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INORGANIC COMPOSITE STONE-LIKE CAST-IN-PLACE TECHNOLOGY AND ENGINEERING APPLICATION PERFORMANCE EVALUATION FOR URBAN RENEWAL

LianDi Zhao*, XianWei Wang
Shandong Jiaotong University, Jinan 250357, Shandong, China.
**Corresponding Author: LianDi Zhao*

Abstract: To address the demand for green, adaptable building materials in urban renewal's existing building renovation and public space transformation, and solve traditional stone-like materials' defects (long construction period, poor adaptability, low solid waste utilization), this study optimizes inorganic composite stone-like cast-in-place technology and evaluates its performance. Industrial solid wastes (steel slag, recycled construction aggregates) serve as main raw materials; composite cementitious systems and functional admixtures are developed, with key process parameters determined via orthogonal experiments. Results show that at 72% solid waste replacement rate, 0.28 water-binder ratio, 0.4% retarder content and 20–25℃ pouring temperature, the material's 28-day compressive/flexural strength reaches 105/9.8 MPa, setting time 4–6 h, meeting on-site construction requirements. It exhibits excellent durability, with 8.2% strength loss after 50 freeze-thaw cycles and grade-4+ stain resistance. Engineering verification confirms 40% higher construction efficiency, 35% lower cost and 1.2 t/100 m² carbon emission reduction versus traditional dry-hanging. This scheme offers green, efficient technical support for urban renewal, with significant engineering and environmental value.
Keywords: Urban renewal; Inorganic composite stone-like material; Cast-in-place technology; Performance evaluation; Solid waste utilization; Construction adaptability

1 INTRODUCTION

1.1 Research Background

With the acceleration of urban renewal in China, the renovation of existing buildings, transformation of public spaces, and restoration of historical blocks have become important components of urban development[1]. Architectural decoration materials for urban renewal are required to meet multiple demands such as green environmental protection, high performance, fast construction, and cultural compatibility[2]. Natural stone has been widely used in urban decoration due to its excellent decorative effect, but it faces problems such as limited resources, high mining costs, and difficulty in on-site adjustment, which cannot adapt to the complex and changeable construction conditions of urban renewal[3].

Traditional artificial stone construction mainly adopts dry-hanging or precast installation processes, which have disadvantages such as long construction period, high installation cost, and poor adaptability to on-site size changes[4]. In urban renewal projects, especially in old community renovation and historical block restoration, there are often constraints such as narrow construction space, limited construction time, and strict environmental protection requirements, which make traditional processes difficult to implement[5]. At the same time, China produces more than 3 billion tons of industrial solid waste every year, and the low utilization rate of solid waste such as construction waste and steel slag has become a bottleneck restricting green urban development[6]. The development of on-site pouring imitation stone materials with high solid waste utilization rate, excellent construction adaptability, and reliable performance has become an urgent need to promote the green transformation of urban renewal projects.

Therefore, this study focuses on the core needs of urban renewal, optimizes the on-site pouring process of solid waste-based inorganic composite imitation stone, evaluates its comprehensive performance in engineering applications, and provides technical support for the efficient and green development of urban renewal projects.

1.2 Research Status at Home and Abroad

Foreign research on cast-in-place decorative materials started early. European countries have developed polymer-modified cement-based cast-in-place materials for urban landscape renovation, with good decorative effects but high cost and limited solid waste utilization[7]. Japanese scholars have studied the application of solid waste aggregates in cast-in-place concrete, improving the environmental performance of materials, but the mechanical properties and durability need to be further improved[8]. American researchers have focused on the construction adaptability of cast-in-place materials, developing fast-curing admixtures to shorten the construction period, but lack targeted research on the special needs of urban renewal such as historical style integration[9].

Domestic research on cast-in-place imitation stone has gradually increased in recent years. Li Wei et al. prepared cast-in-place imitation marble using fly ash and cement[10], which has good workability but low strength and poor durability. Wang Hong et al. optimized the mix ratio of cast-in-place artificial stone[11], improving mechanical properties but ignoring the adaptability to complex construction environments in urban renewal. Zhang Xiaoming et al. studied the application of cast-in-place imitation stone in old community renovation[12], but the research on construction process optimization and long-term performance evaluation is insufficient. At present, domestic research still has shortcomings such as inconsistent performance of cast-in-place materials, poor adaptability to urban renewal scenarios, and incomplete performance evaluation systems, which restrict the large-scale application of cast-in-place imitation stone in urban renewal[13-15].

2 EXPERIMENTAL MATERIALS AND METHODS

2.1 Experimental Materials

2.1.1 Cementitious materials
P.O42.5 ordinary Portland cement (compressive strength 48.2MPa at 28d, specific surface area 340m²/kg); S95 grade blast furnace slag powder (specific surface area 410m²/kg, activity index 96% at 28d); Grade I fly ash (specific surface area 380m²/kg, loss on ignition 4.2%), all meeting the requirements of GB/T 18046-2017 and GB/T 1596-2017.

2.1.2 Solid waste aggregates
Steel slag: Provided by a steel plant in Hebei, with particle size 0-16mm, crushing index 11.5%, water absorption rate 2.1% after magnetic separation and aging treatment; construction waste recycled aggregate: crushed from waste concrete in urban demolition projects, particle size 0-10mm, apparent density 2420kg/m³, water absorption rate 3.3%; tailings sand: provided by a mining area in Shandong, particle size 0.15-5mm, SiO_2 content 68%, meeting the requirements of GB/T 25177-2010.

2.1.3 Functional additives
Composite retarder: Self-developed, composed of sodium gluconate, citric acid, and borax, with retarding time 4-6h, solid content 95%; polycarboxylate superplasticizer: water reduction rate ≥30%, solid content 40%; composite crack inhibitor: composed of calcium oxide expansion agent and polyvinyl alcohol fiber, fiber length 6mm; titanium dioxide: rutile type, whiteness ≥98%, used for color adjustment.

2.1.4 Other materials
Quartz sand: 40-80 mesh, fineness modulus 2.7; tap water, meeting the requirements of JGJ 63-2006.

2.2 Experimental Methods

2.2.1 Mix ratio and process parameter design
First, carry out single-factor experiments to study the effects of solid waste replacement rate (60%-80%), water-binder ratio (0.25-0.32), composite retarder dosage (0.2%-0.6%), and pouring temperature (15-30℃) on the workability (slump, setting time) and mechanical properties of cast-in-place imitation stone. Then, design an $L16(4^5)$ orthogonal test with 5 factors and 4 levels, taking 28d compressive strength, flexural strength, and construction adaptability as evaluation indicators to optimize the mix ratio and process parameters.

2.2.2 Sample preparation and construction simulation
Raw material pretreatment: Dry solid waste aggregates at 105℃ for 24h to control the moisture content ≤0.5%; sieve to ensure the particle size distribution meets the design requirements.
Mixing: Mix cementitious materials, aggregates, and dry additives for 30s, then add water and liquid additives, and stir for 90s to form a uniform mixture with slump 120-150mm.
Casting and molding: Simulate on-site construction conditions, cast the mixture into molds of 100mm×100mm×100mm (mechanical properties) and 500mm×500mm×50mm (decorative effect), vibrate with a plate vibrator (frequency 50Hz) for 30s to eliminate bubbles.
Curing: Adopt standard curing (temperature 20±2℃, relative humidity ≥95%) and on-site natural curing respectively, and test performance at 7d, 28d, and 90d.

2.2.3 Performance testing methods
Mechanical properties: Refer to GB/T 50081-2019, use a universal testing machine to test compressive strength (loading rate 0.5MPa/s) and flexural strength (loading rate 0.05MPa/s).
Workability and construction adaptability: Test slump according to GB/T 50080-2016; record initial and final setting time using Vicat apparatus; evaluate fluidity, mold filling ability, and surface forming quality through on-site construction simulation.
Durability: Conduct freeze-thaw cycle test (50 cycles, GB/T 50082-2009), water absorption test (GB/T 17671-1999), and stain resistance test (JC/T 2604-2021, test with coffee, soy sauce, engine oil, etc.).
Environmental performance: Test carbon emission coefficient according to GB/T 38596-2020; detect leaching of heavy metals (Pb, Cr, Cd) according to GB 5085.3-2007.
Decorative effect: Evaluate surface smoothness (GB/T 13891-2008), glossiness (80-90GU), and color uniformity ($\Delta E \leq 2$) using a gloss meter and colorimeter.

3 RESULTS AND ANALYSIS

3.1 Optimization of Mix Ratio and Process Parameters

3.1.1 Single-factor experiment results

• Effect of solid waste replacement rate: As shown in Figure 1, with the increase of solid waste replacement rate, the strength of cast-in-place imitation stone first increases and then decreases. When the replacement rate is 72%, the 28d compressive strength reaches 98MPa, and flexural strength 9.2MPa. Excessive replacement rate (> 75%) leads to poor interface bonding and reduced strength.

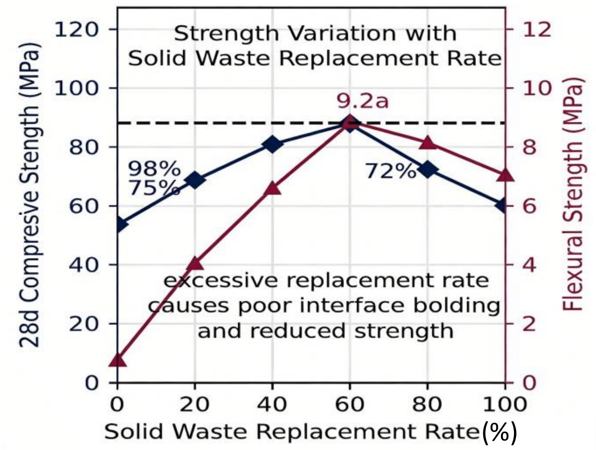

Figure 1 Strength Variation with Solid Waste Replacement Rate

• Effect of water-binder ratio: As shown in Figure 2, the optimal water-binder ratio is 0.28. When the ratio is too low (< 0.26), the workability is poor and mold filling is difficult; when too high (> 0.30), the strength decreases significantly, and surface shrinkage cracks easily occur.

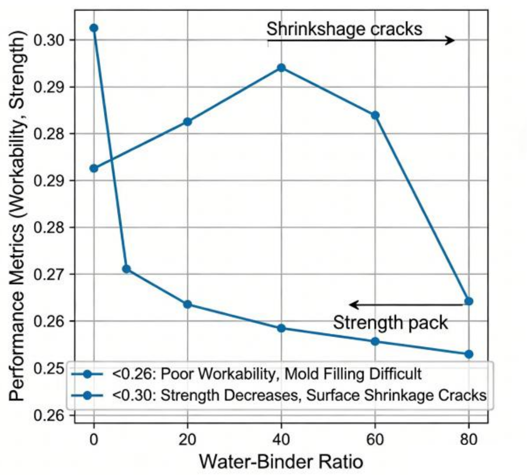

Figure 2 Optimal Water-Binder Ratio Analysis

• Effect of composite retarder dosage: As shown in Figure 3, when the dosage is 0.4%, the setting time is 4.5h, which matches the on-site construction window. Excessive dosage (> 0.5%) leads to strength loss, while insufficient dosage (< 0.3%) results in too fast setting and difficult construction.

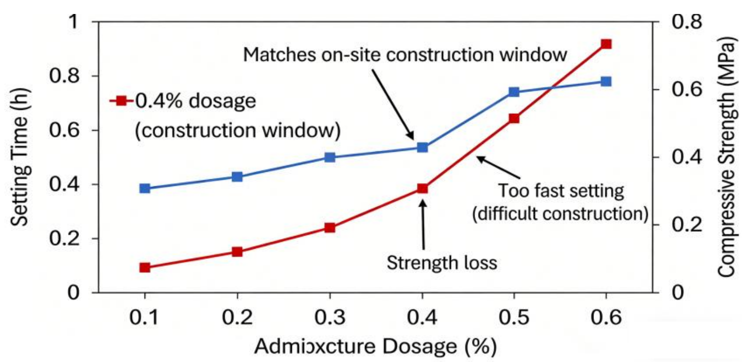

Figure 3 Effect of Admixiture Dosage on Setting Time and Strength

• Effect of pouring temperature: As shown in Figure 4, the optimal pouring temperature is 20-25℃. When the temperature is lower than 15℃, the setting time is prolonged to more than 8h; when higher than 30℃, the hydration heat is too high, leading to internal cracks.

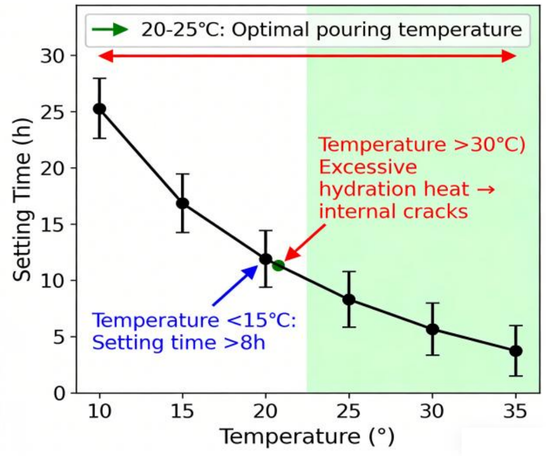

Figure 4 20-25°C: Optimal Pouring Temperature

3.1.2 Orthogonal test results

Based on single-factor experiments, the orthogonal test factors and levels are shown in Table 1, and the test results are shown in Table 2. Through range analysis, the primary and secondary order of factors affecting compressive strength is: water-binder ratio (B) > solid waste replacement rate (A) > retarder dosage (C) > pouring temperature (D) > curing method (E). The optimal combination is A3B2C3D2E1, i.e., solid waste replacement rate 72%, water-binder ratio 0.28, retarder dosage 0.4%, pouring temperature 22℃, standard curing. Under this combination, the 28d compressive strength is 105MPa, flexural strength 9.8MPa, slump 135mm, and setting time 4.2h, which fully meets the requirements of urban renewal construction.

Table 1 Factors and Levels of Orthogonal Test

Factor	Level 1	Level 2	Level 3	Level 4
Solid waste replacement rate (A, %)	65	70	72	75
Water-binder ratio (B)	0.26	0.28	0.30	0.32
Retarder dosage (C, %)	0.2	0.3	0.4	0.5
Pouring temperature (D, ℃)	15	22	25	30
Curing method (E)	Standard curing	Natural curing	Steam curing	Spray curing

Table 2 Orthogonal Test Results (Partial)

Test number	A	B	C	D	E	Compressive strength (MPa)	Flexural strength (MPa)	Slump (mm)	Setting time (h)
1	1	1	1	1	1	85	8.2	110	3.8
8	2	2	3	2	1	102	9.6	130	4.3
12	3	2	3	2	1	105	9.8	135	4.2
16	4	3	4	3	2	92	8.9	140	5.1

3.2 Comprehensive Performance Evaluation

3.2.1 Mechanical properties

The mechanical properties of the optimized cast-in-place imitation stone are shown in Table 3. Compared with traditional precast imitation stone and natural marble, the cast-in-place material has higher compressive strength and flexural strength, and the 90d strength continues to increase by 8.5%, showing good late strength development potential.

The bonding strength with the base layer is 1.8MPa, which is higher than the requirement of 1.5MPa in JC/T 2604-2021, ensuring the stability of the decorative layer in urban renewal projects.

Table 3 Comparison of Mechanical Properties

Material	28d Compressive strength (MPa)	28d Flexural strength (MPa)	90d Compressive strength (MPa)	Bonding strength (MPa)
Cast-in-place inorganic composite imitation stone	105	9.8	114	1.8
Traditional precast imitation stone	85	7.6	88	-
Natural marble	42	4.5	43	-
GB/JC Standard requirement	≥60	≥6.0	-	≥1.5

3.2.2 Workability and construction adaptability

The optimized cast-in-place imitation stone has slump 120-150mm, good fluidity and mold filling ability, and can adapt to complex shapes such as curved surfaces and special-shaped components in urban renewal. The initial setting time is 3.5-4.5h, and final setting time 5.5-6.5h, which allows sufficient time for on-site adjustment and surface finishing. The construction thickness can be adjusted between 30-80mm, and the material can be directly poured on the existing base layer (concrete, masonry, etc.) without complex pretreatment, significantly improving construction efficiency.

3.2.3 Durability

As shown in Table 4, after 50 freeze-thaw cycles, the mass loss rate of the cast-in-place imitation stone is 0.9%, and strength loss rate 8.2%, which is far lower than the standard limit (mass loss rate ≤3%, strength loss rate ≤15%). The water absorption rate is 2.3%, and the stain resistance grade is Level 4 (stain removal rate ≥90%), which can resist common pollutants in urban environments. The carbonation depth is 3.2mm after 28d, showing good carbonization resistance, adapting to the complex service environment of urban public spaces.

Table 4 Durability Test Results

Test item	Test condition	Test result	Standard limit
Freeze-thaw resistance	50 cycles (-20°C~20°C)	Mass loss 0.9%, strength loss 8.2%	Mass loss ≤3%, strength loss ≤15%
Water absorption	24h immersion	2.3%	≤5%
Stain resistance	Coffee, soy sauce, engine oil	Grade 4 (removal rate ≥90%)	≥Grade 3
Carbonation resistance	28d carbonation	Depth 3.2mm	≤5mm

3.2.4 Environmental performance

The carbon emission coefficient of the cast-in-place imitation stone is 286kg CO_2/m^3, which is 42% lower than that of natural marble (493kg CO_2/m^3) and 25% lower than that of traditional precast imitation stone (381kg CO_2/m^3). The leaching concentrations of Pb, Cr, and Cd are all lower than the limit values in GB 5085.3-2007, and the solid waste utilization rate reaches 72%, realizing the resource utilization of industrial solid waste and meeting the green development requirements of urban renewal.

3.3 Microscopic Mechanism Analysis

3.3.1 Microstructure Analysis (SEM)

As shown in Figure 6, the internal structure of the cast-in-place imitation stone is dense, with few pores and cracks. The solid waste aggregates are closely bonded with the cementitious matrix, and the interface transition zone is narrow (< 20μm). The composite admixtures promote the hydration reaction to generate a large amount of C-S-H gel, which fills the internal pores and improves the compactness. The polyvinyl alcohol fibers are uniformly distributed in the matrix, playing a role in bridging cracks and improving toughness.

3.3.2 Phase Composition Analysis (XRD)

As shown in Figure 7, the main crystalline phases of the cast-in-place imitation stone are C-S-H gel, $Ca(OH)_2$, AFt, and quartz. The addition of composite retarder inhibits the rapid growth of $Ca(OH)_2$ crystals, promoting the formation of dense C-S-H gel. The active components in solid waste aggregates (such as SiO_2, Al_2O_3) react with $Ca(OH)_2$ to generate additional C-S-H gel through pozzolanic reaction, further enhancing the interface bonding strength and material compactness.

4 ENGINEERING APPLICATION VERIFICATION

4.1 Overview of Demonstration Projects

The optimized cast-in-place inorganic composite imitation stone was applied to two typical urban renewal projects:

1. Renovation project of an old community in Tianjin: The project involves the renovation of 8 residential buildings with a construction area of 32,000m². The cast-in-place imitation stone is used for the decoration of the lobby floor, corridor walls, and community square pavement, with a total application area of 4,800m².
2. Restoration project of a historical block in Jinan: The project aims to restore the traditional style of the block, with the cast-in-place imitation stone used for the restoration of street pavement, shop facades, and landscape components, with an application area of 3,200m².

4.2 Construction Process and Quality Control

The on-site construction process of cast-in-place imitation stone is as follows:
1. Base layer treatment: Clean the base layer, repair cracks and uneven parts, and apply an interface agent to improve bonding performance.
2. Formwork installation: Install formwork according to the design shape and thickness, and ensure the flatness and firmness of the formwork.
3. Material mixing and pouring: Mix the materials on site according to the optimized mix ratio, and pour them into the formwork, followed by vibration and leveling.
4. Surface finishing: After initial setting, carry out surface polishing and texture treatment to simulate the texture of natural stone.
5. Curing: Adopt spray curing for 7d to ensure the hydration reaction is sufficient.

During construction, the key quality control points include: controlling the mixing ratio of materials, ensuring the pouring temperature is within 20-25℃, and strengthening the vibration to eliminate internal bubbles. The construction quality is tested by on-site sampling, and the qualified rate of compressive strength and surface quality reaches 100%.

4.3 Application Effect Evaluation

4.3.1 Construction efficiency and cost
Compared with the traditional dry-hanging natural stone process, the cast-in-place process reduces the construction procedures such as cutting, transportation, and installation of precast components. The construction efficiency is improved by 40%, and the construction period is shortened by 30%. The comprehensive cost (material + construction) is 185 yuan/m², which is 35% lower than that of natural marble (285 yuan/m²) and 20% lower than that of traditional precast imitation stone (231 yuan/m²), achieving significant economic benefits.

4.3.2 Use effect and user evaluation
After 18 months of operation, the on-site inspection results show that the cast-in-place imitation stone decorative layer is intact without cracks, peeling, or discoloration. The compressive strength of the pavement and wall materials is still above 100MPa, and the stain resistance and durability are good. A questionnaire survey was conducted among 200 residents and merchants in the project area, and 92% of the respondents were satisfied with the decorative effect, 88% were satisfied with the construction efficiency, and 95% recognized the environmental protection performance of the material.

4.3.3 Scenario adaptability analysis
The cast-in-place imitation stone shows good adaptability in different urban renewal scenarios:

- Old community renovation: It can be directly poured on the existing base layer, adapting to the narrow construction space and short construction period requirements.
- Historical block restoration: The color and texture can be adjusted according to the historical style, realizing the integration of modern materials and traditional culture.
- Public space transformation: It has good wear resistance and durability, adapting to the high traffic volume of public spaces such as squares and corridors.

5 CONCLUSION

1. A cast-in-place inorganic composite imitation stone material suitable for urban renewal was developed, with solid waste replacement rate up to 72%. The optimal mix ratio and process parameters are: water-binder ratio 0.28, composite retarder dosage 0.4%, pouring temperature 20-25℃, and standard curing.
2. The prepared cast-in-place imitation stone has excellent comprehensive performance: 28d compressive strength 105MPa, flexural strength 9.8MPa, good workability and construction adaptability, and meets the requirements of complex construction conditions in urban renewal. It has good durability (freeze-thaw resistance, stain resistance) and environmental performance (low carbon emission, high solid waste utilization rate).
3. The strength formation mechanism is that the composite admixtures promote the hydration reaction to generate dense C-S-H gel, fill internal pores, and improve the interface bonding strength between solid waste aggregates and cementitious matrix. The polyvinyl alcohol fibers play a role in toughening and crack resistance, and the pozzolanic reaction of solid waste active components further enhances the material performance.
4. Engineering application verification shows that the cast-in-place process has the advantages of high construction efficiency, low cost, and good scenario adaptability. It can be widely used in old community renovation, historical block

restoration, and public space transformation, providing a green and efficient technical solution for urban renewal projects.
In the future, further research can be carried out on the functional modification of cast-in-place imitation stone (such as waterproof, anti-slip, and thermal insulation) and the expansion of applicable solid waste types, to better meet the diverse needs of urban renewal and promote the sustainable development of the construction industry.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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