Proceedings of CONF-FMCE 2026 Symposium: Smart City and Infrastructure Engineering
DOI: 10.54254/2755-2721/2026.CH37693

Technical Path and Engineering Application of Low Carbonization Preparation of Concrete

Chenxi Wang

Leeds College, Southwest Jiaotong University, Chengdu, China
xhfq0754@leeds.ac.uk

Abstract. The carbon emissions of concrete run through its entire lifecycle, and reducing the carbon footprint of concrete has become an important issue in the field of building materials. Although various research systems for low-carbon concrete have gradually improved, there is still a lack of systematic comparison of the economic and carbon reduction potential of different technological paths in practical engineering. This article divides the sources of carbon emissions into three stages: clinker production, aggregate mining and processing, and mixing and construction. Based on the core principles of optimizing the cementitious material system and coordinating mineral admixtures, a systematic review is conducted on the technical paths of high-dosage mineral compounding, alkali-activated cementitious materials, and solid waste synergistic utilization. The carbon emission reduction and engineering application conditions of each scheme are compared horizontally. The carbon reduction range of the high-dosage compound scheme is 20% to 45%, and the engineering acceptance is the highest. The carbon reduction potential of alkali-activated materials can reach about 70%, but it is limited by material shrinkage cracking and construction adaptability. The carbon reduction rate of the solid waste collaborative utilization plan is between 10% and 40%. The promotion of the three types of schemes is constrained by fluctuations in the quality of raw materials.

Keywords: low-carbon concrete, mineral admixtures, carbon emissions, solid waste utilization

1. Background

The amount of concrete used in construction projects has long been the highest among all types of building materials. According to a report by the International Energy Agency, the carbon dioxide emissions from the cement industry account for approximately 7% of the global total emissions [1]. How to reduce carbon emission intensity while maintaining basic engineering performance has become a research difficulty in the field of civil engineering.

The use of industrial by-products such as fly ash, granulated blast furnace slag, and steel slag to replace some Portland cement is currently the most direct and effective carbon reduction method. However, most existing research focuses on a specific admixture or single improvement process, lacking a horizontal comparison of the carbon reduction benefits and engineering economics of

© 2026 The Authors. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

DOI: 10.54254/2755-2721/2026.CH37693

different technical solutions. Discussions on the early strength deficiencies and long-term durability risks of low-carbon concrete exposed under real construction conditions are also relatively limited.

This article takes various technological paths of low-carbon concrete as the review object. Firstly, the sources of carbon emissions are divided. Secondly, the core technological principles are sorted out. Then, the mainstream technological paths are explained in detail. Finally, the existing shortcomings are analyzed from the perspectives of carbon emission reduction benefits and engineering economics, and future development challenges and directions are discussed. Intended to provide a scientific basis and technical support for the theoretical system construction and engineering practice application in the field of low-carbon concrete.

2. Basic theory

2.1. Classification of carbon emission sources from concrete

The carbon emissions of concrete run through its entire lifecycle, and there are significant differences in emission sources and intensities at different stages. Overall, it can be divided into three main stages.

The production stage of clinker is the most concentrated stage of carbon emissions. The production of cement clinker requires the calcination of raw materials such as limestone and clay at high temperatures above 1400 ℃. The calcium carbonate in limestone decomposes into calcium oxide and releases a large amount of carbon dioxide. At the same time, maintaining the calcination temperature requires continuous combustion of coal or other fossil fuels. The carbon emissions generated by these two parts cannot be eliminated solely by replacing clean energy.

The mining and processing of sand and gravel aggregates cannot be ignored. The extraction process of natural aggregates relies almost entirely on diesel and electric power. Although recycled aggregates eliminate the mining process, their production still consumes a large amount of energy. At the same time, the fuel consumption during transportation will also increase correspondingly with the distance traveled. The calculation based on the scenario of heavy-duty diesel truck road transportation shows that when the transportation distance of recycled aggregates exceeds the critical value of 30km, its carbon emission advantage will significantly weaken or even disappear [2].

The emission sources in the mixing and construction process are relatively clear. At present, the power structure has long been dominated by thermal power, and behind the construction electricity consumption is a large amount of coal consumption and carbon dioxide release [3]. These emissions, although not occurring on the construction site, are indirect carbon loads driven by construction activities and should be included in the carbon emission accounting scope of the entire life cycle of concrete.

2.2. Core technology principles of low-carbon concrete

There are multiple technological paths to reduce carbon emissions from concrete, but the core mechanism mainly focuses on optimizing the cementitious material system and the addition of mineral admixtures. Industrial by-products such as fly ash, granulated blast furnace slag, and steel slag have potential hydration activity and can undergo secondary reactions with cement hydration products under alkaline conditions to generate substances with cementitious properties. Replacing some cement with such materials can achieve carbon reduction. But the larger the replacement ratio,

DOI: 10.54254/2755-2721/2026.CH37693

the better. Once it exceeds a reasonable range, the development of strength will be significantly delayed. In engineering practice, the dosage of fly ash is often controlled at around 30% [4].

The synergistic effect of mineral admixtures is the theoretical foundation of the compounding scheme. The spherical particle morphology of fly ash is beneficial for improving the flowability of fresh concrete, while slag powder can compensate for the slow early strength growth of fly ash due to its high reactivity. The two exhibit a good synergistic effect [5]. In addition, the combination of different particle size admixtures can optimize the particle stacking state, thereby maintaining or even improving the mechanical properties under the condition of reduced cement dosage.

3. The mainstream technological path of low-carbon concrete

3.1. Optimization technology for cementitious material system

The basic idea for optimizing the cementitious material system is to replace some of the Portland cement with industrial by-products. Materials such as fly ash, granulated blast furnace slag, and steel slag can undergo secondary hydration reactions under alkaline conditions, producing substances with cementitious properties. Replacing cement with such materials can effectively reduce carbon emissions.

3.1.1. Compound replacement of Portland cement with high dosage fly ash and steel slag powder

The most widely used mineral admixtures in engineering are fly ash and granulated blast furnace slag. By combining the two and replacing a certain proportion of cement, the comprehensive performance of concrete can be maintained while reducing the amount of clinker used. Kang Jie and Fang Qiang (2026) conducted experiments on a large-volume foundation project for a wind farm in Inner Mongolia, setting up mineral admixture dosage gradients ranging from 20% to 50%. The data show that as the dosage increases from 20% to 40%, the flowability of concrete gradually improves [6]. But after the dosage exceeds 40%, its strength decreases significantly, and the 1d strength drops to around 9MPa [6].

The implementation effect of such high dosage schemes highly depends on the quality stability of raw materials. The loss on ignition, fineness, and glass content of fly ash fluctuate significantly with different coal types and combustion conditions in power plants, and the activity index of slag powder is also affected by the fineness of the powder and storage conditions.

3.1.2. Preparation technology of low-carbon alkali-activated cementitious materials

Alkali-activated cementitious materials are completely independent of Portland cement. Therefore, their carbon emissions per unit mass are much lower than those of ordinary Portland cement. China Construction Fifth Engineering Bureau Co., Ltd. has developed an alkali-activated fluidized soil technology based on undisturbed shield tunneling slag (patent number CN117510169B), which uses alkali-activated cementitious materials combined with a small amount of cement and gypsum to adjust the undisturbed shield tunneling slag into a high-fluidity slurry, and then prepares backfill materials [7]. The entire process does not generate wastewater or waste residue, and has been applied in practical engineering.

From an engineering application perspective, the early strength development of alkali-activated materials is usually faster than that of ordinary concrete. However, its promotion and application are

DOI: 10.54254/2755-2721/2026.CH37693

limited by multiple factors: alkaline activators are mostly strong alkaline solutions, which pose a high risk of corrosion to personnel and equipment during operation. Meanwhile, the shrinkage deformation of the material is relatively large, making it prone to cracking in the early stages. Therefore, currently these materials are more commonly used in relatively controllable production environments such as prefabricated components.

3.2. Solid waste co-blending low-carbon concrete technology

3.2.1. Construction waste recycled powder for concrete preparation

The waste concrete and bricks in construction waste can be crushed and ground into recycled powder with certain activity. Its particle size is less than 75 microns, but the hardened cement slurry powder still retains some unhydrated cement clinker particles, which can exert a weak cementing effect during the hydration process [8]. The Pinglu Canal project in Guangxi has made attempts in the recycling of construction solid waste. The project team will use a large number of old bridges and houses that need to be demolished along the project route to produce recycled aggregates through multiple processes such as crushing, separation, and shaping, and then mix them into high-performance recycled concrete. After more than two years of operation and monitoring, the key indicators such as structural strain and deflection of the bridge meet the design requirements: compressive strength exceeding 120MPa, axial tensile strength exceeding 8MPa, and flexural strength exceeding 20MPa, with sufficient mechanical performance reserves [9].

But the performance variability of recycled powder is relatively large. The complex sources of construction waste result in highly unstable chemical composition and activity levels of the powder. At present, recycled powder is often used in conjunction with fly ash or slag powder in engineering to alleviate the problem of strength decline when mixed alone.

3.2.2. Collaborative mixing scheme for metallurgical and thermal power solid waste

There are various types of solid waste generated in the metallurgical and thermal power industries, including not only fly ash and slag, but also steel slag, desulfurization gypsum, red mud, silica fume, etc. By 2025, Panzhihua will build the first fully solid waste concrete urban road in China. During the construction process, no cement or natural aggregates are used at all - the cementitious materials used are by-product gypsum such as blast furnace desulfurization gypsum and titanium gypsum, and the aggregates used are tailings sand and blast furnace slag. This road digests a total of 209 tons of industrial solid waste, with a comprehensive cost 10% to 30% lower than traditional reinforced concrete roads [10].

Due to the diverse types of solid waste involved in this plan, it is difficult to accurately predict the activity differences and interactions of each type of solid waste through theoretical calculations. Therefore, the actual mixing ratio, grinding fineness, and curing conditions need to be systematically tested for specific raw material batches. The cost consumption of time and manpower is the main difficulty faced by the cross-regional promotion of solid waste collaborative blending solutions.

DOI: 10.54254/2755-2721/2026.CH37693

4. Benefit analysis of low-carbon concrete

4.1. Carbon emission reduction benefits

The carbon reduction effect of the high-dosage mineral compound scheme directly comes from the reduction of cement dosage. Huang Dexiang's research systematically investigated the effect of using 10% to 50% of ultrafine mineral powder as a substitute for cement on carbon emissions. The results showed that the carbon emission coefficient of the composite cement gradually decreased with the increase of ultrafine mineral powder dosage. When the dosage was 50%, carbon emissions could be reduced by 45.9% (304.70 kgCO_2/t) [11]. Another study on high-content blast furnace slag fly ash concrete in the Xinjiang region confirmed that, compared with benchmark concrete of the same grade, it can reduce carbon emissions by 27 to 41 kg per cubic meter, and at the same time, the 28-day compressive strength in low-grade areas is increased by 10% to 40% compared with benchmark concrete [12]. A case study conducted by Tsinghua University on C30 concrete in China showed that the carbon emissions of concrete mixed with 40% granulated blast furnace slag from raw materials to factory gates were 180.0 kg CO_2 e/m^3, which was about 28.5% lower than the 251.9 kg CO_2/m^3 of pure cement concrete [13]. Based on comprehensive literature data, the carbon emission reduction of high-dosage compound schemes is usually between 20% and 45%.

The carbon reduction potential of alkali-activated cementitious materials is most prominent among various schemes. The research results of Luo Kai et al. showed that using Na_2CO3 as an activator can significantly reduce carbon emissions; its carbon emission factor is only 0.79 t CO_2/t, far lower than the 3.3 t CO_2/t of NaOH and 1.8 t CO_2/t of sodium silicate cement. At the optimal mix ratio, the carbon emissions are 228 kg CO_2/t, which is about 70% lower than that of ordinary Portland cement [14].

The carbon reduction benefits of solid waste collaborative utilization schemes vary depending on the specific blending method. Wang Tong et al. reduced the carbon emission intensity of concrete by 36.8% by using a low-temperature synergistic activation process with multiple solid waste cementitious materials. Steel slag can absorb CO_2 during the carbonation process. Research from Tsinghua University shows that the carbonation storage capacity of concrete mixed with 30% steel slag is 73.1 kg CO_2/m^3 (storage rate of 36%), and the carbon emissions throughout the life cycle can be as low as 131.5 kg CO_2 e/m^3 (Table 1) [13].

Table 1. Comparison of carbon emission reduction benefits under different technological pathways

Technical path	Benchmark mix ratio	Reduction in carbon emissions
Compound of high-dosage ultrafine mineral powder [10]	50% ultrafine mineral powder replaces cement	45.90%
Slag admixture (C30) [12]	40% granulated blast furnace slag	28.50%
Red mud-based alkali-activated material [13]	Red mud 35.56%, slag 57.22%, Na_2CO ∝ excitation	Approximately 70%
Compound of multiple solid wastes [14]	Steel slag +fly ash +recycled micro powder (low-temperature activation)	36.80%
Steel slag admixture (carbonization) [12]	30% steel slag	36% (Carbonized Storage)

DOI: 10.54254/2755-2721/2026.CH37693

4.2. Engineering economic analysis

In terms of raw material costs, the market price of fly ash and slag powder is usually 30% to 50% of the unit price of cement, and the high dosage compounding scheme has significant cost advantages in the raw material end. But the economy is not fixed and unchanging. The study assumes that the carbon price is fixed at $30 per ton, while increasing the slag price from $0.05 per kilogram to $0.10, $0.15, and $0.20 per kilogram [15]. Under these price conditions, the difference in total cost per unit strength of mixtures with different slag substitution levels is shown in Figure 1a – c. Research has shown that when the price of slag doubles, as shown in Figure 1a, the unit price cost of all mixtures increases, but mixtures with higher slag content still maintain economic advantages. As the price of slag increases threefold, as shown in Figure 1b, the cost gap further narrows, and the economic benefits of slag substitution begin to be offset. When the price of slag itself rises to four times the original price, as shown in Figure 1c, the high slag content system will lose its cost advantage and even be more expensive than pure cement concrete [15]. This indicates that the economic feasibility of low-carbon concrete depends on slag pricing policies and the stability of the supply chain of industrial by-products.

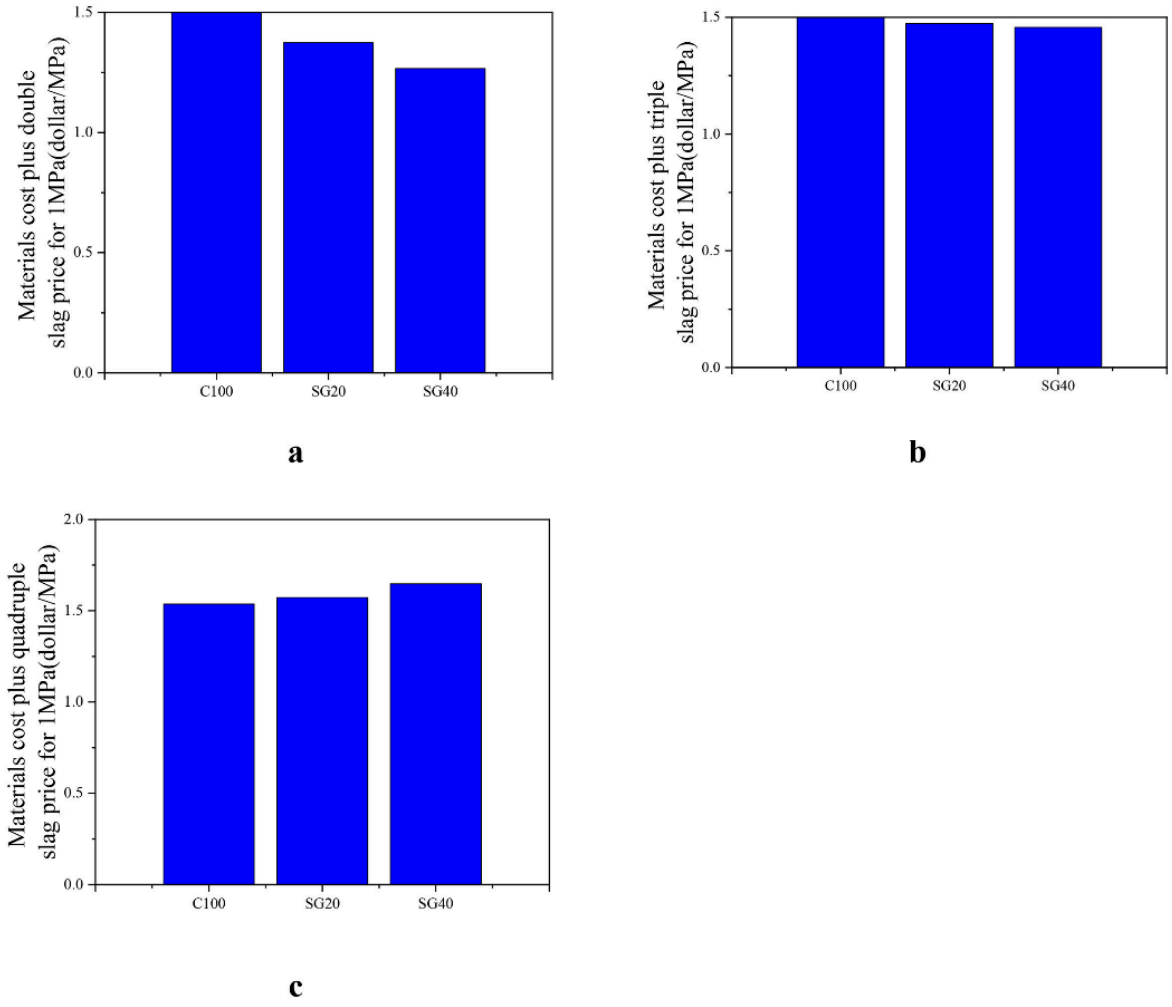


Figure 1. The impact of rising slag prices on the unit strength material cost of concrete: (a) doubled slag prices, (b) tripled slag prices, (c) quadrupled slag prices [15]

DOI: 10.54254/2755-2721/2026.CH37693

The raw material cost of alkali-activated materials varies greatly. When using industrial alkaline waste such as carbide slag and red mud as activators, the cost is relatively low. However, if industrial-grade water glass or NaOH is used, the production cost of the activator itself may offset the low price advantage of solid waste. As mentioned earlier, the carbon emission factor of NaOH is as high as 3.3 t CO_2/t, and that of water glass is 1.8 t CO_2/t, both of which are high-energy-consuming products [14].

In terms of construction cost, the construction process of the high-dosage compound scheme is basically the same as that of traditional concrete, but the low early strength may lead to prolonged formwork removal time. The cost of alkali-activated materials in the construction process is significantly higher, and the risk of shrinkage and cracking requires stricter maintenance measures.

The assessment of lifecycle costs also needs to consider the long-term impact of carbon pricing. Research has shown that with the increase of carbon prices, the economic advantages of admixture substitution schemes will gradually amplify, and high slag content systems have stronger cost competitiveness under high carbon price scenarios [15]. This advantage is based on the premise of stable prices of industrial by-products.

5. Challenges and prospects of low-carbon concrete development

5.1. The current industry is facing technological bottlenecks

The fluctuation of raw material quality is the primary factor affecting the stability of low-carbon concrete performance. Related studies have shown that the optimal dosage of fly ash is positively correlated with its fine particle content of less than 20.4 μ m. Reducing the loss on ignition and increasing the content of MgO, K_2O, CaO, and SO3 can also effectively improve its reasonable substitution ratio [16]. This means that due to the discreteness of raw materials, the same mix proportion may exhibit vastly different workability and mechanical properties under different batches of fly ash.

The difficulty of landing on the construction site reflects the practical difficulties in the construction process. The shrinkage and durability performance of low-carbon concrete strongly depend on the mix design and curing conditions. Taking the Pinglu Canal project as an example, low-carbon ultra-high performance concrete (LC-UHPC) with compressive strength exceeding 120MPa and axial tensile strength greater than 8MPa was used for the construction of bridge deck slabs at the bridgehead [9]. This relies on machine learning-assisted mix design and extensive experimental verification to ensure material performance. It precisely indicates that the preparation process threshold for high-performance low-carbon concrete is relatively high.

5.2. Future technological development direction

The combination of 3D printing technology and low-carbon concrete represents a revolution in construction methods. A European research team has developed low-carbon concrete consisting entirely of industrial waste in the CARBCOMN project, which is formed into independent components through 3D printing and then assembled into load-bearing structures [17]. After printing, it is placed in a CO_2 curing chamber for hardening, while achieving chemical fixation of CO_2 [17]. The construction method of 3D printing without templates itself has material-saving benefits, and the reuse of industrial waste has significant carbon reduction value. The combination of the two is expected to achieve large-scale and low-carbon applications in the field of irregular components.

DOI: 10.54254/2755-2721/2026.CH37693

Digital carbon control throughout the entire lifecycle is a management tool for achieving refined emission reduction. At the level of concrete mix design, scholars have developed a digital platform that integrates international standards, which helps reduce reliance on repeated trial mixes and reduce carbon emissions from the design end.

6. Conclusion

This article provides an overview of the technological path for low-carbon preparation of concrete, sorting out the stage distribution of carbon emissions, the principles and carbon reduction effects of various technologies, and comparing the economics of different schemes.

The carbon dioxide emissions from the cement industry account for approximately 7% of the global total emissions. The inherent carbon load formed by the high-temperature decomposition of limestone and fuel combustion cannot be eliminated through energy substitution. Although the proportion of carbon emissions during aggregate mining and construction is low, its emissions are still worth paying attention to when the transportation distance is extended or the proportion of thermal power is high.

The combination of large amounts of minerals is currently the most technologically mature solution. After replacing some cement with fly ash and slag powder, carbon emissions can be reduced by 20% to 45%. The carbon reduction potential of alkali-activated materials is the largest, which can be reduced by about 70% compared to ordinary cement. However, the corrosiveness and material shrinkage cracking issues of activators mainly limit them to the field of prefabricated components. The carbon reduction effect of solid waste collaborative utilization schemes varies depending on the specific blending method, but the regional dependence of raw material fluctuations and blending ratios limits cross regional replication.

In terms of economy, the high dosage scheme has a cost advantage on the raw material side, but once the price of by-products rises, the advantage will weaken. If water glass or NaOH is used as the activator for alkaline materials, their high energy consumption will offset the low price effect of solid waste. The common shortcomings faced by engineering promotion include low early strength and insufficient long-term durability data. Subsequent research needs to continue to deepen in areas such as optimizing the performance of cementitious materials and improving the full lifecycle accounting methods.

References

[1] Sarfraz, S., Sheryf, Z., Drewniok, M., et al. (2025). Potentials for energy savings and carbon dioxide emissions reduction in cement industry. In *Sustainable Manufacturing as a Driver for Growth* (pp. 765–773). Springer. https://doi.org/10.1007/978-3-031-77429-4_85

[2] Yang, L. (2025). *Research on environmental impact assessment of recycled aggregate concrete based on whole life cycle* [Master's thesis, Shenyang University]. https://doi.org/10.27692/d.cnki.gsydx.2025.000091

[3] Gao, X., Zhu, J., & Xu, X. (2020). Case study on carbon footprint measurement during the construction stage of prefabricated concrete buildings. *Building Energy Efficiency, 48*(4), 131–137. https://doi.org/10.3969/j.issn.1673-7237.2020.04.025

[4] Zheng, S., Li, H., Chen, X., et al. (2024). The influence of fly ash content on the workability and mechanical properties of fully recycled self compacting concrete. *Bulletin on Silicates, 43*(4), 1445–1454. https://doi.org/10.16552/j.cnki.issn1001-1625.2024.04.023

[5] Wang, K. (2024). Study on the effect of polycarboxylate water reducing agent on the properties of cement blast furnace slag fly ash ternary system. *Fujian Building Materials*, (3), 6–10. https://kns.cnki.net/reader/flowpdf?invoice=CmKY0pKwptf83AucNQowiIgCzpEWyIPoV5N%2B%2FhvOXroOqvMpPB3I5Tzg7YLJ54x7ESO1FiAkl0Bfra3116xFocjsxFoOHy1HUqQaJsDHEIo%2FhAYzrzPc7jH3pXBrJrT21N6qHFUEJAE613ii97jH5HONIoB4a6cNeG5LXLlGEO8%3D&platform=NZKPT&sourcetype=nxgp&product=CJFQ&filename=FJJC202403002&tabl

DOI: 10.54254/2755-2721/2026.CH37693

ename=cjfdlast2024&type=JOURNAL&scope=trial&cflag=overlay&dflag=&pages=&language=CHS&trial=&nonce=B5DE017A1C034DB78E29ECBFA23D7495

[6] Kang, J., & Fang, Q. (2026). Study on the workability and early strength of concrete with high content mineral admixtures. *Journal of Cement*, (4). https://doi.org/10.13739/j.cnki.cn11-1899/tq.2026.04.045

[7] Xi, Z., Li, S., Li, Y., et al. (2024). A method for preparing early strength water-resistant fluidized soil based on undisturbed shield tunneling slag (China Patent No. CN117510169B). China National Intellectual Property Administration.

[8] Ma, K., Meng, W., Shen, J., et al. (2024). Research and application progress on performance activation of regenerated micro powder. *Material Introduction, 38*(10), 96–108. https://doi.org/10.11896/cldb.22100042

[9] Xiao, J., & Ying, J. (2026, May 4). "Thin and thick, low carbon and long life" - China's first low carbon UHPC bridgehead deck landing on Pinglu Canal in Guangxi. *Dual Carbon Science and Technology Research Institute*. https://carbon.gxu.edu.cn/info/1032/2309.htm

[10] Lannan. (2026, February 10). How did the 160 meter road 'eat' 209 tons of solid waste? *Sichuan Daily*, p. 08. https://doi.org/10.28672/n.cnki.nscrb.2026.000761

[11] Huang, D. (2025). The influence of high dosage compound ultrafine mineral powder on cement particle size distribution, mechanical properties, and carbon emissions. *Cement Engineering, 38*(4), 33–37. https://doi.org/10.13697/j.cnki.32-1449/tu.2025.04.008

[12] Chen, X., Zhang, X., et al. (2025). Preparation and research of low-carbon concrete based on high content blast furnace slag fly ash. *Development of Building Technology*, (3), 1–3. https://doi.org/10.20259/j.jzjskf.2025.03.0001

[13] Lin, Z., Lang, P., & Fang, K. (2025). Carbon emissions of SCM-containing concrete considering carbonation: A case study for C30 concrete in China. *Journal of Sustainable Cement-Based Materials, 14*(5), 960–972. https://doi.org/10.1080/21650373.2025.2485260

[14] Luo, K., Ye, J., Ren, X., et al. (2026). Carbon footprint accounting and low-carbon design of alkali activated cementitious materials. *Journal of Ceramics, 54*(5). https://doi.org/10.14062/j.issn.0454-5648.20250149

[15] Sun, F., Zhang, H., et al. (2026). A unified prediction framework of the hydration, strength, and sustainability of cement–slag concrete integrating ultrasonic pulse velocity. *Journal of Materials Research and Technology, 41*, 6155–6172. https://doi.org/10.1016/j.jmrt.2026.02.195

[16] Wang, X., & Zheng, J. (2009). Grey correlation analysis of fly ash performance and its optimal dosage. *Journal of Jiangsu University (Natural Science Edition), 30*(1), 95–99. https://kns.cnki.net/reader/flowpdf?invoice=V4f8QbVjwkQkVuK%2FeHfc29FHsqfVsnr2wHDf4WA9NWqbD9wUVtT6PLOHy1R4CvNzfe7SpzI7fy83HSz%2FmxyXwzh9i6gnzjDTJ9OXcmqom0cKuAURQafnOHIuuDaznscl%2BOYDrhU2F53ZBealzKHiKrGMvzNjUHMxOpV60D2XCIs%3D&platform=NZKPT&sourcetype=nxgp&product=CJFQ&filename=JSLG200901024&tablename=cjfd2009&type=JOURNAL&scope=trial&cflag=overlay&dflag=&pages=&language=CHS&trial=&nonce=28AC58D5C1074872A5C153E91EB01F92

[17] Swiss Federal Laboratories for Materials Science and Technology (Empa). (2025, December 15). Custom-made concrete from a 3D printer. https://www.empa.ch/web/s604/eq90-beton-aus-dem-3d-drucker