaches like AHP-TOPSIS to enhance the scientific rigor of evaluations. Additionally, incorporating economic cost and construction feasibility metrics into the assessment framework would be beneficial.

(3) Application of intelligent optimization algorithm: The combination of TOPSIS evaluation model with intelligent optimization algorithms such as genetic algorithm and particle swarm optimization algorithm to

realize automatic optimization of carbon sequestration concrete mix proportion will be an important direction of future research.

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