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Research on the Performance of Recycled Concrete Modified with Nano-Silica and Basalt Fiber

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Abstract: With the increasing depletion of natural sand and gravel resources and the aggravation of environmental pollution, the recycling of waste concrete holds significant ecological and economic value. This study empirically investigates the performance of recycled concrete modified with nano-silica (SiO_2) and basalt fiber, addressing the recycling of waste concrete from construction waste. By optimizing material proportions, the mechanical properties and durability of recycled concrete are enhanced, providing technical support for green building. The research demonstrates that it is feasible to prepare C40 concrete using recycled aggregates from waste concrete. The composite incorporation of nano-SiO_2 (1.8%) and basalt fiber (0.3%, approximately 3 kg/m³) significantly improves compressive strength and durability.

Keywords: Waste Concrete Recycled Aggregate; Nano-silica; Basalt Fiber.

1. Introduction

Waste concrete generated from the demolition of old buildings has become a major component of construction waste. Traditional disposal methods such as landfilling or open-air stacking not only occupy valuable land resources but also generate dust and harmful leachate due to long-term weathering and rainwater erosion, severely polluting air, soil, and groundwater, thereby causing serious ecological and environmental problems. Meanwhile, natural sand and gravel resources are increasingly depleted, leading to a tightening supply-demand problem and a series of environmental and geological issues due to over-exploitation [1]. Against this backdrop, the recycling of waste concrete holds significant practical and strategic value [2]. Through processes such as crushing and screening, waste concrete can be transformed into recycled aggregates to replace natural aggregates in engineering applications like concrete and road base courses, achieving "turning waste into treasure." This effectively alleviates resource shortages, reduces environmental pollution, and lowers engineering costs. Furthermore, this technology aligns with national policies on sustainable development and the circular economy, promoting the green transformation of the construction industry and achieving synergistic development of resource conservation, environmental protection, and economic benefits, which has profound significance for building an environmentally friendly society. To effectively enhance the comprehensive performance of recycled concrete, the incorporation of nano-silica (SiO_2) has become a current research hotspot. Its core mechanisms include: increasing density, strengthening the interfacial transition zone (ITZ), and promoting secondary hydration reactions, thereby significantly improving the strength and durability of concrete. Recycled concrete generally suffers from defects such as low strength, insufficient toughness, and poor crack resistance. To address these issues, the incorporation of basalt fiber has emerged as an efficient technical pathway. Based on extensive research, this study uses waste concrete recycled aggregates to prepare C40-grade concrete and investigates the appropriate dosage of nano-silica (SiO_2) and basalt fiber when added simultaneously.

2. Determination of C40 Concrete as the Target Strength Grade

C40 concrete can withstand substantial loads, making it suitable for structural components requiring high strength, such as high-rise buildings, bridges, and hydraulic engineering, ensuring structural safety and stability. Its high-strength characteristics also allow for reduced cross-sectional dimensions of components, lighter self-weight, and increased usable space. Additionally, it exhibits low permeability, high impermeability (up to P8 or higher), freeze-thaw resistance, and carbonation resistance, effectively resisting erosion from harsh environments (e.g., seawater corrosion, acid rain), extending the service life of buildings, and reducing maintenance costs. Although the unit cost is approximately 35% higher than that of C30 concrete, the initial investment can be offset by reduced long-term maintenance costs (e.g., a 42% reduction in maintenance costs over 15 years), resulting in significant life-cycle cost-effectiveness. It is widely used in critical parts of high-rise buildings, bridge piers, industrial plants, etc., making it a common choice as the "strength threshold" in the industry. The mix design and construction techniques are mature, and raw materials (e.g., 42.5-grade cement, high-quality aggregates) and admixtures (e.g., water reducers, expansion agents) are strictly controlled to ensure stable and reliable performance, complying with national standards (GB/T 50081-2019). Using waste concrete as aggregate to achieve higher strength grades is challenging and has not been widely reported domestically or internationally. Considering pumping requirements, the concrete mix ratio was determined as 0.38:1:1.11:2.72, meaning per cubic meter of concrete uses 175 kg of water, 460 kg of cement, 510 kg of sand, and 1250 kg of waste concrete aggregate. Experiments confirmed that this mix ratio already meets the C40 grade. To further enhance concrete strength, based on existing research, we plan to incorporate nano-SiO_2 and basalt fiber. To determine their optimal dosages, a sequential strategy—first determining the nano-SiO_2 dosage, then the basalt fiber dosage—was adopted. While this strategy may not yield the absolute optimal solution, it ensures a near-optimal result.

3. Determination of Nano-SiO_2 Dosage

In the recycling process of waste concrete, recycled aggregates exhibit defects such as adhered old mortar, high porosity, and strong water absorption, leading to generally lower mechanical properties and durability of recycled aggregate concrete (RAC) compared to natural aggregate concrete.First, the addition of SiO_2 significantly improves concrete strength. Nano-SiO_2 possesses high pozzolanic reactivity, enabling it to undergo secondary hydration reactions with calcium hydroxide (CH)—a product of cement hydration—generating more cementitious C-S-H gel, filling pores, and strengthening the interfacial structure. Liu Yong et al. [3] showed that with a 3% nano-SiO_2 dosage, the 28-day compressive strength of recycled fine aggregate concrete increased by 23.5% compared to the control group, with significant improvements in split tensile and flexural strength. Li Meishou [4] also indicated that vacuum pressure immersion of recycled aggregates with a 2% nano-SiO_2 solution reduced CH content by over 40%, increased C-S-H gel, and resulted in a denser microstructure.Second, SiO_2 has multiple effects on improving durability. Yang Chengbin found that an appropriate amount of nano-SiO_2 significantly reduced carbonation depth (up to 23%), water penetration depth (51% reduction), and crack area (89.4% reduction), but excessive dosage (>7%) caused agglomeration and performance degradation. Qiu Zehui pointed out that at a 3% dosage, the chloride ion migration coefficient of concrete was minimized, the impermeability grade reached P8, and comprehensive durability was optimal.Based on multiple literature analyses, in recycled fine aggregate concrete, the dosage should be controlled between 1% and 3% to avoid agglomeration and hydration inhibition. Experiments were conducted with four groups of nano-SiO_2 (20 nm particle size) dosages: 0.9%, 1.8%, 2.7%, and 0% (control group). Each group was further divided into curing periods of 1, 3, 7, and 28 days. After curing, compressive strength tests were performed (results in Table 1).

Table 1. Effect of SiO_2 Content on Compressive Strength

SiO_2 (%)	Time (days)	Compressive (MPa)	SiO_2 (%)	Time (days)	Compressive (MPa)
0	1	22	1.8	1	27
0	3	28	1.8	3	34
0	7	35	1.8	7	38
0	28	40	1.8	28	46
SiO_2 (%)	Time (days)	Compressive (MPa)	SiO_2 (%)	Time (days)	Compressive (MPa)
0.9	1	24	2.7	1	25
0.9	3	32	2.7	3	34
0.9	7	37	2.7	7	38
0.9	28	45	2.7	28	45

According to the experimental data, without nano-SiO_2, the waste concrete recycled aggregate concrete already meets the strength requirements for C40 concrete. However, after adding nano-SiO_2, the compressive strength is significantly enhanced. Within 1–3 days of curing, the strength improvement is similar across SiO_2 dosages, but between 7–28 days, the strength increase is more pronounced. Notably, at a 1.8% nano-SiO_2 dosage, the compressive strength is higher than at 2.7%.

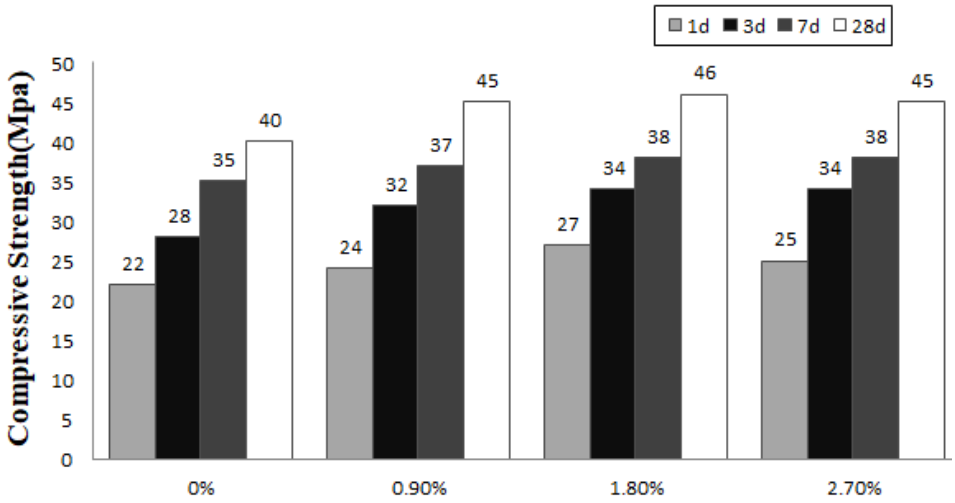


Fig 1. Effect of SiO_2 Content on Compressive Strength

4. Determination of Basalt Fiber Dosage

Recycled concrete generally suffers from low strength, insufficient toughness, and poor crack resistance, primarily due to the adhered old mortar on recycled aggregates, high porosity, and a weak interfacial transition zone. Basalt fiber, as an inorganic mineral fiber, offers high strength, high modulus, corrosion resistance, and good compatibility with cementitious matrices, significantly improving the

mechanical properties and durability of concrete. First, basalt fiber markedly enhances the tensile and flexural performance of concrete. Ordinary concrete is brittle, with tensile strength only about 1/10 of its compressive strength. The incorporation of basalt fiber effectively bridges micro-cracks, inhibits crack propagation, and achieves "crack resistance and toughening." Studies show that with a fiber length of 18 mm and a volume dosage of 0.15%, the split tensile strength can increase by up to 17.9%. Flexural strength increases by 29.33% at a fiber length of 18 mm and dosage of 0.3%. The three-dimensional random distribution network of fibers bridges cracks under stress, dissipates fracture energy, and improves toughness and ductility, shifting the failure mode from brittle to ductile. Second, appropriate dosage and length are key to optimizing performance. Literature analysis indicates that the effect of basalt fiber on concrete performance follows an "increase-then-decrease" trend. The optimal enhancement is achieved with a fiber length of around 18 mm and a volume dosage between 0.1% and 0.2%. For example, reference [6] notes that in recycled concrete, a 0.2% fiber dosage yields peak compressive and flexural strength; reference [7] shows optimal split tensile performance at 18 mm length and 0.15% dosage; reference [8] finds the best flexural performance at 18 mm length and 0.3% dosage. However, excessively long fibers (e.g., 30 mm) or high dosages (>0.3%) can cause agglomeration, uneven dispersion, and excessive water absorption, impairing workability and strength. Experiments were conducted with four groups of basalt fiber (20 mm length) dosages: 0.15%, 0.3%, 0.45%, and 0% (control group). Each group was divided into curing periods of 1, 3, 7, and 28 days. After curing, compressive strength tests were performed (results in Table 2).

Table 2. Effect of Basalt Fiber Content on Compressive Strength

Basalt(%)	Time (days)	Compressive (MPa)	Basalt(%)	Time (days)	Compressive (MPa)
0	1	30	0.3	1	33
0	3	35	0.3	3	38
0	7	37	0.3	7	45
0	28	45	0.3	28	51
Basalt(%)	Time (days)	Compressive (MPa)	Basalt(%)	Time (days)	Compressive (MPa)
0.15	1	32	0.45	1	30
0.15	3	36	0.45	3	37
0.15	7	42	0.45	7	40
0.15	28	47	0.45	28	46

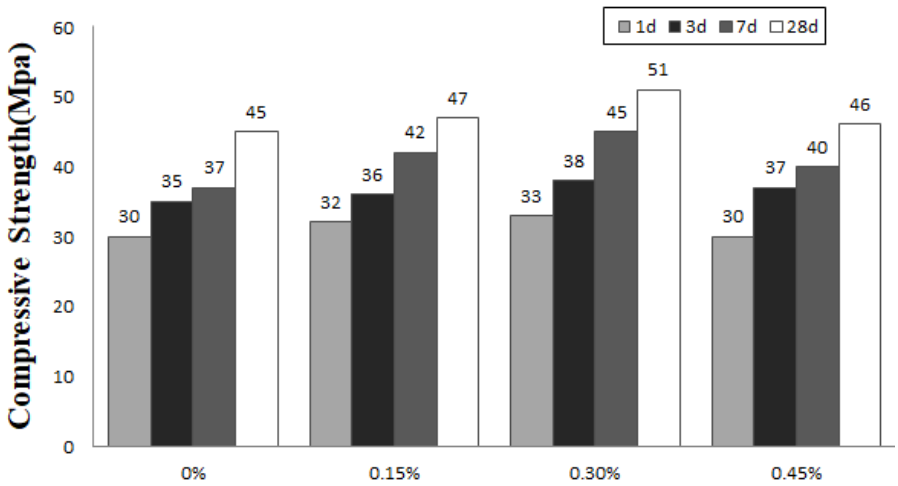


Fig 2. Effect of Basalt Fiber Content on Compressive Strength

The experimental data indicate that adding basalt fiber significantly improves the compressive strength of waste concrete recycled aggregate concrete. At a 0.3% dosage, the compressive strength is higher than at 0.45%.

5. Conclusion

It is feasible to prepare C40 concrete using waste concrete as recycled aggregate. The incorporation of nano-SiO_2 and basalt fiber significantly enhances the compressive strength of concrete. The optimal mix ratio is 0.38:1:1.11:2.72, meaning per cubic meter of concrete uses 175 kg of water, 460 kg of cement, 510 kg of sand, and 1250 kg of waste concrete aggregate. The recommended dosages are:

Nano-SiO_2: 1.8% by weight, with a particle size of 20 nm.

Basalt fiber: 3 kg/m³, with a length of 20 mm.

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