UDC 691.32

THE INFLUENCE OF RECYCLED AGGREGATE CONTENT AND SILICA FUME ADDITION ON THE MECHANICAL PROPERTIES OF RECYCLED AGGREGATE CONCRETE

***Sun Chunhua*[1], *V. V. Kravchenko*[2]**

[1] *Graduate student, Brest State Technical University, Brest, Belarus, e-mail: Sch15275712255@126.com*
[2] *Candidate of Technical Science, Associate of Professor, Department of Concrete and Building Materials Technology, Brest State Technical University, Brest, Belarus, e-mail: vvkravchenko@g.bstu.by*

Abstract

The use of waste from concrete and reinforced concrete structures is one of the current areas of development in the construction industry in the Republic of Belarus and abroad. Despite the active growth of this field, there is insufficient research devoted to the comprehensive study of concretes using recycled aggregates, especially with the introduction of various types of pozzolanic additives. A comprehensive study was conducted on concrete using recycled aggregate, aimed at examining effects of various levels of recycled aggregate in the concrete at 0 %, 25 %, 50 %, 75 %, and 100 % of the total aggregate mass, with the addition of fly ash, on compressive strength, tensile strength, and the adhesion between the reinforcement and the concrete. Experimental results indicate that as the content of recycled aggregate increases, the mechanical properties of the concrete tend to decline. This is primarily due to the inherent lower strength of the recycled aggregate and the presence of two transitional zones in the concrete with recycled aggregate (in the cement paste and the recycled aggregate). However, the addition of fly ash can improve this issue: the pozzolanic reaction of SiO_2 with portlandite $Ca(OH)_2$ leads to the filling of pores in the transitional zones with reaction products and the solidification of their structure. This contributes to the elimination of the distinct phase boundary and, consequently, to the merging of the transition zone of the cement paste with the transition zone of the recycled aggregate, significantly enhancing its adhesion to the cement paste. The research results confirm that concrete made with recycled aggregate exhibits improved mechanical properties compared to control mixes without fly ash.

Keywords: concrete, recycled aggregate, silica fume, mechanical properties.

ВЛИЯНИЕ СОДЕРЖАНИЯ РЕЦИКЛИНГОВОГО ЗАПОЛНИТЕЛЯ И ЗОЛЫ-УНОСА В БЕТОНЕ НА ЕГО МЕХАНИЧЕСКИЕ СВОЙСТВА

Сун Чуньхуа, В. В. Кравченко

Реферат

Вторичное использование отходов конструкций и изделий из бетона и железобетона является одним из актуальных направлений развития строительной отрасли в Республике Беларусь и зарубежных странах. Несмотря на активное развитие данного направления, отсутствует достаточный объем исследований, посвященных комплексному изучению бетонов на рециклинговом заполнителе, особенно при условии введения различных типов пуццолановых добавок. Проведено комплексное исследование бетона на рециклинговом заполнителе, направленное на изучение влияния содержания рециклингового заполнителя в количестве 0 %, 25 %, 50 %, 75 %, 100 % от массы всего заполнителя с добавлением золы-уноса на прочность бетона при сжатии и растяжении, а также прочность сцепления арматуры с бетоном. Экспериментальные результаты показывают, что по мере увеличения содержания рециклингового заполнителя механические свойства бетона показывают тенденцию к снижению. Это, в первую очередь, связано с присущей рециклинговому заполнителю более низкой прочностью и наличием в структуре бетона на рециклинговом заполнителе двух транзитных зон (в цементном камне и рециклинговом заполнителе). Однако добавление золы-уноса способно решить данную проблему: пуццолановая реакция SiO_2 с портландитом $Ca(OH)_2$ приводит к заполнению пор в транзитных зонах продуктами реакции и уплотнению их структуры. Это способствует устранению выраженной границы раздела фаз и, как следствие, к слиянию транзитной зоны цементного камня с транзитной зоной рециклингового заполнителя, что значительно улучшает его адгезию с цементным камнем. Результаты исследования подтверждают, что бетон на рециклированном заполнителе демонстрирует улучшенные механические характеристики по сравнению с контрольными составами без золы-уноса.

Ключевые слова: бетон, рециклинговый заполнитель, зола-унос, механические свойства.

Introduction

Against the backdrop of the continuously expanding scale of construction in the global building industry, the demand for building materials continues to rise. Among these, natural aggregates, as a key component of concrete, are being consumed in particularly large quantities. However, long-term and large-scale extraction has led to the increasing depletion of natural aggregate resources, triggering serious sustainability issues. On the other hand, with urban construction and renewal, large amounts of construction waste are continuously generated. The stockpiling of this waste not only occupies land resources but may also cause compound pollution to soil, water, and the atmosphere, creating a heavy environmental burden. In this context, promoting the resource utilization of construction waste by processing it into recycled aggregates for use in concrete production is regarded as an important pathway to balance the conflict between resource supply and environmental protection, and has garnered widespread attention [1–4]. This approach not only helps alleviate the pressure on natural aggregate resources but also significantly reduces the negative impact of construction waste on the ecological environment, offering notable comprehensive economic, social, and environmental benefits.

Although recycled aggregate concrete demonstrates significant potential for sustainable development, its material performance still faces challenges. Compared to natural aggregates, recycled aggregates have a large amount of old cement mortar attached to their surfaces and contain initial defects such as microcracks, resulting in lower apparent density, higher water absorption, and weaker mechanical strength. These differences in physical and mechanical properties often lead to issues such as relatively low strength and insufficient durability in recycled aggregate concrete at the macroscopic level. The root causes can be attributed to the weakening of the aggregate-cement paste interface zone and the formation of a multiple interfacial structure. To enhance the practical performance of recycled aggregate concrete and promote its application in high-standard engineering projects, it is of great importance to systematically study its performance evolution mechanisms and develop effective enhancement technologies.

Among various modification methods, incorporating silica fume is considered an effective approach to enhance the performance of recycled aggregate concrete. Chen's research findings indicate that the incorporation of silica fume accelerates the setting of cement paste and significantly reduces its fluidity. However, silica fume has a very notable effect on enhancing the later-age (28-day) compressive strength of the paste [5]. Zhao's study found that the incorporation of silica fume can significantly improve the compressive and flexural strength of cement mortar, and there exists an optimal dosage range (approximately 5 % in the study) [6]. Li's research discovered that the pozzolanic reaction of silica fume consumes calcium hydroxide, a hydration product, and generates more dense calcium silicate hydrate (C-S-H) gel with a low calcium-to-silica ratio, thereby optimizing the microstructure of the mortar, making it denser, reducing porosity, and strengthening the interfacial structure [7]. Yang's study found that silica fume significantly enhances the frost resistance of concrete and effectively reduces the diffusion coefficient of chloride ions in concrete. This is because silica fume densifies the concrete structure, hindering the penetration pathways of moisture and corrosive ions [8]. Liu's research found that in low-temperature environments, silica fume can also effectively improve the compressive strength and impermeability of cement mortar. The study revealed that silica fume overcomes the adverse effects of low temperature on cement hydration and microstructure development by optimizing pore structure and promoting hydration [9]. Silica fume is characterized by its extremely fine particle size (approximately 0,1–0,2 μm), large specific surface area, and high pozzolanic reactivity. When added to concrete, silica fume can undergo a secondary reaction with calcium hydroxide, a product of cement hydration, generating additional calcium silicate hydrate gel. This effectively fills capillary pores and microcracks, optimizes the pore structure, and thereby increases the density of the matrix. More importantly, silica fume significantly strengthens the interfacial transition zone between recycled aggregates and the cement paste, improving the bond between the old and new mortar and alleviating stress concentrations caused by the presence of the old mortar. Consequently, it enhances the overall mechanical properties and durability of the concrete [10–12]. In recent years, Hamada et al. [13] provided a comprehensive review of using plastic waste as aggregate in concrete, synthesizing a broad set of laboratory and field studies and assessing environmental and economic implications. Danish and Ozbakkaloglu [14] examined the role of nano-silica in mortars containing e-waste plastic used as fine aggregates, showing that nano-silica can partially recover the strength loss caused by replacing natural sand with plastic particles by (1) filling micro-voids, (2) accelerating pozzolanic reactions that densify the binder, and (3) improving the interfacial transition zone around irregular plastic fragments. Alhajiri and Akhtar [15] produced a systematic review focused on silica fume as a sustainability and economic lever in concrete production.

Some scholars have also studied the use of recycled concrete aggregates and various plastic wastes as aggregates, systematically evaluating their impact on the workability, mechanical properties, and durability indicators such as chloride ion migration of concrete. In addition, the incorporation of steel fibers has been proven to be an effective means to improve the compressive and flexural properties and toughness of concrete, including geopolymer concrete. These studies not only promote the progress of concrete technology, but also provide important technical paths and practical cases for achieving sustainable development and carbon reduction goals in the construction industry [16–18]. Fernando et al. [19–20] investigated strategies to produce high-strength recycled aggregate concrete (RAC) by combining multiple supplementary cementitious materials (SCMs). The study systematically examined the effects of fly ash, silica fume and rice husk ash (RHA) used both as cement replacements and as treatments for recycled aggregates. Shamass et al. [21] combined mechanical testing with environmental assessment to evaluate concretes formulated with blast furnace slag (GGBS), silica fume and recycled aggregate, emphasizing both engineering performance and global warming potential (GWP). Nasir, Butt and Ahmad [22] focussed on recycled plastic aggregate concrete (RPAC) and demonstrated that coupling silica fume with fiber reinforcement (steel and polypropylene fibers) significantly improves mechanical and axial (column) resilience of RPAC.

Therefore, investigating the synergistic effects of recycled aggregate content and silica fume addition on the mechanical behavior and microstructure of recycled aggregate concrete holds significant theoretical value. It will also provide critical technical foundations for material design, performance optimization, and engineering application of recycled aggregate concrete, contributing positively to advancing the green and low-carbon transformation of the construction industry.

1 Experimental Materials and Methods

1.1 Experimental Materials

This experiment used ordinary Portland cement as the cementitious material. Its physical and chemical properties comply with national standard requirements, ensuring stable and reliable hydration reactions and binding capacity for the concrete system.

Natural siliceous river sand was selected as the fine aggregate. This sand features rounded particle shapes and a continuous, well-graded distribution, effectively filling the voids between the coarse aggregate skeleton and significantly enhancing the compactness and homogeneity of the concrete.

The coarse aggregates used in the experiment included two types: The first was natural pink limestone gravel with a maximum particle size of 20 mm, characterized by uniform texture and stable physical properties, as shown in Figure 1. The second was recycled coarse aggregate sourced from construction and demolition waste, as shown in Figure 2. This was processed by manually breaking with a steel hammer, sieving, and cleaning waste concrete components with different mix proportions, cement types, and ages. Its particle size distribution was ultimately controlled within the range of 4,75–19 mm to meet the experimental comparison requirements.

Figure 1 – Pink limestone natural coarse aggregate

To improve the interfacial structure and mechanical properties of the recycled aggregate concrete, reactive silica fume was incorporated. Its main chemical component is amorphous silicon dioxide, characterized by a fine average particle size, large specific surface area, and excellent pozzolanic reactivity.

Furthermore, to ensure the workability of the fresh concrete under conditions of relatively high aggregate content, a polycarboxylate-based high-range water reducer was used to control fluidity, maintaining good plasticity and uniformity during mixing and pouring.

Figure 2 – Recycled coarse aggregate

https://doi.org/10.36773/1818-1112-2025-138-3-9-14

From the perspective of aggregate gradation characteristics, the natural coarse aggregate, sourced from mechanically crushed limestone, has a relatively concentrated particle size distribution and a relatively ideal gradation curve. In contrast, the recycled coarse aggregate, limited by its complex sources and crushing process, has a wider particle size distribution range and a slightly higher fine powder content. The fineness modulus of the natural sand is 2,6, classifying it as medium sand. It effectively fills the voids between coarse aggregates, forming a rational particle grading system and laying a good foundation for the overall workability and mechanical properties of the concrete.

1.2 Experimental Design

This study systematically investigated the synergistic effects of recycled aggregate content and silica fume addition on the properties of recycled aggregate concrete. To comprehensively evaluate the influence of recycled aggregate, five replacement levels were set: 0 %, 25 %, 50 %, 75 %, and 100 % by mass of the total aggregate, allowing for systematic observation of the evolution of concrete properties with varying recycled aggregate content.

Regarding the modification with silica fume, the experiment focused on a reference mix proportion with a cement content of 250 kg/m³ and a water-to-cement ratio of 0,60. Silica fume was added at 10 % of the cement mass to analyze its improvement effects on the microstructure and macroscopic properties of concrete within this specific material system.

The experimental design carefully considered practical engineering application needs, selecting two typical cement contents of 400 kg/m³ and 250 kg/m³, representing common mix proportion ranges for reinforced concrete elements and plain concrete elements, respectively.

To ensure the accuracy and comparability of the experimental results, the dosage of the chemical admixture was adjusted differentially based on the cement content: when the cement content was 250 kg/m³, the admixture dosage was 1,75 % of the cement weight; when the cement content increased to 400 kg/m³, the admixture dosage was correspondingly adjusted to 0,75 % of the cement weight.

By precisely controlling the mix proportion parameters, the workability of all concrete mixtures was consistently maintained within the range of 120 ± 30 mm, effectively ensuring consistent testing conditions and reliable data.

This experimental scheme considers both the systematic variation of recycled aggregate content and provides an in-depth investigation into the modifying effects of silica fume under specific mix proportions, establishing a scientific experimental basis for a comprehensive evaluation of the performance characteristics of recycled aggregate concrete.

1.3 Experimental Methods

1.3.1 Specimen Preparation

After precisely weighing all raw materials according to the established mix proportions, the concrete was mixed using conventional mechanical mixing procedures. The feeding sequence strictly followed the order of cement, aggregates, silica fume, chemical admixtures, and finally water to ensure thorough homogenization of all components. Upon completion of mixing, the fresh concrete was immediately placed into the respective molds for casting. The specimen dimensions were specifically designed according to the different testing items: Compressive strength tests utilized standard 150 mm × 150 mm × 150 mm cubic specimens; Tensile strength tests employed cylindrical specimens with a diameter of 75 mm and a height of 150 mm. Bond performance tests used cylindrical specimens with a diameter of 150 mm and a height of 150 mm. A 16 mm diameter deformed steel bar was pre-embedded along the central axis of the specimen before casting. All specimens were demolded and immediately transferred to a standard curing room. They were continuously cured under constant temperature and humidity conditions (20 ± 2 °C, relative humidity ≥ 95 %) until the designated testing ages.

This preparation protocol, incorporating standardized mold selection, regulated mixing procedures, and strictly controlled curing regimes, effectively ensured consistency among the test specimens and comparability of the test data. The design of the different specimen types fully considered the standardization requirements of the respective test methods. Specifically, the unique configuration of the bond strength specimens with the pre-embedded steel bar accurately simulates the interaction between concrete and reinforcement.

1.3.2 Performance Testing

In accordance with standard testing procedures, systematic evaluations of mechanical properties and physical indicators were conducted on all specimen types at designated ages. Compressive strength tests were performed at 7, 28, and 56 days. Standard cubic specimens were positioned centrally on the loading plates of a compression testing machine. Axial pressure was applied at a constant loading rate while monitoring the load value continuously until specimen failure. The peak load was recorded, and the compressive strength was calculated using the standard formula.

Tensile strength was characterized using the splitting tensile test method. Upon reaching the specified testing age, cylindrical specimens were placed horizontally in a splitting test fixture. A continuous linear load was applied through the upper and lower bearing plates, inducing uniform tensile stress along the diametral plane until splitting failure occurred. The splitting tensile strength was calculated based on the measured failure load and specimen dimensions according to the standard formula.

Bond performance tests were conducted specifically at the 28-day age. Cylindrical specimens with pre-embedded deformed steel bars were used. A specialized pull-out setup was employed to apply an axial tensile force to the steel bar. The ultimate load at which slippage occurred at the concrete-steel interface was precisely measured, and the bond strength between them was determined through calculation.

This testing framework comprehensively covers the macroscopic mechanical properties of the concrete material. All testing procedures strictly adhered to relevant standard specifications, ensuring the accuracy and comparability of the results. The bond strength test protocol effectively simulates the actual stress state in reinforced concrete elements, while the multi-age strength testing reveals the development pattern of the material's properties.

2 Results and Analysis

2.1 Influence of Recycled Aggregate Content

2.1.1 Compressive Strength

The effect of different recycled aggregate replacement levels on the compressive strength of concrete with a cement content of 400 kg/m³ is shown in Figure 3.

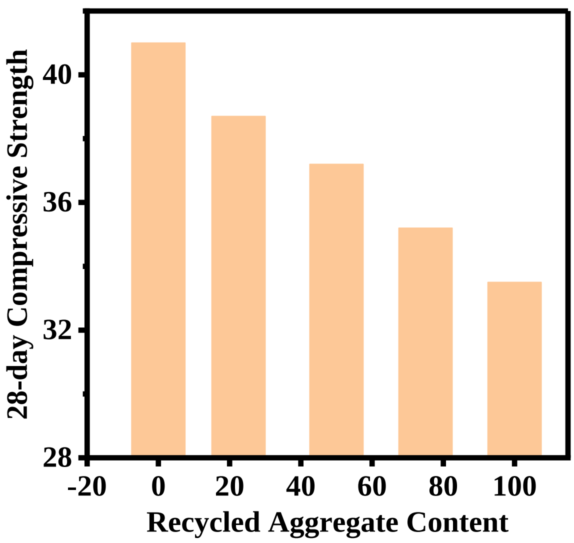

Figure 3 – Compressive strength of concrete with different recycled aggregate content

Based on the experimental results, the influence of recycled aggregate content on the compressive strength of concrete exhibits distinct phase characteristics. When the RA content is limited to within 25 %, the 28-day compressive strength shows no significant difference compared to the reference group (with no recycled aggregate). Specifically, the compressive strength of specimens with 25 % recycled aggregate content was only 3,0 % lower than that of the control group. This minor variation falls within the acceptable engineering margin of error. This phenomenon is primarily attributed to the uniform distribution of recycled aggregates within the concrete matrix at this replacement level, forming a well-graded combination with natural aggregates. Furthermore, strict gradation optimization of the recycled aggregates effectively ensured the compactness of the internal concrete structure, allowing its mechanical properties to be maintained.

However, when the recycled aggregate content exceeds the critical threshold of 25 %, the compressive strength begins to show a significant declining trend. The fundamental reason for this phenomenon lies in the performance disparity between the old cement mortar adhered to the surface of the recycled aggregates and the fresh cement paste. This disparity causes the interfacial transition zone (ITZ) between the two to become a mechanical weak link. As the recycled aggregate content increases, these weak interfaces interconnect and form continuous paths within the concrete, significantly compromising the structural integrity of the material. Under external compressive load, stress tends to concentrate in these weak areas, initiating and propagating micro-cracks, ultimately leading to premature failure of the material, which macroscopically manifests as a significant reduction in compressive strength.

2.1.2 Tensile Strength

The influence pattern of recycled aggregate content on the tensile strength of concrete under the mix proportion with a cement content of 250 kg/m³ is shown in Figure 4. Research indicates a clear negative correlation between the tensile strength of concrete and the recycled aggregate content. As the proportion of recycled aggregates in the concrete increases, the tensile performance of the material shows a systematic decline.

This strength degradation primarily stems from the structural defects in the interfacial transition zone between the recycled aggregates and the new cement paste. Compared to natural aggregates, the old cement mortar attached to the surface of recycled aggregates creates a more complex multiple interfacial structure with the fresh cement paste. When subjected to tensile stress, these interfacial transition zones, due to their lower bond strength and higher number of micro-crack defects, become areas of stress concentration and are highly prone to initiating cracks.

As the recycled aggregate content increases, the number of weak interfaces within the concrete correspondingly rises, forming denser potential failure paths. This makes it easier for micro-cracks to propagate and interconnect under load, ultimately accelerating the tensile failure process of the material, which macroscopically manifests as a significant reduction in tensile strength. This mechanism fully illustrates the importance of controlling the recycled aggregate content to ensure the tensile performance of concrete.

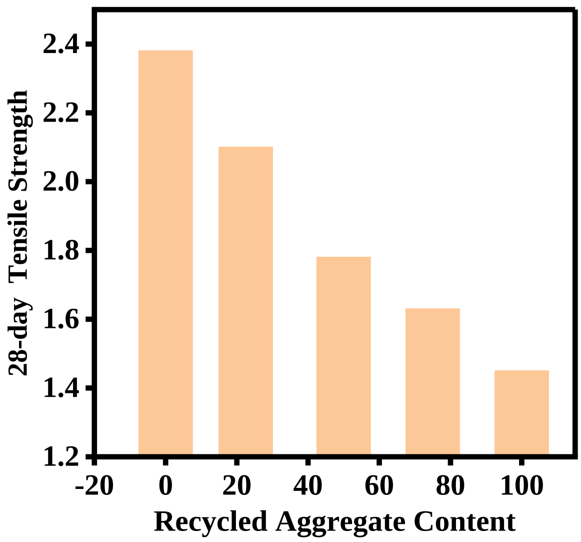

Figure 4 – Effect of different recycled aggregate content on tensile strength of concrete

2.1.3 Bond Strength

Figure 5 illustrates the influence of recycled aggregate content on the bond strength of concrete under the mix proportion with a cement content of 400 kg/m³. The experimental results indicate that the bond performance between concrete and steel reinforcement is highly sensitive to changes in recycled aggregate content, showing a significant negative correlation. As the proportion of recycled aggregates increases, the bond strength demonstrates a systematic declining trend.

This phenomenon is primarily attributed to the adverse effects of the unique surface characteristics of recycled aggregates on the interaction at the interface with the steel reinforcement. The old cement mortar coating the surface of recycled aggregates not only reduces the mechanical properties of the aggregates themselves but also alters the structural characteristics of the steel-concrete interface at the micro-level. The presence of the old mortar layer weakens the mechanical interlock between the concrete and the steel bar surface, while simultaneously reducing the chemical adhesion at their interface. This leads to a significant reduction in the bond between the steel bar and the concrete.

This degradation of interfacial performance accumulates with increasing recycled aggregate content, ultimately significantly affecting the composite action of reinforced concrete. Test data indicate that when the recycled aggregate content reaches 100 %, the bond strength of the concrete decreases by approximately 20 % compared to the reference group without recycled aggregates. This quantitative result fully confirms the significant impact of recycled aggregates on the interfacial performance of reinforced concrete and provides an important reference for rationally controlling the recycled aggregate content in engineering applications. The research findings offer positive guidance for promoting the application of recycled concrete in structural engineering.

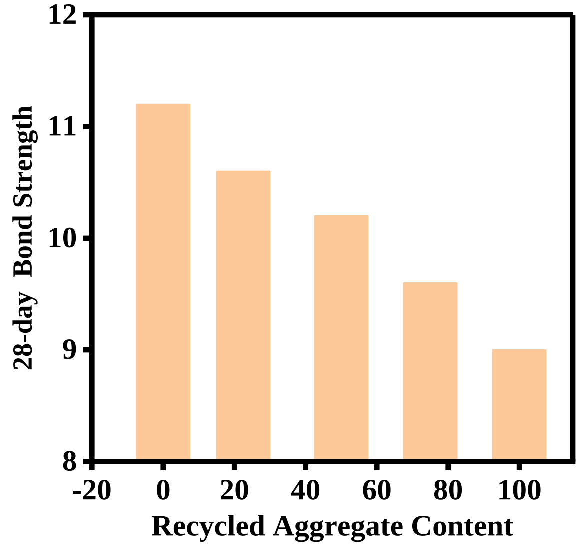

Figure 5 – Bond strength of concrete with different recycled aggregate content

2.2 Influence of Silica Fume Addition

2.2.1 Compressive Strength

Figure 6 presents the influence of silica fume content on the compressive strength of concrete. Under the reference mix conditions with a fixed cement content of 250 kg/m³ and a water-cement ratio of 0,60, the incorporation of 10 % silica fume produced a significant enhancing effect on the concrete's compressive strength.

This notable strength improvement is primarily attributed to the dual improvement mechanisms exerted by silica fume in the concrete. Firstly, silica fume, characterized by its extremely fine particle size (average particle size approximately 0,1–0,2 μm), effectively fills the microscopic pores between cement particles and the defects in the aggregate-paste interface transition zone. This significantly refines the microscopic pore structure of the concrete and increases the material's density.

Secondly, silica fume is rich in amorphous silicon dioxide, possessing excellent pozzolanic activity. It can undergo a secondary hydration reaction with calcium hydroxide, a product of cement hydration, generating additional calcium silicate hydrate (C-S-H) gel with cementitious properties. These newly formed gel products not only further fill capillary pores but, more importantly, strengthen the interfacial transition zone between the cement paste matrix and the aggregates, forming a more stable three-dimensional spatial network structure. This ultimately leads to a significant increase in the macroscopic compressive strength of the concrete.

It is noteworthy that the improvement effect of silica fume is more pronounced in concrete with high recycled aggregate content. This is mainly because it effectively compensates for the weak interfaces caused by the old mortar layer on the surface of recycled aggregates, achieving targeted reinforcement of the shortcomings inherent in recycled concrete.

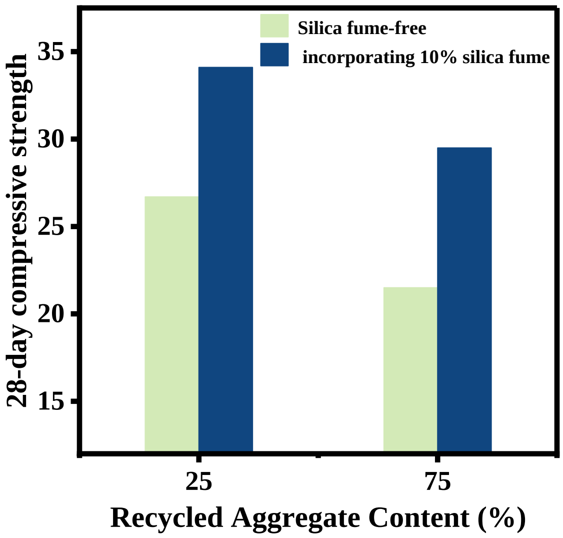

Figure 6 – Effect of silica fume content on the compressive strength of concrete

2.2.2 Tensile Strength

Figure 7 details the influence of silica fume content on the tensile strength of concrete. Research indicates that, under the mix proportion with a fixed cement content of 250 kg/m³, incorporating 10 % silica fume significantly improves the tensile performance of recycled aggregate concrete.

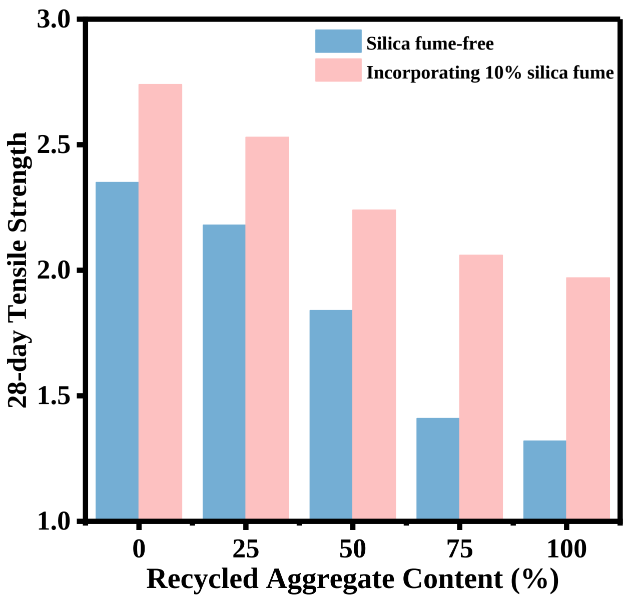

Figure 7 – Improvement in concrete tensile strength with silica fume addition

This notable performance enhancement primarily stems from the multiple optimizing effects of silica fume on the concrete's microstructure. On one hand, due to its ultra-fine particle characteristics (particle size ~0,1–0,2 μm), silica fume effectively fills the micro-pores within the cement paste and the structural defects in the aggregate-paste interface zone, significantly reducing stress concentration inside the material. On the other hand, the amorphous silicon dioxide abundant in silica fume undergoes a pozzolanic reaction with calcium hydroxide, a product of cement hydration, generating calcium silicate hydrate gel with cementitious properties. These newly formed gel products not only enhance the density of the cement matrix but, more importantly, strengthen the interfacial bonding performance between the aggregates and the cement paste.

Through this dual mechanism of microstructural improvement, the concrete exhibits enhanced crack resistance when subjected to tensile stress: the initiation of micro-cracks is suppressed, and the propagation paths of existing cracks are obstructed by a denser gel network, thereby significantly increasing the material's macroscopic tensile strength. It is particularly noteworthy that the improvement effect of silica fume is especially pronounced in concrete with high recycled aggregate content. This is mainly because it effectively compensates for the weak interfaces caused by the old mortar layer on the surface of the recycled aggregates, achieving targeted reinforcement of the material's inherent deficiencies.

2.2.3 Bond Strength

Experimental research indicates that incorporating 10 % silica fume significantly improves the 28-day bond strength of recycled aggregate concrete. This performance enhancement is primarily attributed to the positive role of silica fume in the concrete's microstructure. The active silicon dioxide component abundant in silica fume undergoes a pozzolanic reaction with calcium hydroxide, a product of cement hydration, generating calcium silicate hydrate gel with cementitious properties. These newly formed gel products effectively fill the micro-pores and defects at the interface between the steel reinforcement and the concrete, significantly improving the compactness of the interface zone.

Concurrently, the micro-filling effect of silica fume optimizes the microstructure of the interfacial transition zone, enhancing the concrete's ability to encapsulate the steel bar surface, thereby increasing both the mechanical interlock and the chemical adhesion between the two.

It is noteworthy that the improvement effect of silica fume on bond strength diminishes as the recycled aggregate content increases. This is mainly because a higher recycled aggregate content introduces more initial interfacial defects. Although silica fume effectively improves the interfacial properties, it struggles to fully compensate for the inherent strength loss caused by the old mortar layer on the surface of the recycled aggregates. This phenomenon suggests that silica fume is more suitable for use as an enhancing material in concrete with moderate recycled aggregate content.

Conclusion

This study systematically investigated the effects of recycled aggregate content and silica fume addition on the key mechanical properties of recycled aggregate concrete, including compressive strength, tensile strength, and bond strength. The main conclusions are as follows:

1) the recycled aggregate content is a critical factor influencing the mechanical properties of concrete. Experiments demonstrated that when the recycled aggregate content is limited to within 25 %, the compressive strength shows no significant difference compared to the reference group. However, once the content exceeds this critical threshold, the compressive strength exhibits a clear declining trend;

2) under the mix proportion with a cement content of 250 kg/m³ and a water-to-cement ratio of 0,60, incorporating 10 % silica fume significantly enhances the overall mechanical properties of recycled aggregate concrete. Micro-mechanism analysis reveals that silica fume, through the physical filling effect of its ultra-fine particles and the pozzolanic reaction of its active SiO_2 component, effectively refines the pore structure of the cement matrix and strengthens the bond at the aggregate-paste interface. This consequently leads to notable improvements in the concrete's compressive strength, tensile strength, and bond strength with steel reinforcement;

3) based on the experimental findings, a graded utilization strategy is recommended for practical engineering applications: For structural components with high strength requirements, the recycled aggregate content should be controlled within 25 %. For non-load-bearing elements or applications with lower strength demands, the recycled aggregate content can be appropriately increased, but it should be accompanied by the simultaneous addition of a suitable amount of silica fume (recommended around 10 %) to compensate for the associated strength loss. This technical pathway of "content control + performance enhancement" can provide reliable assurance for the engineering application of recycled aggregate concrete, thereby promoting the sustainable development of construction resource.

References

1. Study on flexural fatigue performance of recycled aggregate concrete / You Fan, Nian Mengfei, Zheng Jianlan, Luo Surong // Journal of Building Structures. – 2022. – Vol. 43 (4). – P. 134–141. – DOI: 10.14006/j.jzjgxb.2020.0728.
2. Orthogonal Experiment and Numerical Simulation of Influencing Factors on Compressive StrerRecycled Aggregate Concrete / Z. Xiaofei, J. Xionghao, L. Yu-ting, D. Hongyan // Water Resources and Power. – 2025. – Vol. 43 (1). – P. 93–98. – URL: https://qikan.cqvip.com/Qikan/Article/Detail?id=7200138928 (date of access: 11.11.2025).
3. Economic Study on Recycled Coarse Aggregate Concrete Structure / L. Jiawei, G. Xuyao, L. Ruming [et al.] // Construction Economy. – 2023. – Vol. 44 (S2). – P. 469–472. – URL: https://qikan.cqvip.com/Qikan/Article/Detail?id=7111325258 (date of access: 11.11.2025).
4. Chengfang, Y. Mechanical Properties of Nano-silica Sol Modified Mixed Recycled Aggregate Concrete / Y. Chengfang, L. Haofei, G. Jiaxiang // Journal of Materials Science and Engineering. – 2022. – Vol. 40 (4). – P. 580–584. – DOI: 10.14136/j.cnki.issn1673-2812.2022.04.006.
5. Chao, C. Effect of Silica Fume on the Properties of Cement Paste with Alkali-free Accelerator / C. Chao, S. Zhenping // Materials Reports. – 2019. – Vol. 33 (14). – P. 2348–2353. – DOI: 10.11896/cldb.18040280.
6. Xinxing, Z. Effect of silica fume on flexural and compressive strength of cement mortar / Z. Xinxing, H. Huimin // Engineering and Construction. – 2021. – Vol. 35 (3). – P. 598–599. – URL: https://qikan.cqvip.com/Qikan/Article/Detail?id=7105138361 (date of access: 11.11.2025).
7. Microstructural Investigation of Silica Fume Modified Cement/Lime Mortar / L. Jianquan, X. Hongsheng, T. Hongbo, L. Guozhong // Bulletin of the Chinese Ceramic Society. – 2006. – Vol. (4). – P. 66–71. – URL: https://d.wanfangdata.com.cn/periodical/ChVQZXJpb2RpY2FsQ0hJMjAyNTA2MjISDmdzeXRiMjAwNjA0MDE2GghpMzlINmd6ZQ== (date of access: 11.11.2025).
8. Wenwu, Y. Frost resistance and chloride ion diffusion of silicalfume concrete in a marine environment / Y. Wenwu, Q. Jueshi, H. Yubin // Journal of Chongqing University. – 2009. – Vol. 32 (2). – P. 158–162. – URL: http://qks.cqu.edu.cn/cqdxzren/article/abstract/20090209 (date of access: 11.11.2025).
9. Effects of silica fume on compressive strength and impermeability of cement mortar with alkali-free accelerator under low temperature environment / Liu Yawei, Hu Yang, Luo Qi [et al.] // Bulletin of the Chinese Ceramic Society. – 2024. – Vol. 43 (9). – P. 3273–3281. – URL: http://gsytb.jtxb.cn/CN/Y2024/V43/I9/3273 (date of access: 11.11.2025).
10. Sua-iam, G. Characteristics of non-steady-state chloride migration of self-compacting concrete containing recycled concrete aggregate made of fly ash and silica fume / G. Sua-iam, N. Makul // Case Studies in Construction Materials. – 2024. – Vol. 20. – DOI: 10.1016/j.cscm.2024.e02877.
11. Somwanshi, R. B. Review on carbonation concrete for GGBS & SF by Taguchi method / R. B. Somwanshi, A. R. Nardey, P A. Gadge // Innovative Infrastructure Solutions. – 2025. – Vol. 10. – DOI: 10.1007/s41062-025-02250-0.
12. Najaf, E. Using recycled concrete powder, waste glass powder, and plastic powder to improve the mechanical properties of compacted concrete: cement elimination approach / E. Najaf, H. Abbasi // Advances in Civil Engineering. – 2022. – DOI: 10.1155/2022/9481466.
13. Hamada, H. M. Enhancing sustainability in concrete construction: a comprehensive review of plastic waste as an aggregate material / H. M. Hamada, A. Al-Attar, S. Beddu // Sustainable Materials and Technologies. – 2024. – Vol. 40. – DOI: 10.1016/j.susmat.2024.e00877.
14. Danish, A. Impact of nano-silica on the mechanical properties of mortar containing e-waste plastic as fine aggregates / A. Danish, T. Ozbakkaloglu // Materials Today: Proceedings. – 2023. – DOI: 10.1016/j.matpr.2023.03.182.
15. Alhajiri, A. M. Enhancing sustainability and economics of concrete production through silica fume: a systematic review / A. M. Alhajiri, M. N. Akhtar // Civil Engineering Journal. – 2023. – Vol. 9 (10). – P. 2612–2629. – DOI: 10.28991/CEJ-2023-09-10-017.
16. Waqas, R. M. Behavior of quarry rock dust, fly ash and slag based geopolymer concrete columns reinforced with steel fibers under eccentric loading / R. M. Waqas, F. Butt // Applied Sciences. – 2021. – Vol. 11 (15). – DOI: 10.3390/app11156740.
17. Combined effect of silica fume and various fibers on fresh and hardened properties of concrete incorporating HDPE aggregates / S. Nasir Abbas, I. Qureshi, M. K. Alkharisi [et al.] // Construction and Building Materials. – 2024. – Vol. 445. – DOI: 10.1016/j.conbuildmat.2024.137940.
18. Effect of steel fibres on the compressive and flexural strength of concrete / A. Ahmed Jhatial, S. Sohu, N.-ul-K. Bhatti [et al.] // International Journal of Advanced and applied sciences. – 2018. – Vol. 5 (10). – P. 16–21. – DOI: 10.21833/ijaas.2018.10.003.
19. Handong, Y. The effect of silica fume and steel fiber on the dynamic mechanical performance of high-strength concrete / Y. Handong, W. Sun, H. Chen // Cement and Concrete Research. – 1999. – Vol. 29 (3). – P. 423–426. – DOI: 10.1016/s0008-8846(98)00235-x.
20. Development of high strength recycled aggregate concrete-composite effects of fly ash, silica fume and rice husk ash as pozzolans / A. Fernando, S. S C P H Gowsijan, K. Selvaranjan, K. Gamage // Materials and Structures. – 2022. – Vol. 55. – P. 185. – DOI: 10.1617/s11527-022-02026-3.
21. Mechanical and GWP assessment of concrete using blast furnace slag, silica fume and recycled aggregate / R. Shamass, O. Rispoli, V. Limbachiya, R. Kovacs // Case Studies in Construction Materials. – 2023. – Vol. 18. – DOI: 10.1016/j.cscm.2023.e02164.
22. Nasir, A. Enhanced mechanical and axial resilience of recycled plastic aggregate concrete reinforced with silica fume and fibers / A. Nasir, F. Butt, F. Ahmad // Innovative Infrastructure Solutions. – 2025. – Vol. 10. – DOI: 10.1007/s41062-024-01803-z.

Material received 21.11.2025, approved 25.11.2025, accepted for publication 26.11.2025