

Review

Research Progress of Concrete Preparation Based on Solid Waste Properties of Coal Gangue

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Abstract: Coal gangue (CG) is one of the most frequent solid wastes in the world, and it poses a severe hazard to both human society and natural ecosystems. In light of the progressive increase in environmental awareness and the unavoidable trend of the requirements of a sustainable development plan, how to efficiently use these vast quantities of CG has become an important subject in China. Concrete aggregate, which can not only solve environmental pollution but also compensate for the scarcity of natural gravel and sand resources, is the most cost-effective and eco-friendly way to utilize CG resources in accordance with the strategic requirements of green and sustainable development. However, how to deal with the preparation of high-quality gangue aggregate needs to be targeted research; blindly using gangue for concrete may bring some safety hazards. This requires that based on the source, distribution, storage, chemical composition, mineral composition of the gangue and the problems in the utilization process, efforts are made to open up the key routes of gangue concrete utilization, and to provide theoretical guidance for the high-value and environmentally friendly utilization of the CG. This paper summarizes the CG aggregate characteristics and its impact on concrete performance, discusses the technical means to improve the performance of CG aggregate concrete, and analyzes if the current CG aggregate in the concrete application of the problem still exists, with a view to gradually realize the CG of low-energy consumption bulk utilization. The popularization and application of CG aggregate will accelerate the solution of the environmental pollution problem it brings, and can to a certain extent alleviate the current situation in that the supply of natural sand and gravel resources is insufficient to meet the demand; the sustainable development of today's research on CG aggregate for concrete has important environmental and economic significance.

Keywords: coal gangue; aggregate; concrete; bulk utilization

Academic Editor: Ray Kai Leung Su

Received: 12 November 2024

Revised: 31 December 2024

Accepted: 31 January 2025

Published: 26 February 2025

Citation: Cheng, L.; Zhao, L.; Cheng, L.; Gao, Y.; Guo, H.; Che, Y.; Fu, H.

Research Progress of Concrete Preparation Based on Solid Waste Properties of Coal Gangue.

Sustainability **2025**, *17*, 2007.<https://doi.org/10.3390/su17052007>**Copyright:** © 2025 by the authors.

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1. Introduction

Coal gangue (CG) is not only the main tailings of coal mining and processing but also one of the most commonly occurring solid wastes in the world, accounting for around 10 to 25% of the total coal production [1–3]. Currently, China is the biggest producer of coal, with production reaching 4 to 5 billion tons and growing at a rate equal to 150 to 200 million tons per annum [4,5]. This is despite the fact that coal output in the rest of the globe, save for the Asia-Pacific area, has been decreasing since 2019 (due to the development of numerous new energy sources and renewable fuels) [5,6]. However, China, as the world's largest producer

and user of coal [7], accounts for almost half of worldwide coal usage [8]. The annual output of CG ranges between 300 and 350 million tons [3,9], and China has accumulated a large amount of CG reserves of over 2600 large mountains [10], with cumulative reserves reaching 7 billion tons and an annual growth rate of 150 million tons, making it one of the largest industries [11,12]. Figure 1 shows the specifics.

Large quantities of CG endanger human society and natural ecosystems. CG is typically disposed of in open piles, requiring significant land resources and containing heavy metals (HMs) like Cu^{2+} , Pb^{2+} , and Zn^{2+} . Prolonged weathering and leaching can cause soil and water pollution, threatening ecosystems and human health [13–16]. Furthermore, the unburned coal, oxygen, and pyrite in the gangue can readily cause spontaneous combustion, emitting hazardous gases such as SO_2 , CO, and NO_x that are difficult to manage. China's energy consumption structure is dominated by coal, despite its higher environmental impact compared to other energy sources [17–19]. As a result, the resource exploitation of CG is vital.

CG long-term storage circumstances, when the internal temperature reaches a particular value, will most likely result in spontaneous combustion; therefore, it is frequently split into original gangue and the spontaneous combustion of CG. The original gangue appears predominantly black or gray-black, with a surface heavily adherent to coal slime and fine gangue particles [20]. The carbon content of spontaneous combustion gangue is low, the porosity is relatively high, and the accumulation density ranges between 900 kg/m^3 and 1300 kg/m^3 . Additionally, spontaneous combustion CG has a certain volcanic ash activity, its surface layer is predominantly ceramic red or ceramic yellow, and the internal carbon combustion is insufficient in the black heart. CG has low density, high porosity, and strong water absorption, making it a viable resource with high plasticity [21–24]. Figure 2 shows the details.

Given the gradual increase in environmental awareness in various mining and industrial industries, as well as the unavoidable trend of the requirements of the sustainable development strategy, the utilization rate of CG in developed regions such as the United States and Europe is higher than 90%; however, China, as a major coal producer, only accounts for around 60% of the overall annual utilization of CG [25]. Appropriately using these vast amounts of CG has been a major concern in China. It must be based on the gangue's source, distribution, storage, chemical composition, mineral composition, and problems encountered during the utilization process, with a focus on the key routes of gangue concrete utilization, the establishment of an HM risk control system in the utilization of gangue resources, and theoretical guidelines for the high-value environmentally friendly usage of CG.

Concrete is the most common building material, with aggregates accounting for around 70% to 80% of its volume [26]. The global yearly use of concrete is almost 17.5 billion tons, while the annual consumption of aggregates surpasses 13 billion tons [27]. Among these, China's average yearly use of concrete exceeds 436 million tons, while aggregates reach 349 million tons [28]. In terms of production, due to the scarcity of natural aggregates in many countries, as well as the large-scale mining of natural aggregates, which has put a strain on the ecological environment, the solution to the supply of aggregate resources has become a hotspot for concrete research at the moment [23]. As a result, given the fast expansion of the construction sector and the constant increase in the amount of concrete produced, an environmentally benign material to replace natural gravel and sand in concrete is urgently required. Researchers have explored the use of recycled concrete, industrial wastes, and tailings as aggregates in concrete [29–35]. Among them, gangue has qualities comparable to natural gravel, is cheap, extensively dispersed, and decreases pollution, making it one of the most promising solid wastes for use in the building sector.

Gangue concrete is a specific type of concrete made by combining CG as the primary component with cement, sand, water, and other elements. The use of CG as coarse aggregate in the mass production of gangue concrete offers an excellent solution to the coal disposal issue. However, the application of gangue concrete is faced with many challenges that must be addressed, including poor compressive strength (20~30 Mpa) and splitting tensile strength (1.4~2.0 Mpa) [1,2,4,11].

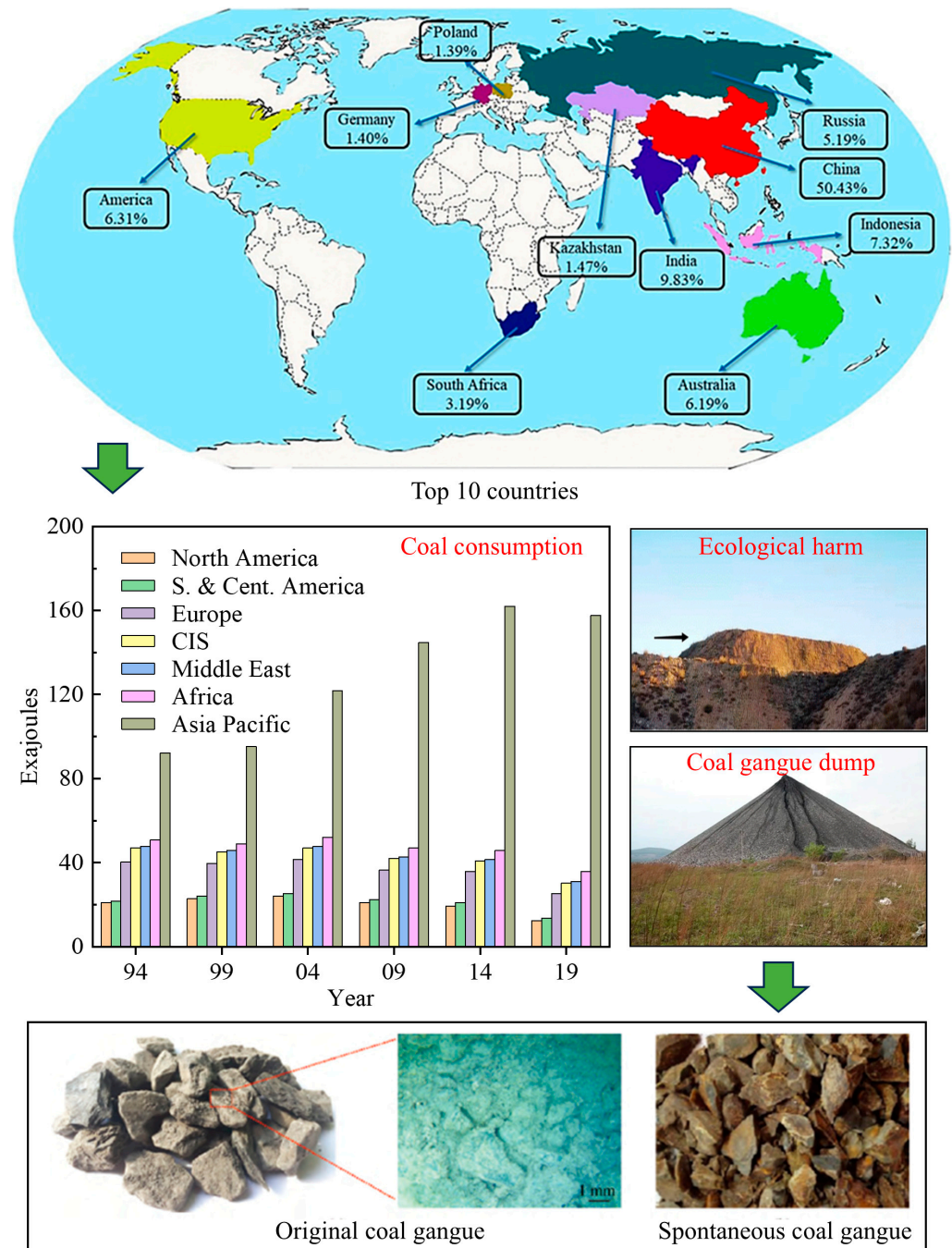


Figure 1. Comprehensive utilization of CG [24].

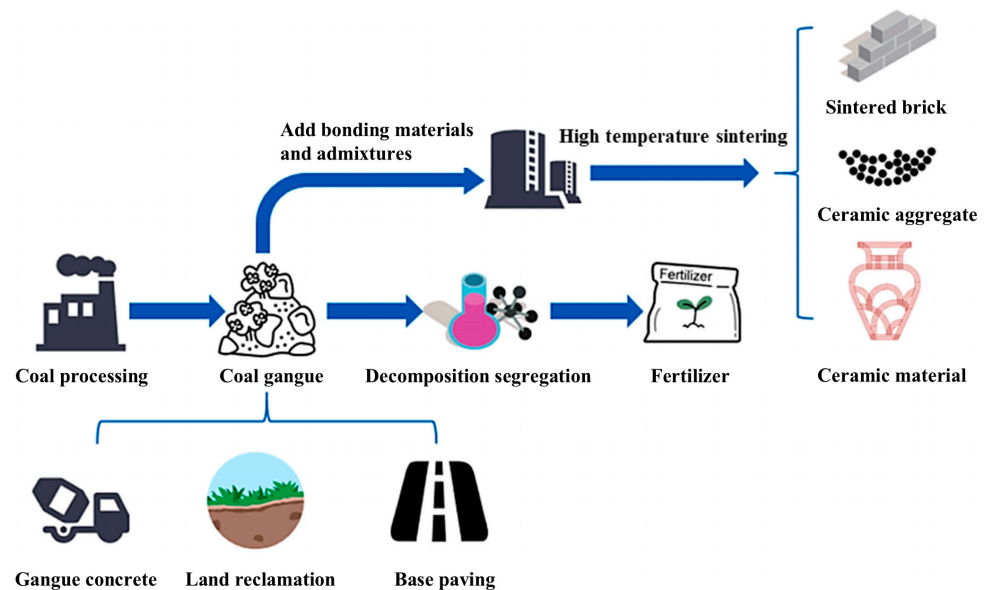


Figure 2. The top 10 coal-producing countries in the world [6], global coal consumption by region [5,6], ecological harm caused by coal mining [10], and types of CG [20,23].

Scholars have investigated the fundamental features and resource exploitation of CG, concluding that it is suitable for CG resources [36–44]. They believe that the physicochemical properties of CG differ significantly across regions and that it is necessary to categorize and analyze the mineralogical composition and physicochemical characteristics of CG before choosing appropriate methods of treatment and utilization [45]. The use of calcined gangue aggregate in cementitious materials has higher flexural and compressive strengths than natural gangue aggregate, implying that the combustible phase in the gangue has a substantial impact on its characteristics [46]. Activated CG is a cementitious material that enhances the dewatering of cement mixtures, and understanding the variables controlling the characteristics of gangue aggregates is critical for their use [47]. There is a growing number of studies on improving the physicochemical characteristics and efficacy of gangue aggregates [48–50]. In addition, the durability and mechanical qualities of gangue aggregate concrete have been extensively researched. Li et al. [51], Gao et al. [52], Xiao et al. [53], Zhang et al. [54], and Qiu et al. [55] studied the impact of aggregate replacement rate on the mechanical characteristics of gangue concrete and developed relevant mechanical prediction models. Zhao et al. [56], Zhang et al. [57], and Wang et al. [58] provided prediction models for the shrinkage and stress–strain properties of gangue concrete while researching the shrinkage and elastic modulus of non-combusted and self-combusted gangue aggregate concrete. Dong et al. [59] looked into how gangue fine aggregate influences mortar strength and provided a strategy to enhance fine aggregate activity as a foundation for gangue fine aggregate concrete design. The effects of maximum particle size and gangue aggregate replacement rate on shotcrete slump and mechanical characteristics were studied by Xiao et al. [60] to establish the theoretical foundation of gangue as a shotcrete aggregate. Cong et al. [61] employed an orthogonal test approach to investigate the development process and mechanical properties of autoclaved aerated gangue concrete and discovered the ideal proportion and appropriate amount of CG, respectively. They also investigated the mechanical properties of alkali-stimulated gangue concrete, which used CG as an auxiliary cementitious material and aggregate. Zhu et al. [62], Wang et al. [58], Liu et al. [63], and Wang et al. [64] proposed values for the optimal fineness and CG replacement rate for this form of concrete based on the proof that CG may be employed as an alkali-excited concrete material. These studies highlight the importance of analyzing gangue’s mineralogical

composition, analyzing its combustible components, and analyzing the factors influencing its properties for better utilization in concrete projects [65–69].

Since the 1950s and 1960s, China has been pursuing comprehensive CG use. CG is mostly utilized in power generation, brick production, landfill, road construction, and the chemical sector, but its utilization rate remains low, at around 60% each year. CG includes more silica-aluminum minerals, with the clay mineral kaolinite dehydroxylating into active metakaolinite after calcination, resulting in more gangue being calcined and pulverized for use as a cement mixing ingredient and concrete additive. However, the energy consumption of calcined and ground gangue is high, and the energy consumption and activity fluctuation of calcined gangue active powder material is the primary impediment to its efficient manufacturing. And using CG as concrete aggregate provides both economic and environmental benefits while also compensating for a shortage of natural aggregate resources. The study and exploitation of CG aggregate is primarily divided into two ways: (1) the gangue is crushed, screened, or heat-treated and utilized as ordinary concrete aggregate. (2) The CG is burnt to produce lightweight aggregate ceramic granules. The two methods of preparing gangue aggregate have distinct characteristics: the first is easy and convenient, with low energy consumption; the second is the manufacture of lightweight ceramic particles, which are ideal for the construction of thermal insulation, sound insulation, and light-weight concrete. The physical and chemical qualities of gangue vary by area; thus, how to cope with the creation of high-quality gangue aggregates requires specialized study; using CG for concrete blindly may pose certain safety risks [23].

This paper summarizes the gangue aggregate characteristics and their impact on concrete performance, discusses technical means to enhance the efficacy of gangue aggregate concrete, and analyzes the current gangue aggregate in the concrete application of the problem that still exists, with the goal of gradually realizing gangue low-energy consumption bulk utilization. The popularization and application of CG aggregate will hasten the resolution of the environmental pollution problem it brings, and can, to some extent, alleviate the supply of natural sand and gravel resources exceeding the demand of the status quo; the sustainable development of today's research on gangue aggregate for concrete has important environmental and economic implications.

2. Physical and Chemical Characteristics of Coal Gangue

In terms of specific reports on the impact of CG characteristics on the physicochemical characteristics of gangue aggregate, related scholars have conducted a lot of work, but the overall generalization about the influence of CG physical properties, chemical properties, fractal characteristics, and other aspects of CG on the efficiency of gangue concrete has yet to be improved. This paper discusses chemical and physical mechanisms affecting CG performance and whether they can be utilized as aggregates for engineering applications. It also identifies the key factors influencing CG aggregate performance and provides theoretical support for selecting and making use of CG aggregate.

2.1. Physical Properties of CG

The practicality of gangue as a concrete aggregate is the focus of study in key coal-producing locations, and the physical attributes of gangue from various origins varies to varying degrees, as seen in Table 1.

Table 1. Fundamental physical characteristics of aggregates from various origins.

Samples (China)	Apparent Density (kg/m ³)	Packing Density (kg/m ³)	Void Fraction (%)	Water Absorption (%)	Crushing Value (%)	Porosity (%)	Ref.
Gravel (Jiaozuo)	2661	1467	45	0.6	11	0.55	[70]
CG (Lu'an)	2452	1364	44	3.3	16	1.32	[70]
RCGA (Jinan)	2595	1430	/	3.7	14.6	44.8	[71]
SCGA (Jinan)	2637	1380	/	4.6	18.3	47.6	[71]
Limestone (Jinan)	2860	1554	/	0.6	8.1	43.1	[71]
Natural sand (Fuxin)	2584	1576	/	1.5	15.2	39.0	[72]
Gangue sand (Fuxin)	2465	1196	/	11.4	22.8	51.4	[72]
SCGA (Taian)	2657	1478	42.6	4.87	9.94	/	[73]
SCGA (Taian)	2640	1457	43.1	4.61	10.14	/	[73]
NCA (Shenyang)	2705	/	/	1.35	4.5	/	[74]
SCGA (Shenyang)	2497	/	/	9.80	25.2	/	[74]

Li et al. [70] emphasized two aspects: (1) The total porosity of gangue and gravel is 1.32% and 0.55%, respectively. The pore size distribution of CG ranges from 0.40 to 100 μm , while that of gravel ranges from 6 to 100 μm . Gangue has a larger range of pore sizes than gravel. (2) A comprehensive investigation of apparent density, bulk density, pore ratio, water absorption, mud content, and firmness reveals that CG has a greater crushing value than gravel (16 > 11). Compared to gravel, gangue has weak mechanical qualities. At the same time, the gangue is mainly quartz (0.22, 18.37) GPa, calcite (0.76, 32.10) GPa, and kaolinite (5.27, 58.46) GPa, which makes the gangue in each phase of the mechanical properties of the difference obvious. The gravel's micromechanical properties (2.51, 80.98) GPa are continuous and stable, explaining why CG has a high crushing value. Wu et al. [71] developed permeable concrete with limestone as the natural aggregate and self-combusted and non-spontaneously combusted gangue as alternate aggregates. The three aggregates, with particle sizes ranging from 5 to 10 mm, have distinct physical characteristics, and this variation has a significant influence on concrete performance. In comparison to limestone natural aggregate, self-ignited coal gangue aggregate (SCGA) and raw coal gangue aggregate (RCGA) have lower apparent density, bulk density, and higher crushing value and porosity. It should also be mentioned that gangue aggregate has a six to eight times higher water absorption rate than limestone aggregate concrete, resulting in increased permeability. But because of the gangue's self-similar multistage pore structure, concrete's mechanical qualities are diminished. Furthermore, spontaneous combustion gangue possesses superior physical characteristics from the perspective of self-similarity pore structure improved water permeability. With a 20% to 30% carbon content and a tiny quantity of unclean coal mixed in, the gangue aggregate has a looser structure than regular gravel, more flaky particles and pores, and more performance swings. Although gangue aggregate appears

to have a density that is more similar to that of natural gravel, it is more porous, has a crushing value of 16% to 23%, and absorbs more water. Although calcination to remove carbon is one of the current effective measures to improve the performance of gangue aggregates, some studies have shown that calcination treatment of CG will increase the water absorption of its aggregates. The amount of carbon in CG has a greater impact on aggregate strength, water absorption, and crushing value.

Gangue fine aggregate particles are finer, angular, and more porous compared to natural sand, according to Zhang et al. [72], which suggests that gangue fine aggregate has better occlusion as a fine aggregate in concrete. However, self-strengthening is not facilitated by tiny fissures on the surface of gangue fine aggregate particles. In order to produce two single-size graded aggregates (10~15 mm and 15~20 mm), Wu et al. [73] crushed and screened SCGA. SCGAs have a porous structure, as evidenced by their cumulative porosity equal to 18.27% and mean pore size equaling 74.22 nm. The drying density of SCGA was determined to be 2497 kg/m³ in a study by Zhang et al. [74], which is 7.7% lower compared to that of natural aggregate concrete (NCA). After 24 h, SCGA absorbed substantially more water than NCA, with rates of 9.80% and 1.35%, respectively. It should be noted that water absorption of SCGA occurs mostly during the first hour, accounting for 87% of the 24 h total. Meanwhile, SCGA has worse mechanical qualities, with a crushing index 5.6 times lower compared to NCA. The changes in physical attributes between SCGA and NCA are mostly attributable to variations in aggregate microstructure.

2.2. Chemical Properties of CG

CG is a silica-aluminum material with the main chemical composition of Al₂O₃ and SiO₂, with a small quantity of Fe₂O₃, CaO, and other metal oxides, as well as carbonaceous material. The chemical content and distribution of gangue from different origins vary [75], as shown in Table 2. The oxide concentration of the gangue determines its classification as clay rock gangue (with Al₂O₃ ranging from 15 to 30% and SiO₂ in the range of 40–70%), sandstone gangue (SiO₂ > 70%), calcareous rock gangue (CaO > 30%), and aluminous rock gangue (Al₂O₃ > 40%) [76]. The gangue may be classified into three types: clay rock gangue (SiO₂ 40%~70%), sandstone gangue (SiO₂ > 70%), aluminum rock gangue (Al₂O₃ > 40%), and calcium rock gangue (CaO > 30%). CG is a mineral combination composed primarily of kaolinite, quartz, illite, feldspar, montmorillonite, calcite, and dolomite [77]. The gangue mineral composition is similarly modified by origin and other variables, although two minerals, quartz and kaolinite, are usually found. Calcination is a common method for improving the performance of gangue aggregate. After calcination, the carbonaceous and other weak components of the original gangue are reduced, and the kaolinite minerals in the gangue are dehydrated and decomposed at high temperatures [78], resulting in metakaolin with activity.

Table 2. Chemical compositions of aggregate from different origins.

Samples (China)	Loss	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	Na ₂ O	K ₂ O	SO ₃	TiO ₂	Ref.
RCGA (Jinan)	12.27	1.52	59.54	16.31	6.55	1.82	\	\	1.87	\	[71]
SCGA (Jinan)	8.81	1.12	58.77	22.56	4.89	1.53	\	\	1.61	\	[71]

Table 2. Cont.

Samples (China)	Loss	CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	MgO	Na ₂ O	K ₂ O	SO ₃	TiO ₂	Ref.
Limestone (Jinan)	39.85	51.92	5.31	1.43	0.38	0.87	\	\	1.08	\	[71]
Natural sand (Fuxin)	\	0.38	86.72	7.53	1.78	0.61	0.15	1.65	0.14	0.26	[72]
CG (Fuxin)	\	3.69	57.81	20.66	9.15	2.31	0.68	3.31	0.30	1.15	[72]
SCGA (Taian)	8.81	1.12	58.77	22.56	4.89	1.53	\	\	1.61	\	[73]
NCA (Shenyang)	\	8.34	46.82	15.79	15.75	6.90	1.80	2.72	\	\	[74]
SCGA (Shenyang)	\	0.53	59.32	25.28	4.50	2.00	1.70	4.66	\	\	[74]
River sand (Shanxi)	\	3.90	66.98	15.27	3.70	0.88	3.46	4.59	0.13	0.66	[79]
CG (Xishan)	20.50	0.39	42.70	24.01	3.41	0.21	0.16	0.51	4.65	3.23	[79]
CG (Lvliang)	13.00	0.66	51.72	29.93	0.97	0.35	0.18	1.37	0.70	0.94	[79]
CG (Changzhi)	7.00	3.12	54.33	22.60	6.24	0.84	0.73	2.57	0.13	1.85	[79]
CG (Xiqu)	12.00	0.36	52.09	28.29	1.88	0.34	0.09	1.24	0.17	3.25	[79]
CG (Chongqing)	\	7.53	39.08	20.49	14.72	1.21	0.89	1.24	10.87	2.89	[80]
CG (Guiyang)	\	3.42	47.08	21.68	16.84	1.92	1.04	1.93	\	4.71	[81]
Natural sand (Fuxin)	\	0.38	86.72	7.53	1.78	0.61	0.15	1.65	0.14	0.26	[82]
CG (Fuxin)	\	3.69	58.81	20.66	8.15	2.31	0.68	3.31	0.30	1.15	[82]
CG (Fuxin)	\	3.65	55.57	21.00	6.57	2.50	1.90	4.10	0.82	0.84	[83]
CG (Fenxi)	\	7.15	35.46	16.11	3.86	3.50	-	-	-	0.80	[84]
CG (Hegang)	\	3.5	64.7	17.0	4.5	0.4	0.8	6.4	0.2	1.0	[85]
River sand (Hegang)	\	4.2	71.7	13.8	1.4	0.5	3.4	4.3	0.3	0.2	[85]
Limestone (Hegang)	\	8.9	51.5	15.3	8.0	8.9	3.4	2.0	0.1	0.9	[85]

Wu et al. [71] discovered that the major physical phase of limestone natural aggregate in the manufacturing of permeable concrete is calcium carbonate (CaCO₃), whereas the main physical phases of gangue replacement aggregate are quartz (SiO₂) and metakaolin (Al₂Si₂O₅(OH)₄). The oxide concentration (59.54% and 58.77% SiO₂, 16.31% and 22.56% Al₂O₃) of these two varieties of self-combusted and non-self-combusted gangue falls under the category of clay gangue. The use of CG as a substitute for limestone natural aggregate may effectively boost the alkali reaction of concrete aggregate and improve

the water permeability performance of concrete due to the self-similarity pore structure silica-aluminum skeleton of gangue aggregate. Zhang et al. [72] revealed that the chemical composition of natural and veinstone fine aggregates is mostly SiO_2 and Al_2O_3 , whereas the primary mineral components of veinstone fine aggregates are quartz and feldspar, suggesting chemical stability. According to the physical and chemical qualities, CG can be used to replace natural fine aggregate in the making of concrete. Wu et al. [73] found that self-ignited coal gangue powder (SCGP) is mostly constituted of kaolin minerals rich in Al_2O_3 and SiO_2 and used prepared low-alkalinity cementitious materials as binders and SCGA as aggregates to generate an eco-concrete that is low-carbon, high-greenness, and plant-compatible. Zhang et al. [74] observed that SCGA included more Al_2O_3 and SiO_2 compared to NCA, which might explain its lower volcanic ash activity. SCGA has a lesser hardness than NCA because it contains less Fe_2O_3 and CaO . Ke et al. [79] discovered that the gangue of 0~1 mm in the four locations had the maximum calorific value in Xishan and Xiqu, and comparatively low in Lvliang and Changzhi, particularly in Changzhi. Xiqu gangue has a greater combustion loss of 12% because it is coking CG, resulting in the maximum heat release. Changzhi gangue has the lowest 7% combustion loss, suggesting the lowest carbon content. Wang et al. [80] determined that the primary components of CG include SiO_2 , Al_2O_3 , Fe_2O_3 , CaO , SO_3 , and so on, with the SiO_2 , Al_2O_3 , and Fe_2O_3 components accounting for 74.29% of the raw material and the CG raw material containing 0.039% carbon. When combined with the X-ray diffraction spectroscopy (XRD) patterns and compared to the ICSD and PDF cards, the strong XRD peaks of CG corresponded to the crystal planes of SiO_2 , demonstrating that square quartz was the primary mineral phase of CG. Additionally, there were certain XRD peaks of Al_2SiO_5 and Fe_2O_3 in CG, indicating that the mineralogical composition of CG comprises pyrite and kaolinite. Su et al. [81] determined that kaolinite and quartz were the primary sources of silica and alumina in CGP, accounting for 68.76 wt%. This implies that the oxide has possible volcanic ash activity. However, silicon oxide and alumina are difficult to engage in cement hydration processes, and their influence on concrete characteristics is poor. As a result, once these oxides are activated, coal gangue powder (CGP) will be an effective alternative for cement in concrete preparation.

Zhang et al. [82] discovered that the primary chemical compositions of fine aggregates of gangue sand (GS) and natural river sand (NS) are SiO_2 and Al_2O_3 . Except for SiO_2 , GS has more oxides than NS. However, GS passes the hazardous chemical standards for Class II sand. Both fine aggregates are composed primarily of quartz and feldspar, showing that GS characteristics are stable. Based on the chemical and mineralogical compositions, the GS in this study corresponds to the sandstone veinstone and may be used as a fine aggregate for structural concrete [83–85].

2.3. Fractal Characterization of Coal Gangue

Professor Mandelbrot [86] introduced the concept of fractal theory, which states that the surface roughness and inhomogeneity of pore structures can be quantitatively described using self-similarity (similarity between the local and the whole) and scale-independence (invariance of geometric transformations). The fractal dimension is described as the “measure of scale” that reflects the validity and irregularity of the space inhabited by a complex shape while also noting the change in measurements as they approach zero. Some researchers have used fractal theory to quantitatively explain particle distribution features.

According to Li et al. [87], the fractal dimension of crushed CG particles increased with axial force, ranging from 2.15647 to 2.58933. The permeability of crushed gangue follows the rule of graded distribution, with amplitudes ranging from 10~11 to 10~9 m^2 . The fractal dimension is inversely proportional to the permeability. Ye et al. [84] classified

gangue into eight grain sizes: <0.15, 0.15~0.30, 0.30~0.60, 0.60~1.18, 1.18~2.36, 2.36~5.00, 5.00~10.00, and 10.00~15.00 mm. The distribution mass percentage of gangue was then fitted using Equation (1), and five separate groups of aggregates ended up with particle size distribution fractal dimensions of 2.002, 2.199, 2.401, 2.600, and 2.802.

$$\lg \frac{M(\phi)}{M_0} \propto (3 - D) \lg \phi \quad (1)$$

It should be noted that fractal dimensions of 2.002, 2.199, 2.401, 2.6, and 2.802 correspond to mix slumps of 242, 244, 249, 244, and 242 mm, respectively. This indicates that the slump rises first as the fractal dimension increases. The excess paste theory states that the voids present between the coarse aggregates are filled with fine aggregates, the voids between the fine aggregates are filled by the paste, and the remaining paste is wrapped around the surface of the aggregates to form a lubricating layer that stabilizes the flow of the mixture [88]. In cemented gangue backfill material (CGBM) mixtures with a specific slurry content, increasing the mass fraction of fine aggregate resulted in a tighter degree of particle packing in the aggregate system as the fractal dimension of the aggregate particle size distribution increased from 2.002. As a result, the thickness of the slurry wrapped around the aggregate surface rises, widening the gap between the aggregate particles, increasing the fluidity of the CGBM and, to some extent, the slump.

However, the slump starts to reduce when the fractal dimension increases after it goes beyond a particular threshold (between 2.401 and 2.600). It is evident that the aggregate system's overall specific surface area and the solid particles' water requirement both rise with an increase in fine aggregate concentration [89]. As a result, more slurry is needed to encapsulate the aggregate surface for the same amount of water as the total specific surface area increases. This lessens the surplus slurry's thickness, which lessens the CGBM mixture's slump. For fractal dimensions of 2.002, 2.199, 2.401, 2.6, and 2.802, the static yield stresses were 221.2, 84.4, 78.1, 137.5, and 148.2 Pa, respectively. It was evident that the static yield stress of CGBM tended to reduce initially and subsequently grew at a slow rate as the fractal dimension of the aggregate increased. When the fractal dimension is more than 2.401, the increased specific surface area makes it easier to aggregate cement particles and their hydration products with the production of flocs or three-dimensional lattice structures. Consequently, flocculation between the fine particles rises in tandem with the overall amount of fine aggregate, increasing the CGBM's static yield stress. The observation that adding fine aggregate improves static yield stress was consistent with Ivanova and Mechtcherine's investigation [90–93]; fine sand particles may have physical–chemical interactions with the cement paste, resulting in enhanced structuration within concrete. As the fractal dimension increases, the density of the stacked gangue aggregate rises and ultimately falls. The pile compactness aggregate system of gangue reached its maximum value for pile fractal dimension equal to 2.6, and the water in the pores of CGBM was fully discharged. In this case, the plastic viscosity and yield stress of CGBM were the lowest, indicating that a proper particle size distribution of gangue aggregate can enhance CGBM efficacy. Figure 3 shows the details.

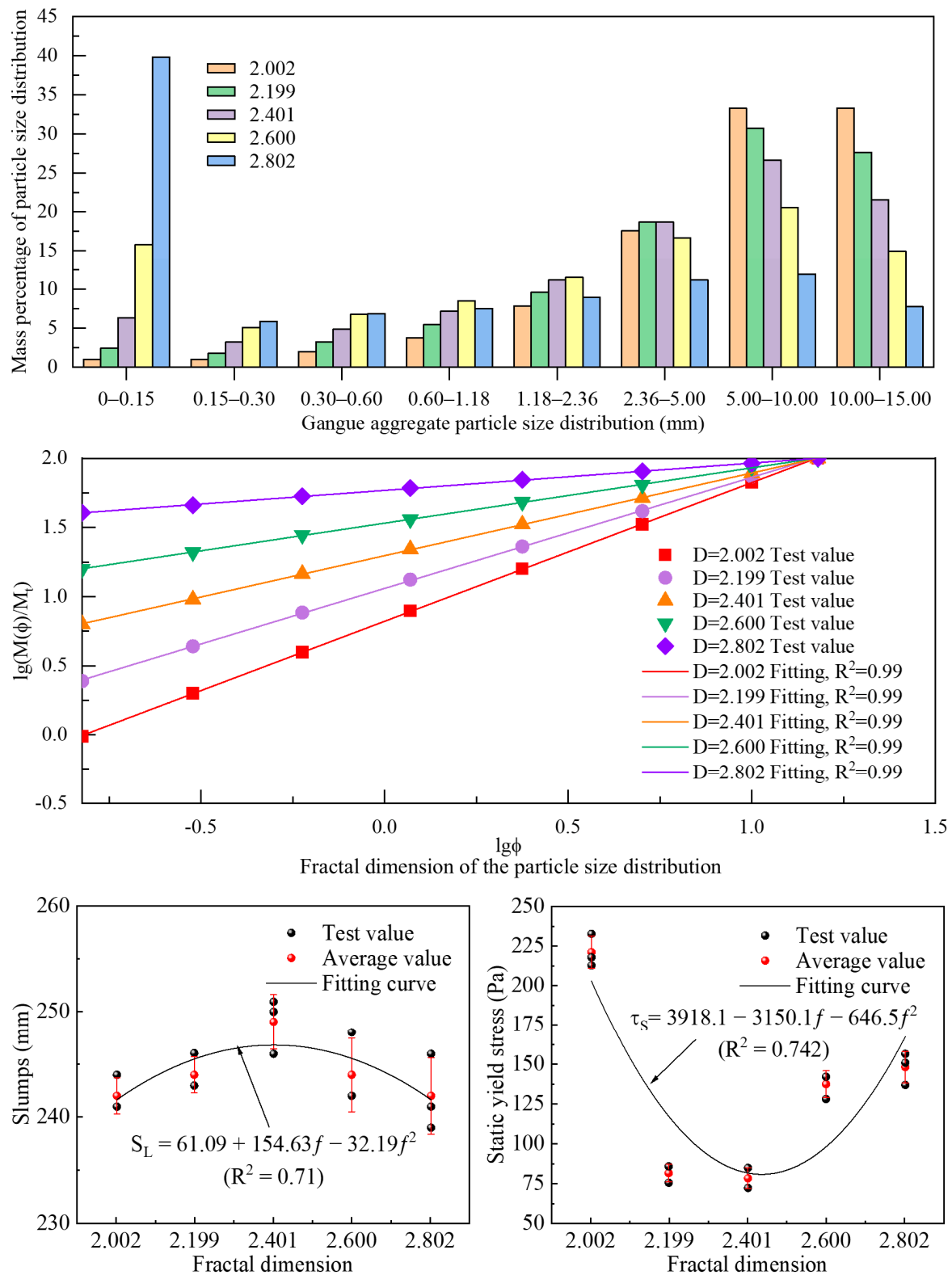


Figure 3. Distribution mass percentage of CG aggregate, fractal dimension of the particle size distribution of CG aggregate, relationship between slump and fractal dimensions, and relationship between static yield stress and fractal dimensions [84].

3. Preparation of CG Concrete

The most basic and energy-efficient use of CG is to crush and filter it for use as aggregate. The capacity of CG to be employed as an aggregate without treatment is

determined by its physicochemical qualities. Gangue characteristics vary widely in different places, and direct crushing must tightly manage the performance index of gangue in order to fulfill the concrete aggregate requirements.

Gangue used as aggregate may require a specific heat treatment. Heat treatment is primarily used to remove gangue from carbon and organic matter, minimize gangue aggregate in weak components, and address interface with cement matrix bonding difficulties. Furthermore, heat treatment can induce phase shift in minerals, create active chemicals to increase the surface activity of the CG aggregate, and improve interfacial interaction between the gangue aggregate and the cement matrix. Heat treatment gangue has two types: spontaneous combustion gangue and artificial calcined gangue: (1) spontaneous combustion gangue, which is a long-term accumulation of gangue internal temperature, rises to produce spontaneous combustion caused by uneven heating, combustion is insufficient, and the effect of carbon removal and activity enhancement is difficult to control. (2) The calcination temperature, holding duration, and stacking technique of artificially calcined gangue may be regulated and adjusted, resulting in more complete carbon removal and a more uniform activity augmentation [23].

Wu et al. [71] prepared gangue aggregate by a slurry wrapping pretreatment process. First, non-autogenous and autogenous gangue are crushed with a jaw crusher; next, the crushed material is filtered to a particle size range extending from 5–10 mm. Lastly, modified gangue aggregate is manufactured using a disc granulator and solid waste-based sulfoaluminate cement (WSAC). Wang et al. [80] crushed the undisturbed bulk CG first, then used a jaw crusher. The raw material is crushed and passed through a 0.15 mm square-hole screen. The resulting 0.15 mm gangue is then fed into a ball mill. The CG was pulverized for a specified amount of time before being put through a 0.075 mm square hole sieve to obtain a single mechanically activated CGP. The powdered CG powder was placed into a beaker containing water, vigorously mixed, and permitted to stand for 8 h. After electrostatic separation to obtain floats and sediments, the sediments and floats were dried inside an oven at 60 °C until they reached a consistent weight. A 30% substitution rate for the cement mortar strength test technique was used in accordance with ISO for the CG precipitates generated from the various treatment procedures. Wu et al. [1] inserted polypropylene fibers (PPF) into gangue concrete, and the integration of gangue at a 40% replacement rate greatly increased the uniaxial compressive strength of polypropylene fiber-reinforced gangue concrete (PGC) by up to 19.4%. Meanwhile, the advent of PPF has expanded the scope of PGC. When compared to PGC-40-0, PGC-40-0.2 had a 33.76% lower damage factor and a 19.42% lower residual strain. Finally, a PPF level of 0.2% was shown to be ideal for increasing PGC fatigue efficiency. Scanning electron microscopy (SEM) experiments revealed that polypropylene fibers improved the microscopic appearance of gangue concrete. Overall, the best preparation process parameters for gangue aggregate concrete may be established by comparing the mechanical strength, density, porosity, water permeability, frost resistance, and other features of concrete. Figure 4 shows the details.

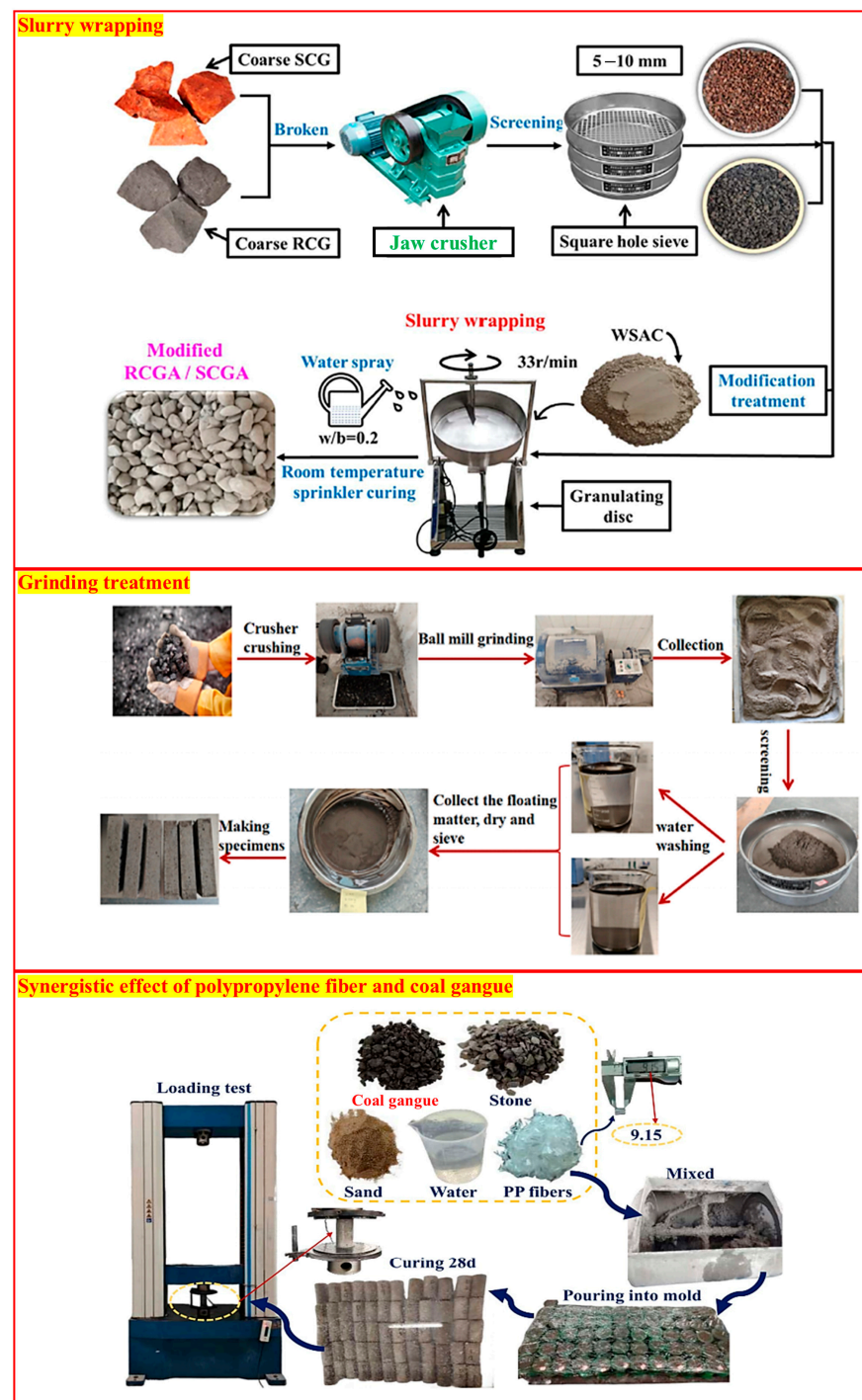


Figure 4. Slurry wrapping modification treatment of CGAs [71], process flow chart of CG treatment [80], concrete preparation process [1].

4. Properties of CG Concrete

CG aggregates have lesser strength and more water absorption than natural crushed stone, which limits their applicability. Analyzing the influence of CG aggregate on concrete characteristics and identifying solutions to enhance concrete qualities is a crucial step toward encouraging efficient, low-energy, large-scale industrial usage of gangue. This research examines three important features of the use of gangue concrete: (1) mechanical qualities, (2) durability, and (3) economic feasibility.

4.1. Mechanical Properties of CG Concrete

The CG aggregate's porosity is high, and the crushing process will result in more micro-cracks. As a result, CG aggregate exhibits a greater water absorption rate compared to natural crushed stone aggregate, and it absorbs more water in fresh concrete during mixing, affecting the mechanical characteristics of CG aggregate concrete significantly.

Wu et al. [71] discovered that the compressive strength of coal gangue pervious concrete (CGPC) at various hydration ages significantly decreased with increasing the CG substitution rate. When compared to natural aggregate (NA), CG is weaker, more porous, and absorbs more water [94]. Furthermore, when the CG content increases, the water binder ratio gradually increases, leading to a reduction in the compressive strength of CGPC. The compressive strength of CGPC comprising RCGA and SCGA was considerably greater than that of RCGA when the substitution rate of NA was 25%, 50%, 75%, and 100%, respectively, regardless of the NA substitution rate. Despite the 28 d compressive strength declining by 10.2% when SCGA totally replaced NA, all strength values above 25 MPa meet the standard's 20 MPa limit. Only when RCGA replaces NA by less than 50% can 28-day compressive strength be achieved. Furthermore, the compressive strengths of MS100 (mixtures prepared 100% with modified SCGA), MR100 (mixtures prepared 100% with modified RCGA), and S50R50 (mixtures prepared from 50% SCGA and 50% RCGA) were compared to SCG100 (mixtures prepared 100% with SCGA) and RCG100 (mixtures prepared 100% with RCGA). The compressive strength of S50R50 for 28 d was 22.3 MPa, which was actually lower compared to SCG100 but higher in comparison to RCG100. This implied that adding SCGA to CGPC improved the strength compared to the complete RCGA. MS100 and MR100 demonstrated 13.3% and 20.6% higher 28 d compressive strengths than RCG100 and SCG100. It illustrates that CG modified by dynamic encapsulation had a considerable impact on the compressive strength of CGPC. Furthermore, as the CG replacement rate increases, the density of CGPC decreases. The decrease in density follows a trend similar to that of compressive strength. When the replacement rate of CG was changed from 0 to 100, it can be observed that the density of the SCGA- and RCGA-based CGPC reduced from 2025 kg/m³ to 1840 and 1900 kg/m³, respectively (which is more lightweight than traditional concrete with a density value approximately equal to 2400 kg/m³). The distinction is that RCGA-based CGPC has consistently higher density than SCGA-based CGPC. This is because SCGA exhibits a wider pore size distribution and a greater median pore size compared to RCGA, resulting in lower density. In comparison to RCG100 and SCG100, the densities of MR100 and MS100 were found to be 4.1 and 4.8% higher, respectively. This is explained by the formation of a dense cementite "shell layer" structure on the outer surface of the modified CG, which impacts the density of the aggregates and, thus, the characteristics of the prepared CGPC. Overall, the compressive strength of both RCGA- and SCGA-based CGPCs rises linearly with density, indicating that density is a significant factor influencing CGPC compressive strength. It should be emphasized that while the aggregate gradation of the coal gangue aggregates (CGAs) was identical to that of the NA, the connected porosity and permeability of the CGPC enhanced to some amount as the replacement rate rose. The permeability coefficients of SCGA- and RCGA-based CGPC rose from 5.01 mm/s to 5.92 and 5.85 mm/s, respectively, as the replacement level was adjusted from 0 to 100. On the other hand, the connected porosity increased from 16.4% to 18.9 and 18%, respectively.

There might be two explanations for this phenomenon: (1) The particle morphology of CGAs is more angular and lamellar than that of NA, which may introduce more air into the mixture during mixing; (2) CGAs' unique surface porous structure and higher roughness relative to NA may trap more matrix slurry, influencing the thickness of the matrix encapsulation on the surface, and then the porosity and water permeability. Under

the identical CG substitution rate, SCGA-prepared CGPC had a bit higher connected porosity and permeability compared to RCGA-prepared CGPC, which could be attributed to the fact that SCGA's surface porosity and pore size are larger than those of RCGA, trapping more of the matrix slurry. It should be noted that the specifies permeability and porosity standards for pervious concrete (PC) of at least 0.5 mm/s and 15%, respectively. As a result, the CGPC produced with RCGA and SCGA clearly meets the requirements. Furthermore, as compared to SCG100 and RCG100, CGPC MS100 and MR100 had a 7.8% and 5.2% lower porosity and permeability, respectively. This is owing to the "shell layer" generated by the cladding modification of CGA, which thickens the slurry cladding on the aggregate surface. Under the condition, producing CGPC with the same aggregate–binder ratio results in increased matrix content, which influences porosity and water permeability. The permeability of PC usually rises as porosity increases; however, the amount of permeability is determined not just by pore volume, but also by pore distribution and connection. As a result, it is more relevant to investigate PC's connected porosity to demonstrate a relationship between it and water permeability. Whether based on SCGA or RCGA, the density and compressive strength of CGPC reduced as the level of NA substitution by CGAs increased. However, connected porosity and water permeability increased by some amount, owing to the lower density, lower strength, higher water absorption, and larger porosity of RCGA or SCGA. Despite the greater hydrogel ratio, the SCGA-based CGPC has a much higher compressive strength than the RCGA-based CGPC at an identical replacement level, owing to the stronger interfacial bonding strength between the matrix and SCGA. Furthermore, density and compressive strength have a high linear association, as does the connected porosity and permeability coefficient. Overall, the compressive strength of CGPC made from slurry-coated modified CGAs was substantially increased. Even though the density rose, while the permeability coefficient and associated porosity were somewhat reduced, all of the parameters were still far over the standard's bounds. Figure 5 shows the details.

Zhang et al. [74] determined that SCGA has low physical qualities but good water absorption capability. Most prior research used the equal mixing ratio concept, which resulted in a smaller slump for self-combusted gangue aggregate concrete (SCGAC) compared to natural aggregate concrete (NAC). The researchers achieved the compressive strength of SCGAC at various curing ages and quantified the effect of SCGA content on the compressive strength of concrete under the premise of similar concrete compatibility; the fine structure of SCGAC was visualized through SEM imaging to reveal the deterioration mechanism of SCGAC compressive properties; the proposed SCGAC compressive strength is based on five independent machine learning (ML) algorithms and three integrated ML algorithms. The results suggest that fresh concrete with varying SCGA replacement rates can display similar slump values (70–75 mm) by employing pre-preg SCGA and refining concrete proportions. SCGA performed poorly due to the poorer interfacial transition zone (ITZ) between SCGA and cement mortar, and the compressive strength of concrete with 100% replacement was lowered by 15.3%, 16.7%, 22.0%, and 21.6% at 7, 14, 28, and 90 days, respectively, when compared with NAC. The integrated ML model outperforms the stand-alone ML model in terms of predictive ability, with the XGB model performing best. Characteristic importance analysis using SHAP values indicated that SCGA density, SCGA water absorption, and aggregate cement ratio were the most important parameters influencing SCGAC compressive strength. Figure 6 shows the details.

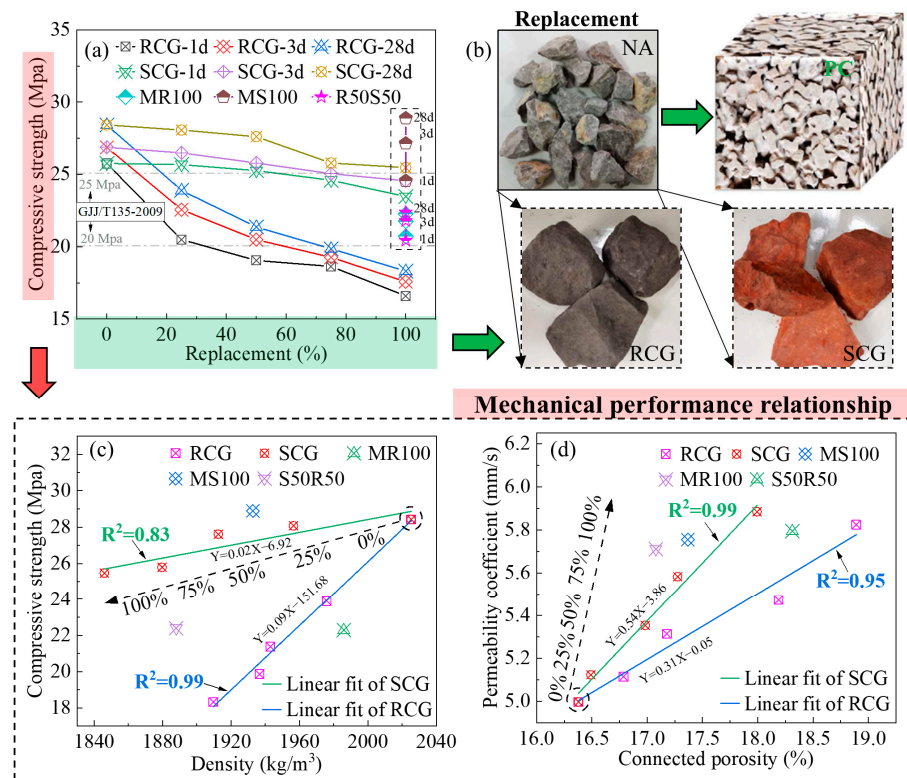


Figure 5. The impact of various substitution rates on the age strength of CG concrete (a), the schematic process of CG replacing natural aggregates (b), and the relationship between the mechanical characteristics of concrete (c,d) [71].

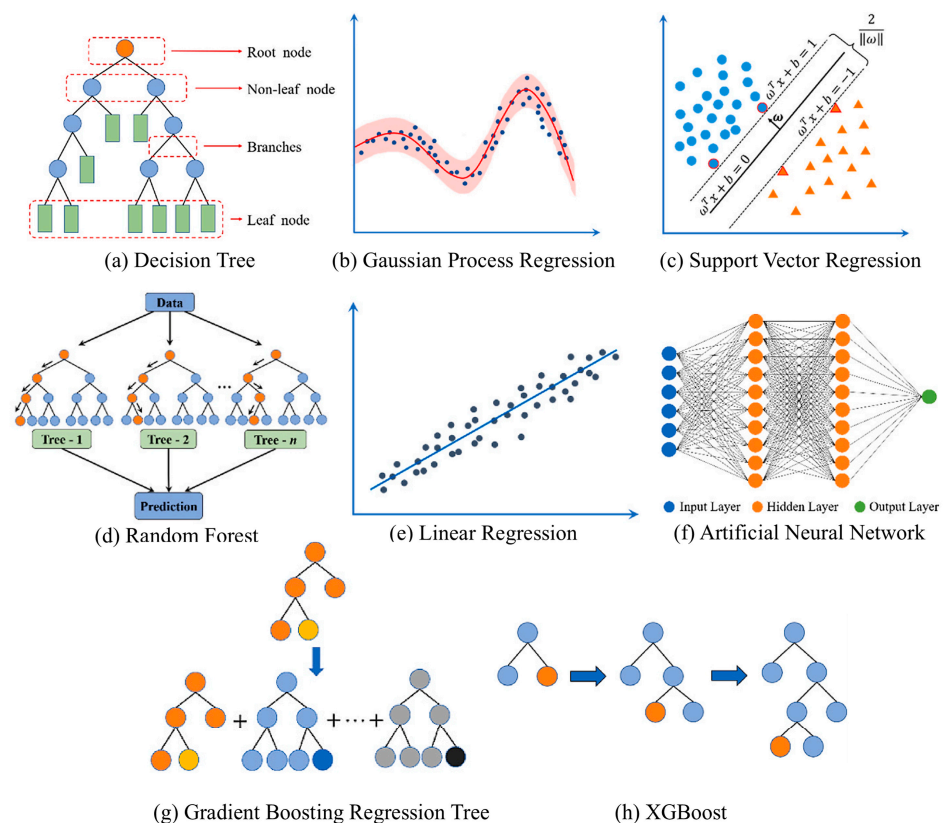


Figure 6. Schematic diagram of machine learning model [74].

Zhang et al. [95] determined that the porous structure of gangue causes a loss in the strength of gangue concrete. At 100% replacement, CG concrete's compressive strength was lowered by 15~20% [96,97]. Gangue's porous structure enhances freeze–thaw stress, which is connected with capillary water absorption capabilities. Simultaneously, air and CO₂-containing chloride ions are more likely to penetrate the concrete, leading to increased gangue aggregate replacement and worse CG concrete durability [98,99]. As a result, it has limited use on a wide scale in concrete structural parts. To use gangue sand in structural concrete, the researchers studied the environmental and mechanical aspects of gangue sand steel pipe concrete (GSCFST) and reinforced gangue sand concrete (RGSC) short columns. The impact of gangue sand replacement rate (rGS) on the mechanical qualities and the environmental effect of short columns was explored using axial pressure testing. The findings revealed that the failure mechanisms of RGSC and GSCFST were comparable, independent of rGS. The GSCFST reduces stiffness and ultimate load capacity less than the RGSC. When the replacement rate is set to 100%, the stiffness and ultimate bearing capacity of the RGSC are lowered by 29.2 and 11.4%, respectively, while those of the GSCFST are reduced by 8.2 and 5.1%. The RGSC ductility coefficient did not vary significantly with varied gangue sand replenishment rates. Conversely, the ductility of GSCFST tends to rise with increasing rGS, which is owing to the higher inhibitory influence of the steel pipe on the core concrete, but the compressive strength of the core concrete reduces as the replacement ratio increases. Based on the experimental findings, the ontological relationship of gangue sand concrete was employed for numerical modeling, and a design technique for the ultimate bearing capacity of GSCFSF and RGSC with rGS is provided. The projected values of GSCFSF and RGSC deviated from the tested and simulated values by approximately 10% and 6%, respectively. The comprehensive life cycle assessment (LCA) revealed that rGS linked favorably with willingness to pay and negatively with the axial strength of the two short columns. Cross-section diameter and material strength have the most beneficial impact on the performance efficiency coefficient (kM-E) of the mechanical environment. Under identical rGS circumstances, the kM-E of GSCFST was larger compared to that of RGSC.

Zhang et al. [82] utilized artificial coal gangue sand as fine aggregate in concrete to mitigate the negative effects of coal gangue buildup and conserve natural resources. The mechanical and environmental features of gangue sand concrete were investigated experimentally and conceptually using different concrete strength classes (C30, C50) and replacement rates (0, 25%, 50%, 75%, 100%). The findings indicate that gangue sand reduces the bonding characteristics of cement mortar to the transition zone of coarse aggregate. The modulus of elasticity and axial compressive strength of gangue sand concrete decrease as replacement ratio increases, regardless of concrete grade. When the replacement rate was set to 100%, the modulus of elasticity and axial compressive strength of C30 grade concrete declined by 2.9% and 12.6%, respectively, while C50 grade concrete decreased by 5.0% and 21.5%. Based on the test findings, prediction equations and a uniaxial compressive stress–strain model for the mechanical characteristics of gangue sand concrete at various replacement rates were developed.

Wu et al. [100] developed a discrete element model (DEM) [101–104] that takes into account medium properties and interfacial differences in order to reveal the fine-scale fracture characteristics of cemented piles. They also investigated the impact of mass fraction and aggregate strength on the strength, energy, deformation, and cracking of cement piles. The findings demonstrate that the binary intergranular fracture ITZ, which is of general relevance between aggregate and cement matrix, is dominant in just one fracture feature; however, the damage produced by damaged aggregate is greater than this fracture feature. The damage induced by the shift in the fracture properties of the cemented

pile rock material is catastrophic. The compressive strength of the sample formed from 12.88 MPa gangue was roughly 30% less compared to that of the 32.77 MPa specimen. The fracture characteristic shift is proportional to the aggregate mass fraction. As the aggregate mass fraction grew from 42.7 to 57.7%, the aggregate strength, or steered aggregate to cementitious matrix strength ratio, declined from 52 to 32 MPa. As a result, the construction of cemented piles of stone must pay greater attention to the compatibility of gangue aggregates, as defined by the gangue aggregate's strength ratio to the cement matrix and its mass fraction. Figure 7 shows the details.

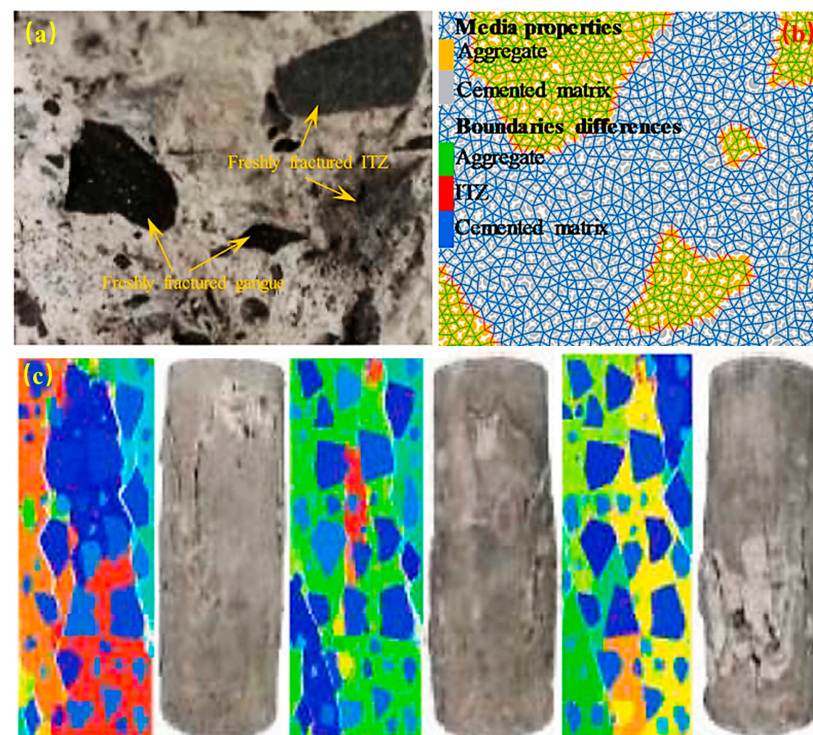


Figure 7. Fracture characteristic of gangue in cemented rockfill (a), DEM model of cemented rockfill (b), failure comparison between DEM model and experimental results of cemented rockfill (c) [100].

Zhang et al. [105] developed a gangue lightweight foam concrete for constrained filling in coal mines. The effects of water–cement ratio, fly ash content, CG content, and foam content on compressive strength, water absorption, dry density, and porosity of gangue foam concrete were investigated using one-way and orthogonal experiments. It was discovered that the water–cement ratio and foam concentration had the greatest impact on the mechanical qualities of the samples. The CG content is the most important component influencing the specimen's porosity. Meanwhile, CG content has a substantial effect on the microstructure of the sample. When the CG concentration was 30%, the sample exhibited the highest pore performance index but inadequate connection between pores. Overall, the foam concrete mixed with CG has acceptable mechanical characteristics and pore structure, making it a useful reference for gangue foam concrete utilized in the closed filling treatment of the highway in the mining hollow region.

Zhang et al. [106] studied the compressive performance of short circular steel-tube concrete (CFST) columns made with SCGA using laboratory testing and finite element simulations to determine the influence of SCGA replacement. This study focuses on the damage mechanisms, ultimate compressive strength, ductility, and elastic stiffness of the specimens, as well as the confinement effect of steel tubes. The results reveal that the SCGA-prepared specimens have a comparable damage pattern to the reference steel pipe concrete. The specimens' compressive strength, elastic stiffness, and ductility dropped by

2.93~4.81% (8.25~10.18%), −16.17~8.24% (3.01~22.16%), and 7.78~10.61% (11.86~16.34%), respectively, as the SCGA substitution rate rose from 0 to 50% (100%). A finite element model based on ABAQUS software is suggested and compared to test data. According to numerical studies, the key factors impacting the compressive characteristics of steel pipe concrete are the SCGA replacement rate and the confinement effect. After comparing the experimental data to the current design requirements, a modified design equation that considers the replacement ratio and confinement effects is presented to forecast the final compressive strength of SCGA-prepared specimens. The correctness of the developed adjustment equation was evaluated using a mean of 0.984 and a standard deviation of 0.076. This establishes an experimental basis for applying SCGA to small steel-tube concrete columns. The correction coefficient, K_s , which accounts for the coupling between the SCGA replacement ratio and the constraint effect, has an R^2 of 0.908, indicating that the equation explains 90.8% of the variance in K_s . When the projected ultimate compressive loads were compared to the actual data, the obtained equations were found to be highly accurate, with a mean value of 0.984, a standard deviation of 0.076, and a coefficient of variation of 0.077%. Figure 8 shows the details.

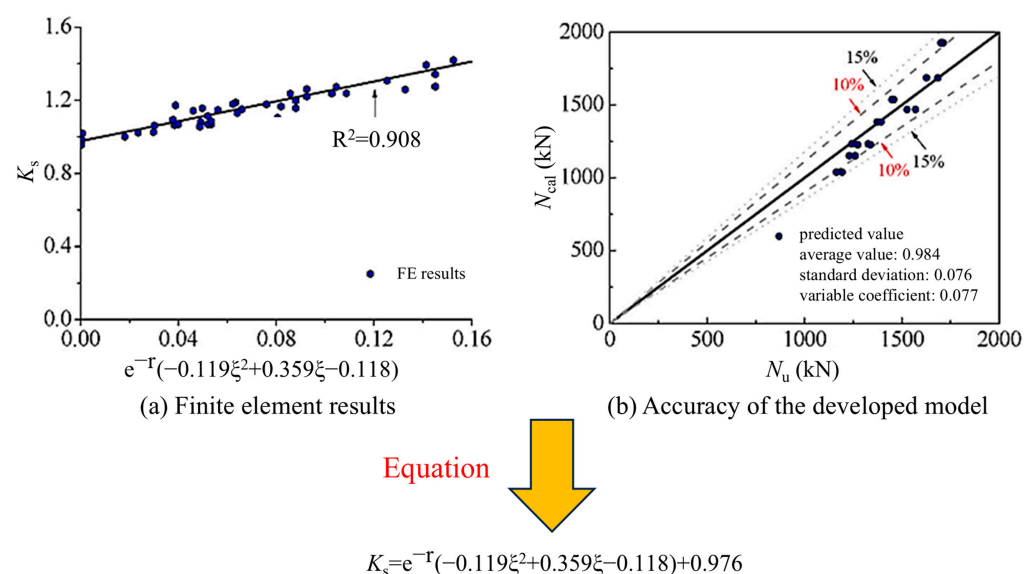


Figure 8. A comparison between the compressive load calculated by the model and the actual data [106].

Wang et al. [85] looked at the axial compression performance of carbon fiber-reinforced polymer (CFRP)-constrained self-combusted gangue coarse aggregate (SCG-CA) steel pipe concrete short columns. The researchers accomplished this by evaluating 18 CFRP-constrained SCGCA steel pipe concrete specimens and 9 SCGCA concrete specimens with varying SCGCA replacement ratios and CFRP sheath stiffness. The study found that the combined constraint provided by the CFRP sheath and steel pipe considerably boosted the ductility and strength of SCGCA concrete. Their constraints become less effective as the rate of replacement increases. Furthermore, the researchers changed the previous theoretical model of CFRP-constrained natural coarse aggregate (NCA) steel pipe concrete to CFRP-constrained SCGCA steel pipe concrete. Figure 9 shows the details.

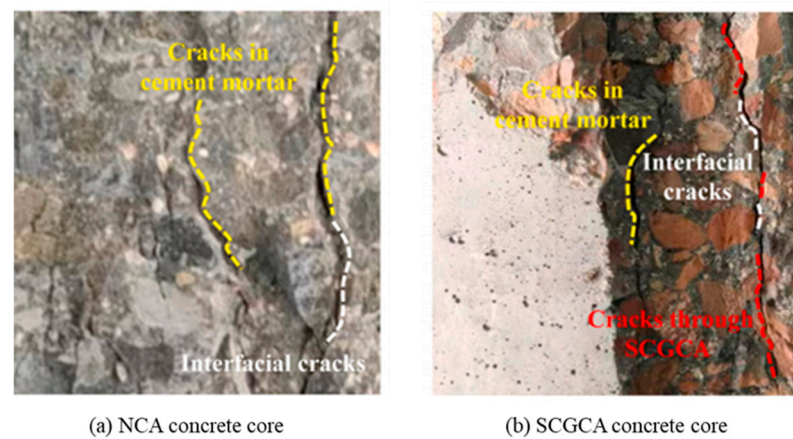


Figure 9. Internal cracks patterns [85].

Guan et al. [107] performed monotonic axial loading tests on 36 concrete specimens made of self-combusted gangue (SCG). To assess the mechanical characteristics of fiber-reinforced polymer (FRP)-constrained SCG concrete, various concrete strengths and glass fiber-reinforced plastic (GFRP) pipe thicknesses were used as variables. When SCG concrete is constrained by GFRP pipes, its compressive strength and ductility improve dramatically. Furthermore, SCG concrete has unique expansion properties and displays strong volumetric compaction behavior after loading.

Sun et al. [16] examined the impact of gangue aggregate to sand ratio, fiber weight % to cement ratio, and gangue aggregate particle size on the working and mechanical parameters of lightweight gangue shotcrete, including compressive strength, splitting strength, and density. The researchers built and evaluated 504 specimens, and the findings are presented as a test and training dataset for six machine learning models to examine their prediction abilities. In modeling, a back propagation neural network was used to obtain high correlation coefficients between compressive strength and density, while a support vector machine was used to determine splitting strength, and both models were combined with particle swarm optimization for accurate and reliable predictions. Finally, sensitivity analysis was performed to determine the importance of the ranking input components. Figure 10 shows the details.

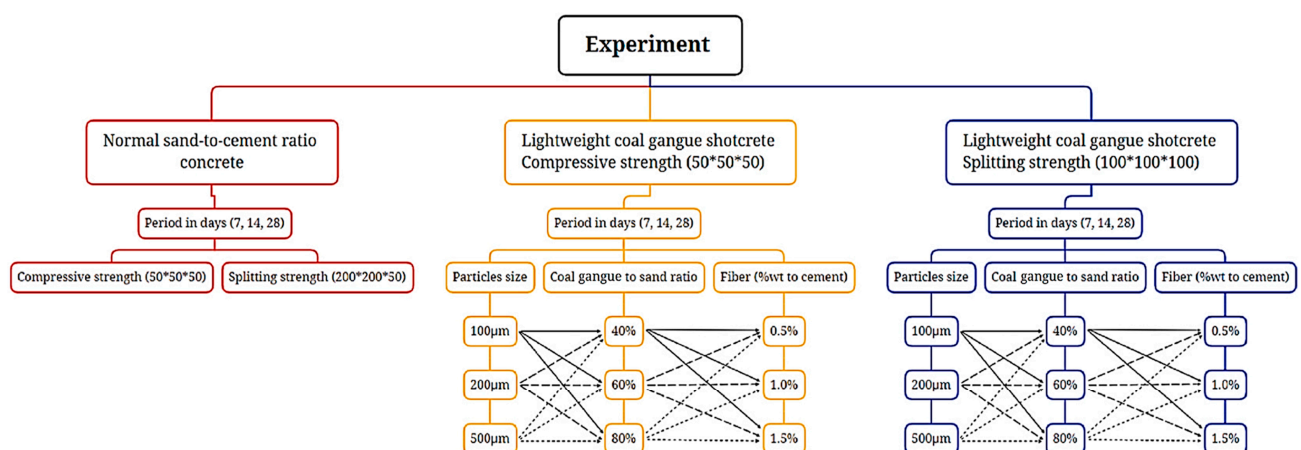


Figure 10. Schematic representation of the experimental tests [16].

Wu et al. [108] concluded that using gangue powder as a cementitious material is vital for long-term gangue management. However, the limited activity of CG powder in concrete caused severe strength deterioration, restricting full-scale recycling. The researchers added

CG powder to a non-fiber ultra-high performance concrete (UHPC) matrix. This method is expected to increase CG reutilization while maintaining UHPC's outstanding mechanical qualities, as the filling impact of the particles dominates UHPC performance rather than chemical activity. The compressive strength of UHPC containing CG powder was shown to enhance later on as a result of the volcanic ash reaction. This implied that the introduction of CG powder improved the self-shrinkage and chloride ion permeability of UHPC. Calcined CG (C-CG) powders offer higher strength with a dense pore structure than CG powders due to improved chemical activity. However, the modest increase in strength ($< 5\%$) supports the usage of untreated CG powders from an energy consumption perspective. Replacing CG powder with C-CG powder enhances packing density, reducing the quantity of water required to fill spaces between particles. Figure 11 shows the details.

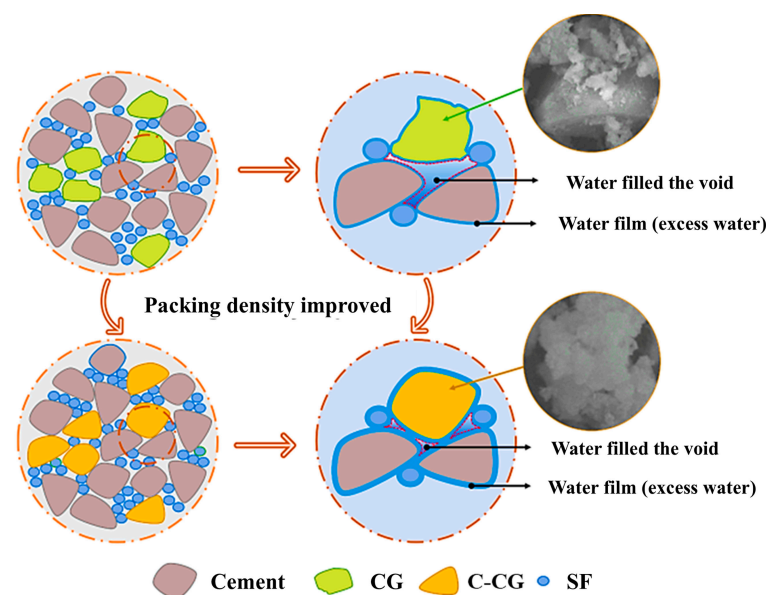


Figure 11. The volume of a genuine mixture is compared to that of a stable particle structure containing identical particles [108].

Li et al. [109] defined concrete as a composite material consisting of a large number of randomly dispersed aggregates embedded within a matrix of stiff cementitious material that fills the gaps between the aggregate particles and binds them together. Thus, the mechanical characteristics of concrete are determined by the properties of the matrix and the aggregate volume fractions. In the two-phase, three-dimensional (3D) spherical model of concrete, the outer layer represents the matrix, and the inner core represents the aggregate. The outside surface of the sphere is assumed to be under homogeneous radial tensile stress. Based on elasticity theory, it is possible to determine the radial displacement and radial stress components in the matrix and the aggregate, as well as the effective modulus of elasticity equations that can be employed to determine the modulus of elasticity of mortar and aggregate in concrete. Figure 12 shows the details.

Wang et al. [80] discovered that the flexural and compressive strengths of 5 min mechanically-activated water-washed cementitious materials were 4.97 and 30.3 MPa, respectively. The CG admixture was inversely related to the mechanical characteristics of the concrete and positively and then inversely related to the durability of the concrete, owing primarily to the fact that the CG admixture lowered the alkalinity of the system and influenced the hydration reaction. Using a life cycle approach, the researchers discovered that carbon emissions from CG-based cementitious systems were much lower than those of cementitious materials, demonstrating that the usage of CG is a potential low-carbon energy-saving and emission-reduction solution in the building sector.

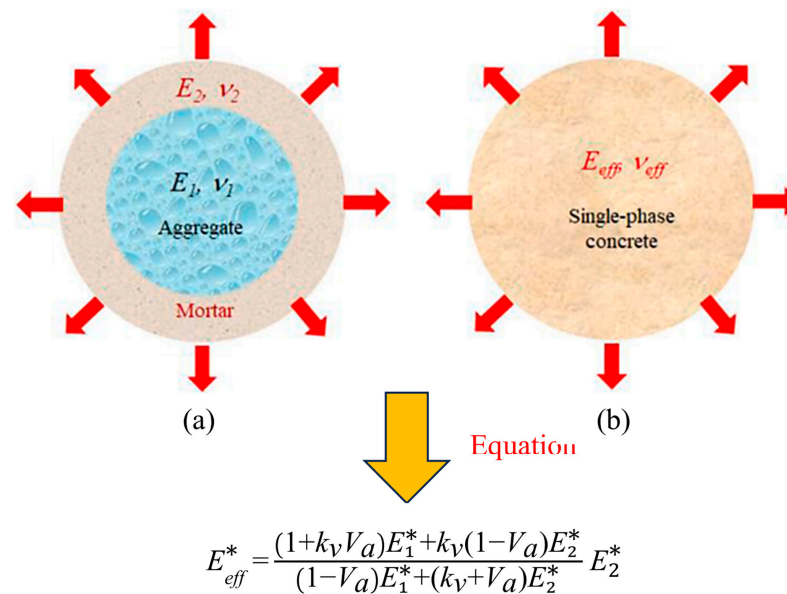


Figure 12. Two-phase spherical concrete model (a), single-phase spherical concrete model with effective characteristics (b), and elastic modulus equation [109].

4.2. Durability Properties of CG Concrete

Durability has always been an inherent and crucial issue with concrete. This is due to issues such as poor gangue aggregate strength, excessive water absorption, and higher carbonaceous weak components, all of which can affect concrete durability. It is critical to analyze the impact of gangue aggregate on the durability of concrete and develop technical solutions to increase its durability.

Wu et al. [71] identified frost resistance as a major predictor of CGPC durability. Figure 13a,b illustrate the mass loss rate (MLR) of hardened CGPC with varying CGA replacement rates following 50 freeze–thaw cycles (FTCs). It can be observed that the rate of mass loss accelerates with an increase in the number of FTCs. Clearly, the MLR of the SCGA-based CGPC was significantly lower compared to that of the RCGA-based CGPC at an identical substitution rate condition. The MLR of RCGA-based CGPC increased significantly following more than 20 FTCs until crushing failure, especially when the substitution rate exceeded 50%. In contrast, the MLR of SCGA-based CGPC stayed relatively low at this point, suggesting that SCGA-prepared CGPC had superior frost resistance to RCGA. A behavior rationale might be that SCGA binds more tightly to the matrix phase, as frost damage often occurs at the aggregate–matrix interface, where the link is weaker. Surprisingly, the frost resistance of CGPC produced with modified CGA (RCGA or SCGA) was significantly increased. Following 25 FTCs, MS100 and MR100 had MLRs that were 52% and 63% higher compared to those of SCG100 and RCG100, respectively. The result might be due to the thick “shell layer” produced on the surface of the modified CGA, which inhibits H₂O molecules from accessing the transition zone of the aggregate–matrix interface, hence avoiding the creation of swelling stresses that would damage the interface structure. Furthermore, with the exception of RCG75 and RCG100, all toughened CGPC have an MLR of lower than 5% following 25 FTCs, meeting the standard’s requirements. Freeze–thaw cycle studies revealed that SCGA-based CGPC had a higher frost resistance than RCGA-based CGPC, and the cold resistance of CGPC made using slurry-coated modified CGA was significantly enhanced. The leaching toxicity of hazardous components is a crucial aspect in determining the environmental effect of CGPC. Figure 13c depicts the leaching concentrations of HMs such as Cr, Ni, Mn, Cu, As, Zn, Cd, and Pd in crushed CGPC. Through analysis, the leaching concentrations of all HMs in all groups of hardened CGPC

mixtures remained within the regulatory limits, indicating that CGPC has no negative environmental effects. HM ions can be integrated into the hydration process of the cement and solidified as hydration products such as $\text{Al}(\text{OH})_3$ gels, Aft (AFm), and C-(A)-S-H gels [110]. Furthermore, increasing the Aft and gel phases within the matrix results in a denser interwoven network structure and, hence, a greater immobilization capacity for HM ions. In the assessment of HM leaching toxicity on the environmental effect of CGPC, the environmental friendliness of CGPC was identified, which offers a broad application possibility and development space. Figure 13 shows the details.

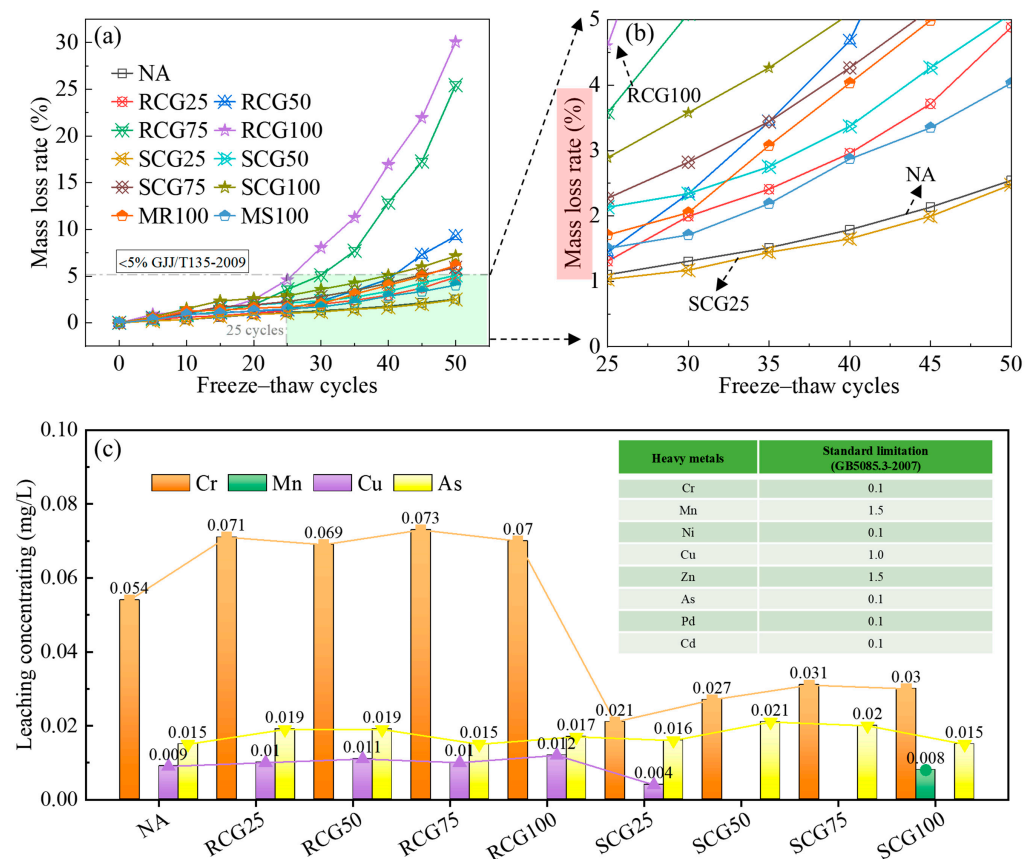


Figure 13. Freeze-thaw cycle resistance (a,b), HMs leaching concentration (c) of CGPC [71].

Zhao et al. [111] examined the durability and mechanical characteristics of pavement concrete with RCGA as coarse aggregate, taking into account the similarities between natural aggregates and RCG. The researchers created 396 samples with RCGA ratios of 0, 30, and 50%, as well as water–cement ratios of 0.36 and 0.45. As a result, the fluidity, compressive, split tensile, and flexural strengths, modulus of elasticity, abrasion resistance, impermeability, and resistance to freezing and thawing (water and de-icing salts) of the RCGA concrete were determined, and the microstructure was analyzed to investigate freeze–thaw damage to the concrete. The results revealed that RCGA had a detrimental impact on the mechanical characteristics and durability of concrete. The higher the RCGA concentration, the lower the strength and modulus of elasticity, as well as the more severe deterioration of abrasion, permeability, and freeze–thaw resistance in the concrete. Furthermore, the microstructure indicates that the ITZ between the RCGA and cement paste is a weak area of the concrete. RCGA concrete’s appearance did not alter much until 60 FTCs. When the number of cycles reached 120, the cement mortar on the surface of the RCGA concrete spalled somewhat, revealing some coarse aggregate. However, there was no substantial difference in plain concrete. As the number of cycles climbed to 200, a large quantity of

mortar in the RCGA concrete spalled off, leaving the coarse aggregate on the sample's surface exposed. After 200 cycles of standard concrete, just a little amount of cement paste was removed from the surface. The standard states that concrete with 30% RCGA can be used in Class III pavements under freeze–thaw and de-icing salt conditions. Figure 14 shows the details.

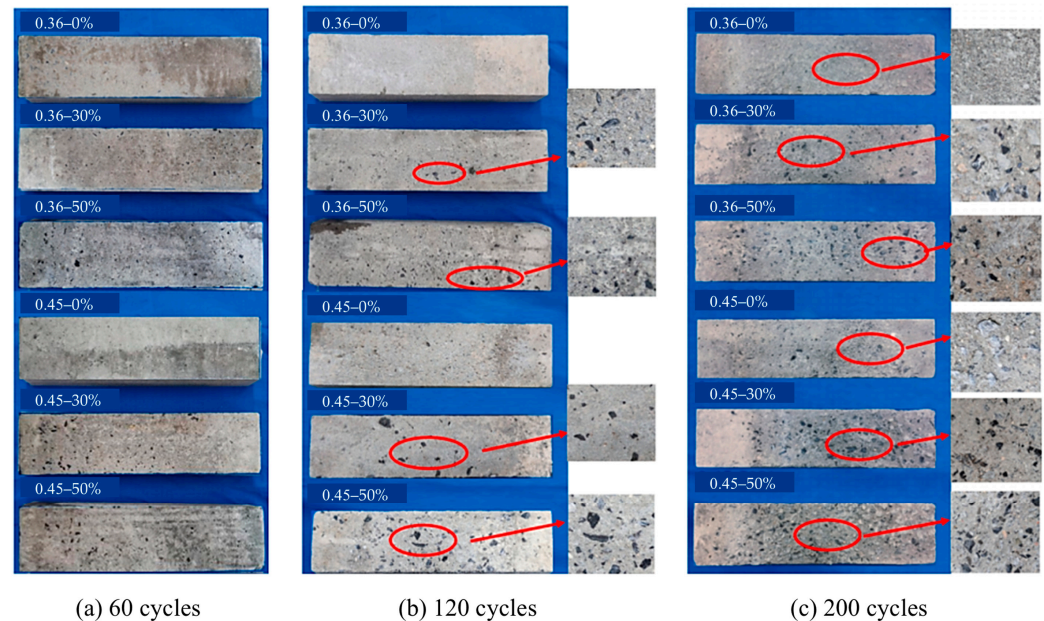


Figure 14. The appearance of RCGA concretes following FTCs [111].

Qiu et al. [112] used CG as aggregate in concrete to maximize resource usage from solid waste. The deterioration law of gangue concrete under the combined action of cyclic loading and freeze–thaw was studied by the researchers using both macro- and microscopic methods. They also examined the microscopic morphology and pore structure deterioration law of gangue concrete, quantified the relationship between the pore structure and the damage of compressive strength, and analyzed the specimens' mass loss, relative dynamic modulus of elasticity loss, and compressive strength loss under the composite action. The findings demonstrated that the specimens' mass increased initially before decreasing, while their relative compressive strength and dynamic elastic modulus gradually dropped as the cyclic load and the number of FTCs increased. A more complicated pore structure is indicated by a bigger fractal dimension. As the number of freezing and thawing cycles and cyclic loads increases, the fractal dimension falls, suggesting a progressive degradation of the pore structure under the combined action. The quantitative relationship between compressive strength damage and pore structure under the combined effect of cyclic loading and FTCs is demonstrated by the clear regression effects between these variables and composite pore structure parameters and fractal dimension.

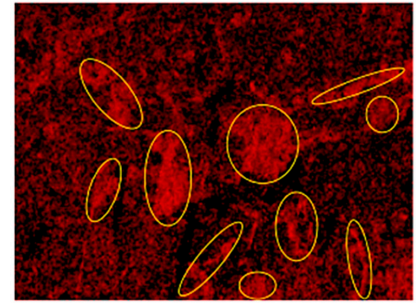
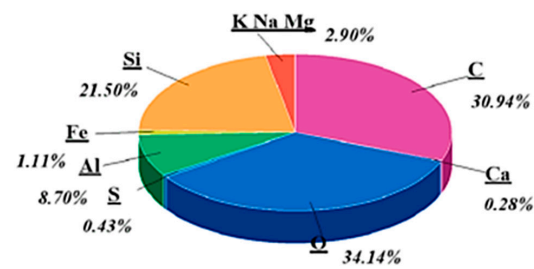
Duan et al. [24] discovered that the HMs in CG were As, Pb, and Cr. The valence states of As, Pb, and Cr in CG are As^{3+} , As^{5+} , Pb^{2+} , Pb^{4+} , Cr^{3+} , and Cr^{6+} , respectively. The valence states of As, Pb, and Cr in CG are predominantly carbonate-bound and metal-oxide-bound, and they are present in triclinic layered silicate minerals dominated by kaolinite. Given that HMs in CG are eventually ingested into the human body through soil, the researcher, while constructing a complete environmental safety control system for HMs, establishes a risk control system and control limits for characteristic HMs in CG resource utilization according to the relevant environmental quality standards and the human health risk assessment of HMs, so as to provide theoretical guidance of CG high-value environmentally friendly

utilization. This has significant social and environmental implications for the truly green and sustainable growth of the CG industry.

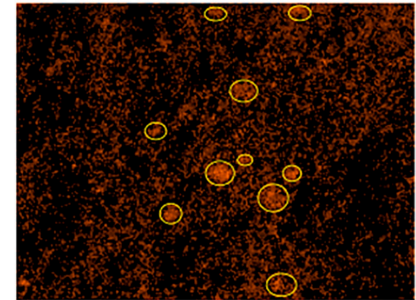
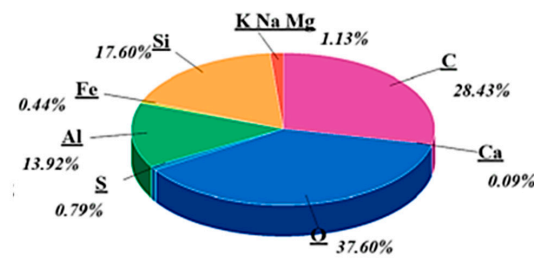
Gao et al. [113] used a 126-day coal gangue aggregate concrete (CGAC) shrinkage test to create a model for predicting the shrinkage behavior of gangue-infused coarse and fine aggregate concrete (CGCA and CGFA). The experiment used various substitution rates for CGCA and CGFA, such as 0%, 50%, and 100% for each kind. It was discovered that both CGCA and CGFA considerably enhanced the shrinkage strain of concrete, which rose by 145% when both were utilized at 100%. CGCA had a more pronounced effect on contraction than CGFA. The inclusion of CGCA resulted in quicker concrete shrinkage development, but CGFA had no significant influence on shrinkage progression over time. Shrinkage stresses were considerably greater in all CGACs than in baseline normal aggregate concretes (NACs), regardless of CGFA or CGCA replacement rates. In the baseline NAC, replacing limestone gravel (CAN) and river sand (FNA) with 100% CGCA and CGFA caused a 144.8% increase in shrinkage. CGCA had a greater effect on shrinkage strain than CGFA, with 100% CGCA resulting to an increase in ultimate shrinkage strain of 64.9%~72.6% compared to just 37.4%~43.1% for 100% CGFA. This finding supports the practicality of CGFA applications. Furthermore, the inclusion of CGCA significantly enhanced the shrinkage of the concrete. To obtain the same degree of shrinkage strain, concrete containing 100% CGCA takes just 62% the time as NAC. However, there was no significant difference in shrinkage over time with the inclusion of CGFA. The researcher created a shrinkage model for CGAC using theoretical derivation, which can accurately predict the time-dependent behavior and ultimate shrinkage of concrete containing CGFA and CGCA, with an average value of 0.99 and coefficients of variation (COV) of 0.07. More than 95% of the data were determined to be within a 10% variance. The entire contraction model of CGAC may be expressed as Equation (2):

$$\varepsilon_{cs}^{CGAC}(t, t_0) = k_a k_w \varepsilon_{ca}^{NAC}(t, t_0) + \beta^{CGAC}(t, t_0) k_h k_v \varepsilon_{shd}^{NAC} \quad (2)$$

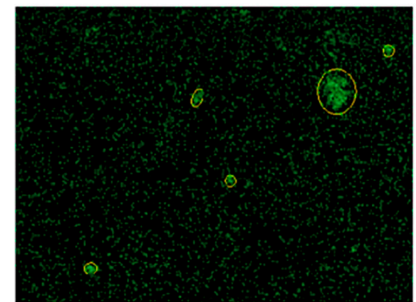
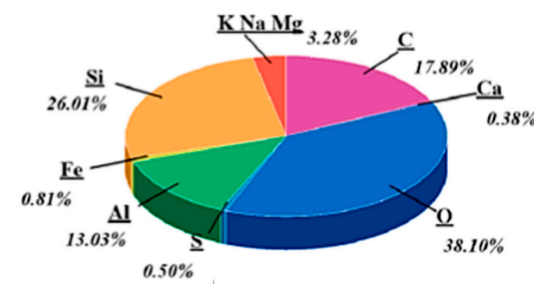
Jiao et al. [114] studied the development of CG aggregate concrete and the resource utilization of CG solid waste. They crushed CG samples into aggregates, characterized their macroscopic features and microstructures, and investigated the key influencing factors of CG aggregate physicochemical properties. The results reveal that the CG with the lowest burnout loss and carbon content has a lower crush value, less water absorption, and greater stability. Carbon concentration and distribution have a substantial effect on the macroscopic physicochemical features of CG agglomerates. Carbon is evenly distributed in the gangue as a defect, increasing the crushing value of CG aggregates while significantly decreasing their robustness, resulting in the “second-order unfavorable effect” and the “open-window effect.” At the same time, this reduces the durability of CG aggregate concrete. Furthermore, the composition and physicochemical characteristics of a large number of CG samples were obtained, and a “three-dimensional surface” was used to investigate the correlation of the compositional superposition impact on the physicochemical qualities. This investigation demonstrates the negative impact of carbon defects on the physicochemical parameters of CG aggregates. Furthermore, the researchers examined the gangue’s micromechanism (as shown in Figure 15), with the yellow circle representing the location with the highest C concentration. It is obvious that C has a similar and uniform distribution characteristic across all four CG types. This finding offers a convincing explanation for the impact of elemental carbon on the physicochemical features of CG agglomerates. Figure 15 shows the details.



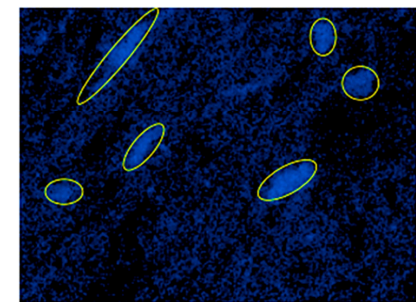
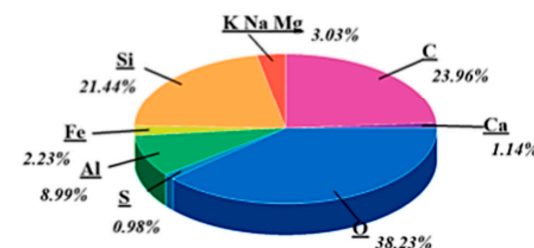
(a) Xishan



(b) Xiqu



(c) Changzhi



(d) Lvliang

Figure 15. Element composition content of CG, and C element capture diagram of CG in various regions [114].

Gao et al. [23] concluded that the important criteria for gangue concrete's high temperature resistance are high temperature residual strength and thermal characteristics. It was discovered that when the temperature rises, the thermal density of gangue concrete falls, mass loss increases, residual strength reduces, thermal conductivity rises, and specific heat capacity varies. In the temperature range from 20 °C to 400 °C, increasing CG coarse aggregate replacement reduces the residual strength of concrete while increasing specific

heat capacity and thermal conductivity. However, between 500 and 800 °C, the residual strength of the concrete rose marginally as CG coarse aggregate replacement increased, whereas mass loss varied considerably. Temperature and coarse aggregate replacement rate changes affected the thermal conductivity of gangue concrete, which displayed a linear growth pattern as the temperature was increased. Similarly, the thermal conductivity of gangue concrete increases linearly with the aggregate replacement ratio. As a result, Equation (3) may be used to describe how gangue concrete's thermal conductivity changes with temperature at various replacement rates.

$$\lambda = 0.454 + 0.14r + (0.0223 + 0.06r) \left(\frac{T}{100} \right) \quad 20 \leq T \leq 800 \quad (3)$$

Lu et al. [115] stated that the development of multifunctional asphalt composites with high thermal repair capability has become a critical priority for attaining pavement maintenance and sustainable infrastructure. However, establishing a compromise between obtaining high healing efficiency while preserving mechanical strength and limiting functional additive aggregation is difficult. To address this issue, a novel dual-response microwave heating repair solution for asphalt concrete that incorporates CG and functional aggregates is presented. The use of functional aggregates can form a robust and functional skeletal structure in asphalt concrete, promoting microcrack healing at the aggregate–asphalt interface. Furthermore, the addition of CG to the asphalt mixture promotes the healing of microcracks in the mastic. It is worth noting that the addition of bifunctional additives to the optimized asphalt concrete resulted in only a 2% drop in maximum tensile strength and a 1.5% decrease in cracking resistance when compared to standard porous asphalt samples. Furthermore, after five damage healing cycles, the optimized asphalt samples exhibited healing index values greater than 60%. To create hot repair asphalt concrete, 100% CG and functional aggregates are recommended. This integrated strategy considers the beneficial reuse of CG powder, as well as the associated environmental and economic advantages. Even after multiple damage repair cycles, the healing index (HI) of asphalt concrete (with functional aggregates and CG) remained considerable, reaching around 60% and 50% at the fifth and sixth cycles, respectively, indicating outstanding heating repair capabilities. This combination technique results in an effective healing process that helps to preserve the integrity and functioning of asphalt concrete even after several damage repair cycles. Overall, the researchers offered a promising strategy for attaining effective heating repair capacity in asphalt concrete, with significant practical applications in the field of sustainable pavement engineering. Figure 16 shows the details.

Wang et al. [116] examined the permeability of gangue and fly ash concrete for use in agricultural drainage ditches. The results reveal that concrete made with waste gangue and fly ash has higher water permeability than conventional concrete. The water permeability of concrete samples rises with an increase in fly ash and coal gangue content; the higher the fly ash and coal gangue concentration, the greater the water permeability of concrete. When fly ash and gangue were utilized, the density and compressive strength of the concrete samples decreased. The ideal mix ratio for concrete with an appropriate compressive strength (10 MPa) is 30% gangue replacement and 15% cement replacement with fly ash. In field applications, concrete has a high subsurface drainage modulus. Indoor simulations were conducted to determine the best concrete mix for agricultural drains, with an infiltration rate of 0.072 cm·h^{−1} and a subsurface drainage modulus of up to 0.01 m^{−3}·s·km^{−2}. This type of concrete can be utilized in regions where the subsurface drainage modulus is not more than this value. It is worth mentioning that the trace elements in fly ash and gangue are far lower than the allowable limits. The total quantity of coal gangue and fly ash per square kilometer of farmland is 2558 kg, which is lower than the 450,000 kg/hm^{−2}

required in the relative standard. Drainage ditches provide considerable economic and social benefits in terms of waste management and environmental preservation. The design is consistent with national industrial strategy, easy to promote and implement, and has numerous application possibilities. However, further study is needed to evaluate the endurance of this fly ash and gangue-based concrete in real applications, particularly in field environments with a high water table. Figure 17 shows the details.

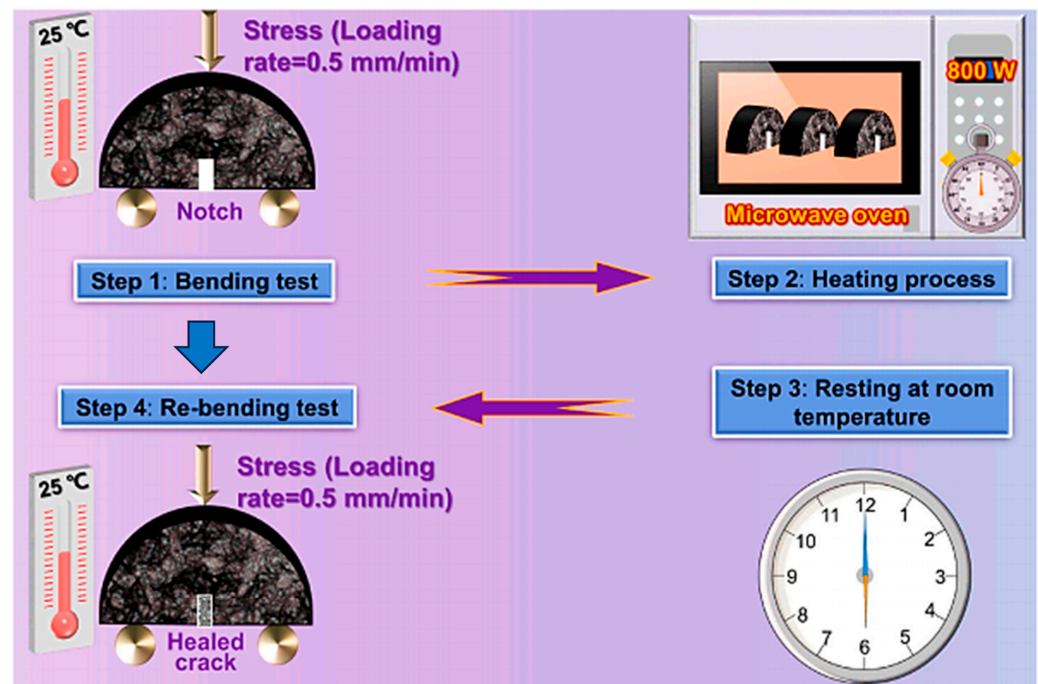


Figure 16. Illustration of the damage–healing–damage cycle of asphalt concrete samples [115].

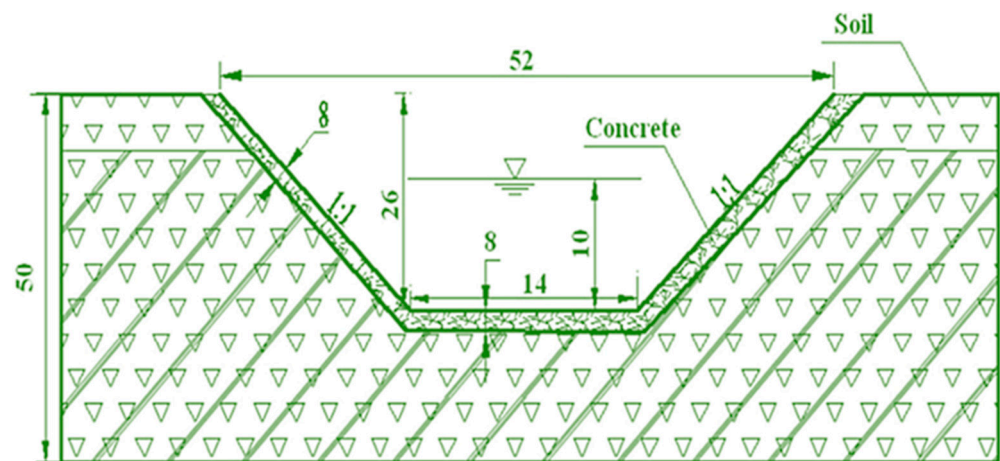


Figure 17. Sectional drawing of an indoor drainage ditch with fly ash and CG (units: cm) [116].

Wu et al. [73] studied the vegetation compatibility of a high greenness, low-carbon, plant-compatible eco-concrete made using SCGA, as illustrated in Figure 18a. The experimental chamber was filled with 8–10 cm thick planting soil. Plant-compatible eco-concrete (PEC) test blocks were then placed on top of the soil, followed by a layer of 2–3 cm planting soil (as shown in Figure 18b). Tall fescue, which has a well-developed root system and a high alkali tolerance, was chosen as a turfgrass for the PEC seeding test to investigate its adaptation to plant-compatible eco-concrete throughout growth. Figure 18c–f show the growth state of tall fescue at various stages. Tall fescue germinated and grew to a height of

around 2~3 cm within 10 days after seeding. Later, the tall fescue became taller and more lush. Tall fescue continued to develop strongly after 32 days of planting, with a root system of more than 10 cm (as shown in Figure 18g) and a stem length of 23.5 cm (as shown in Figure 18h), which readily penetrated through the porous LCPEC layer into the underlying soil. In addition, as seen in Figure 18i, the researcher planted ryegrass and knotweed, both of which thrived over the 30-day growth cycle. It should be noted that no external source of nutrients or chemical fertilizers is added to the planting soil; instead, constant watering is necessary to suit the plants' moisture requirements. This demonstrates that LCPEC is well-suited to vegetation and has a wide range of applications in the fields of mine rehabilitation and road slope protection.

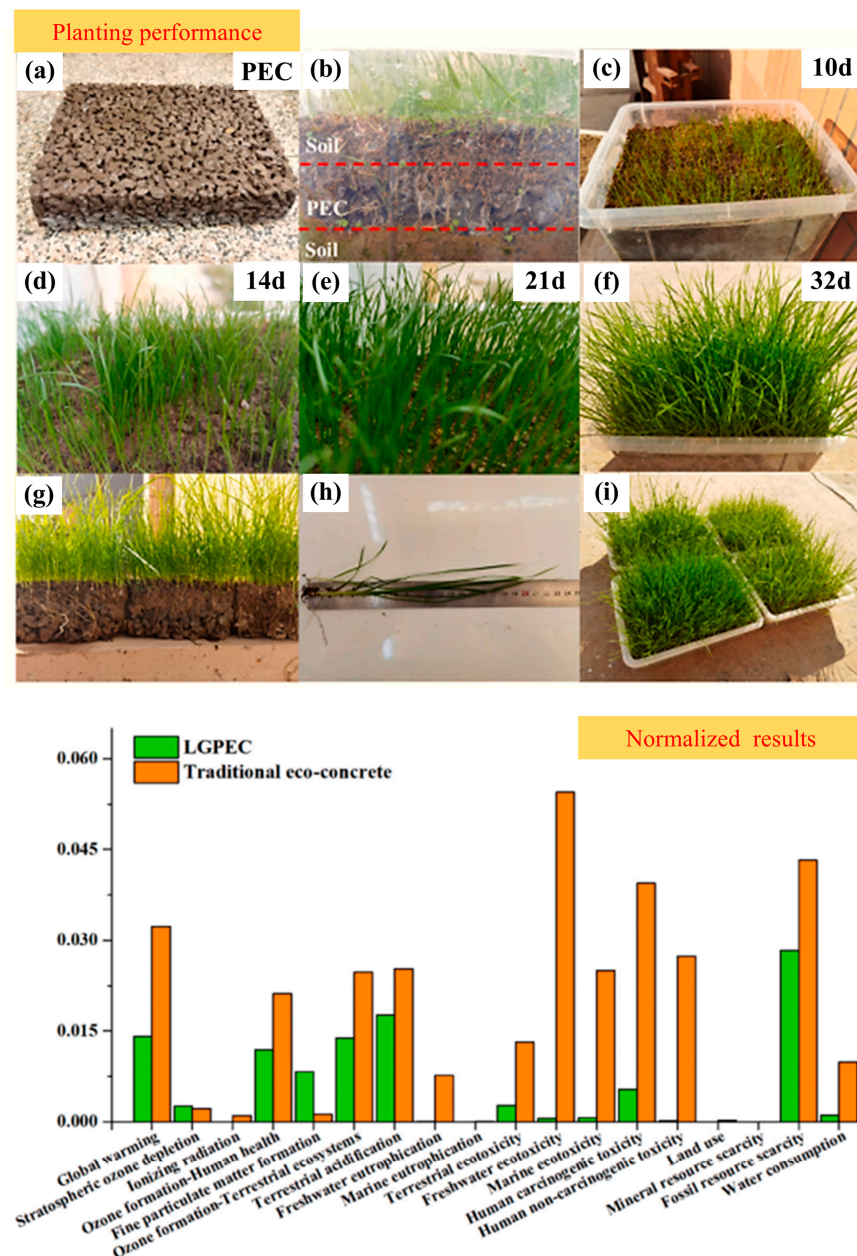


Figure 18. Planting performance of LCPEC prepared by LACM and SCGAs (a–i), and the differences in normalized LCA results between traditional eco-concrete and LCPEC [73].

The researchers found that, as a product made solely from solid waste, the potential economic and environmental advantages of employing low-alkalinity cementitious materials (LACM) to make LCPEC in cooperation with SCGA may be assessed using economic

analysis and life cycle evaluation. The evaluation function was based on a yield of 1 cm^3 of concrete, with the strength classes of the two types of concrete remaining constant. The environmental implications of LCPEC were assessed by employing the life cycle assessment (LCA) method and compared to standard eco-concrete. It is known that the environmental impacts of LCPEC primarily include ozone creation, global warming, fine particulate matter generation, human health, fossil resource shortages, and terrestrial acidification. With the exception of stratospheric ozone depletion and fine particulate matter formation, conventional eco-concrete exhibits higher values in all 18 environmental impact categories. It is important to note that LCPEC's greenhouse gas emissions are only 32.5% of those of conventional eco-concrete, indicating that it is more environmentally friendly. The specifics are displayed in Figure 18.

5. Mechanism

CGPC is a “three-phase” composite system made up of aggregates, a binder matrix, and an aggregate–matrix interface, in which aggregates with a single particle size gradation are joined “point-to-point” via the binder matrix to produce a honeycomb structure. The strength growth and creation of CGPC from raw materials are determined by the binder's hydration, the type of the aggregate, and the strength of the interfacial connection between the aggregate and the matrix. Furthermore, porosity, water–cement ratio, aggregate particle size, and active mixture all have an impact on PC compressive strength [117]. The aggregate–matrix interface also has a significant impact on strength, particularly for porous PC, where the interface makes up a substantially greater proportion of the material compared to that in regular concrete [118]. For CGPCs manufactured at certain mixing ratios, CGAs were changed by slurry encapsulation to dramatically increase mechanical characteristics and frost resistance, and the compressive strength of SCGA-based CGPCs was significantly higher compared to that of RCGA-based CGPCs [71]. As a result, it is critical to understand the mechanism by which the physicochemical properties of the interface transition zone (ITZ) between the matrix and the aggregate affect the compressive strength of CGPC for the use of gangue aggregate concrete. The ITZ is located between the binder matrix and the aggregate, in addition to having a greater impact on PC than normal concrete [119]. In general, the ITZ of silicate cement-based concrete is distinguished by three primary properties: (1) significant porosity, (2) the presence of a large number of orientated $\text{Ca}(\text{OH})_2$ crystals, and (3) the appearance of microcracks [120,121]. The compaction and strength of the ITZ are significantly lower than those of the hardened cement body, which is the weakest link in the PC construction. Thus, optimizing the structure of ITZs is critical for enhancing PC performance [122]. Pervious concrete is a composite material that resembles the “aggregate–matrix–aggregate” sandwich structure, with the ITZ between the matrix and the aggregate serving as a “bridge” for transmission. The bridge structure quality impacts the binding strength between the matrix and the aggregate, which influences the macroscopic strength of CGPC. In general, microcrack expansion and loose structures with high porosity that develop in ITZ are the primary causes of PC strength loss.

Wu et al. [71] discovered that CGPC made from SCGA modified using the slurry encapsulation technique had increased compressive strength and frost resistance, as well as enhanced the properties and structure of the SCGA matrix ITZ. The probable causes of the strength improvement are listed as follows: (1) SCGP inclusion during slurry encapsulation results in a low water-to-cement ratio; (2) the porous structure of needle rod-shaped ettringite (Aft) crystals contributes to self-extension development within the pores. SCGA's pore size is enormous, and its porous structure is extensively spread. These micropores may absorb a certain quantity of free water until saturation as SCGA comes into contact with water, allowing adhesive pastes with a low water–gel ratio to penetrate these free

water-rich micropores easily. Components in the slurry, such as activated $\text{SiO}_2/\text{Al}_2\text{O}_3$ and CaSO_4 , are easily dissolved within adsorbed water of the micropores and undergo hydration reactions with the clinker minerals, leading to self-extension growth of AFt within the pores and intertwining with the $\text{Al}(\text{OH})_3$ gel and C-S-H gel to develop a dense network structure. The development of AFt in micropores not only degrades the CGPC structure but also fills the micropores and generates a strengthened compact structure of ITZ, resulting in a tighter aggregate–matrix link and higher bond strength. This is the primary reason why SCGA-based CGPC has great strength. After 28 days of hydration, a network structure developed by the interweaving of a large number of needle-like AFt with the gel phase can be seen within the matrix, in which the disordered arrangement of AFt acted as the network skeleton and the $\text{Al}(\text{OH})_3$ gel or C-S-H gel acted as the filler between the interstices of the skeleton, which together constitute the source of strength of the matrix phase. On the one hand, the SCGA matrix's strength mechanism is attributed to the low water-to-cement ratio “shell layer” structure generated by the slurry encapsulation modification and the volcanic ash impact of SCGP, which results in a more compact ITZ structure. On the other hand, this is due to the porous nature of the SCGA surface and the increased dense structure generated by AFt self-extension development within the micropores. Figure 19 shows the details.

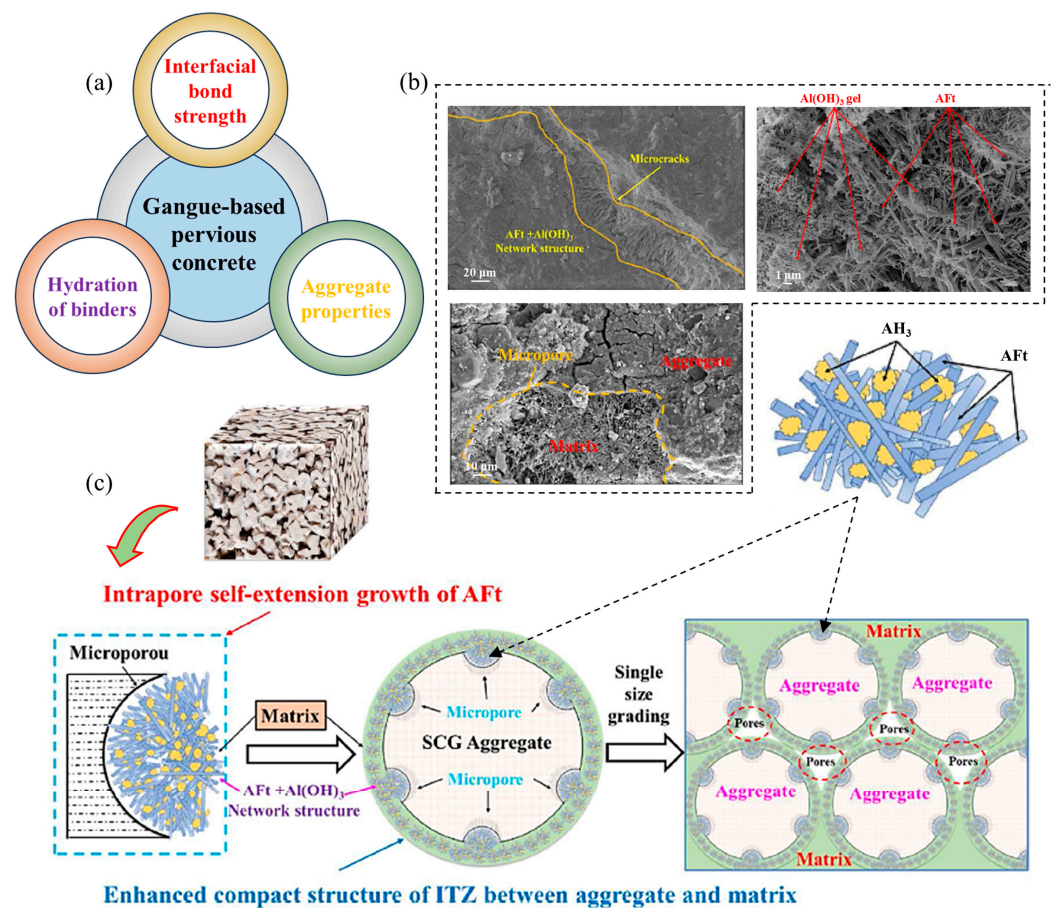


Figure 19. Strength source of CGPC (a), self-extensional growth of AFt (b), and microstructure mechanism of hydration interface of coal gangue aggregate (c) [71].

Su et al. [81] observed that CG is high in SiO_2 and Al_2O_3 , indicating probable gelling activity. As a result, preparing gangue powder from cementitious materials has a wide range of applications. The researchers studied the influence of thermally activated gangue powder's cementing activity on the pore structure, micromorphology, and mineral compo-

sition of concrete's interfacial transition zone, as well as the process behind it. The results revealed that concrete created using 15% heat-activated cement instead of cement at 800 °C had flexural and compressive strengths that were 0.39% and 5.94% lower than those of pure cement concrete, respectively, and 7.47% and 20.17% greater than those of original gangue powder concrete. This is mostly due to the activation of gangue powder rich in active Al_2O_3 and SiO_2 heat-activated gangue at 800 °C, which combines with calcium hydroxide, a cement hydration product, to generate calcium silicate gel. The pores in the interfacial transition zone are then filled and changed into smaller pores, optimizing the pore structure and microscopic morphology of the interfacial transition zone while also tightening the link between the matrix and aggregate.

Wu et al. [10] found that CG content had the reverse impact on compressive strength. Among them, fibers improve strength by preventing cracking, while CG content remains crucial. In the end, polypropylene fibers effectively reinforced CG concrete under cyclic stress at 20% and 40% CG replacement. This is because polypropylene fibers minimize energy consumption in gangue concrete, with the impact varying based on quantity and percentage. The elevated stress amplitude induces abrupt residual strain fluctuations, which are alleviated by polypropylene fibers, increasing the resistance of the sample to damage. Repeated loading raises the damage factor of the concrete samples. The higher the content of CG, the more damaging it is. Polypropylene fibers can minimize damage to a maximum of 33.76%.

Xu et al. [123] observed that the split tensile strength of fiber-reinforced coal gangue-based geopolymer concrete (FRCGGPC) may be greatly enhanced, although the improvement in compressive strength is not immediately apparent. The control group, which included steel fibers (SF) and polyester fibers (PF), had the highest compressive strength. At the same dose, SF and PF improved the split tensile strength of FRCGGPC more than basalt fiber (BF). The findings of the SEM study revealed that the fibers were securely bound to the matrix with a good force transfer effect, increasing the strength of the matrix material within a specific dose range. When there is an excessive amount of fiber, it is simple to aggregate, resulting in a deterioration in the specimen's mechanical characteristics. Figure 20 shows that there is no overdispersion between the phases of FRCGGPC, and the integrity is good. Each fiber is contained within the pulp. The interaction between the matrix and the fibers is obvious, as some fibers are dragged out. This circumstance shows that the fibers share a portion of the external load and so fracture, implying that the fibers greatly boost the tensile strength of CCGPC. CCGPC's split tensile characteristics increased; however, there were inconsistencies across the three fibers. SF was the most effective, followed by PF and BF, which showed the least improvement. Fibers corrode in alkaline settings, and recombination occurs during dissolution. This immediately reduces the amount of fibers available to exchange external stresses while weakening the limiting influence on crack generation and extension. Furthermore, ductility does not define the fraction of the BF that can bear stress after being damaged. Because of the flat surface, friction between the BF and the substrate is minimal. However, the microscopic properties of PF and SF in the matrix differ significantly from those of BF. The most important impact of SF on CCGPC split tensile properties. The following is from the standpoint of science fiction: (1) The surface of SF is rough and covered with a substantial quantity of adhering matrix. The fibers and matrix have a high contact stress, which effectively limits their relative motion and prevents fracture formation. (2) The wavy form of SF significantly improves mechanical occlusion between it and the matrix. (3) Because SF is difficult to break under tensile circumstances, it maximizes its bridging effect throughout the loading phase. From the perspective of PF, (1) the surface of the PF that is not encapsulated in the matrix is not as smooth as the BF surface. Some fiber surfaces not only exhibit a modest

amount of adhering matrix but also scratches and depressions. This suggests that there is friction between the fibers and the matrix. Rough fibers provide more complicated strains at the contact interface, limiting the relative motion of the fiber matrix. The impact also extends to a circular radius at a distance from the contact interface. Furthermore, smooth fibers generate relative sliding and mild relative forces at the contact point. (2) PF is a hydrophobic fiber with low surface roughness that may be improved by surface treatment to increase contact stress with the concrete matrix. The adhesion substrates in Figure 20i are activated polar groups formed in an alkaline environment. The agglomeration issue is obvious throughout the mixing phase, and the scattered fibers are unable to fully use the matrix's overall restrictions. Agglomeration also causes holes in the matrix to develop, as well as weak connections around them. Figure 20j clearly shows that the removed PF end has apparent tearing features, as well as some deformation at the fracture site. This demonstrates the PF's ductile qualities and how it counteracts part of the energy from external stresses while bridging the substrate. It was eventually removed after reaching its own carrying capacity limit. Figure 20 shows the details.

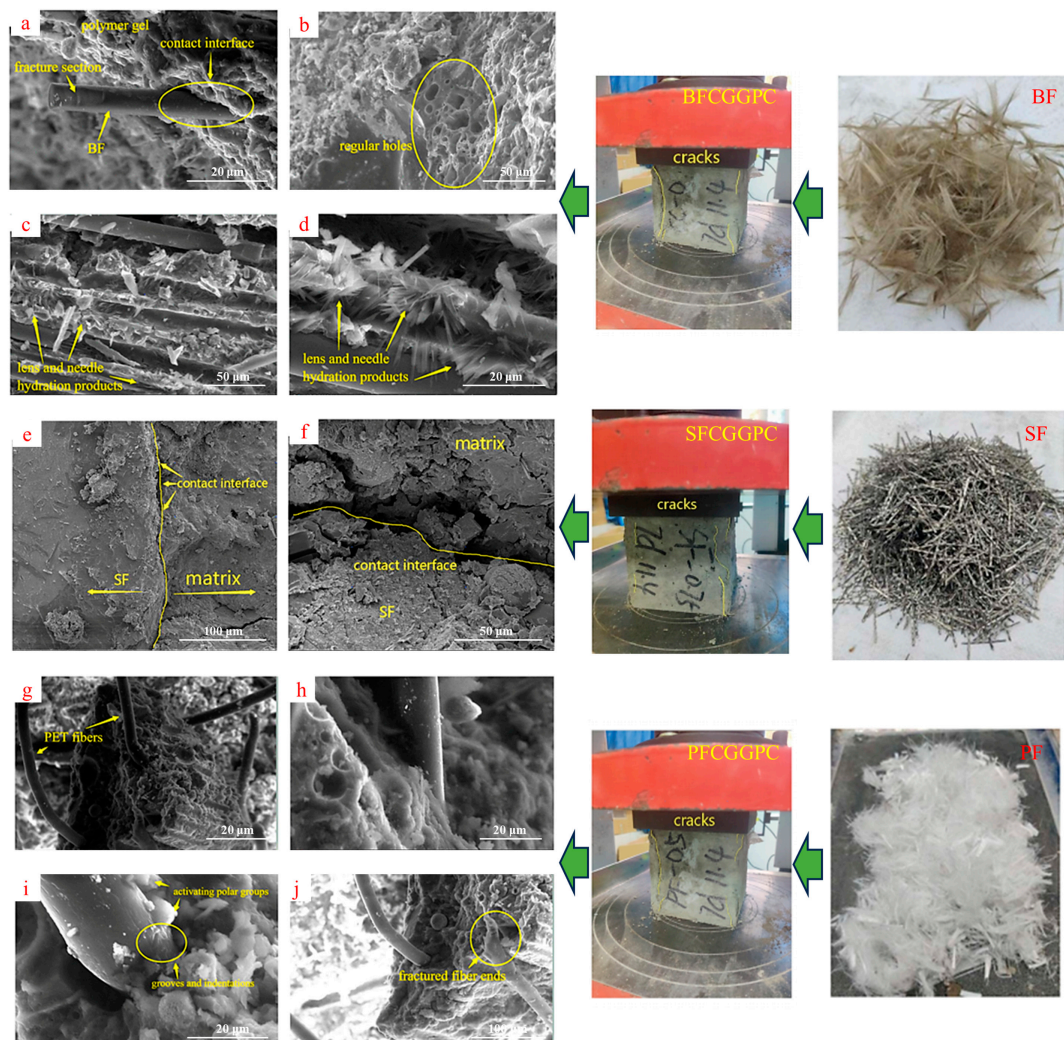


Figure 20. BFCGGPC: contact interface (a), regular holes (b), lens and needle hydration products (c), lens and needle hydration products (d); SFCGGPC: contact interface (e,f); PFCGGPC: PET fibers (g,h), grooves, groups, and indentations (i), fractured fiber ends (j) [123].

Ji et al. [124] stated that capillary water absorption is an important component in determining the durability of concrete buildings. Adding activated gangue powder (ACGP)

to concrete enhanced its frost resistance. Gangue-based concrete (GBC) has poorer capillary water absorption than regular concrete, as well as a lower water content and absorption, and the impact is most noticeable when ACGP is applied at a 20% concentration. The depth of water absorption steadily rises in proportion to the number of FTCs and absorption duration. The considerable linear association between water content and suction depth sheds fresh light on forecasting difficult-to-measure suction depths using easily available water content. The depth of water absorption was much greater than the thickness of the damage layer, and this disparity increased with the addition of ACGP. In addition, the researchers discovered an essentially linear relationship between the depth of water absorption and the thickness of the damage layer. Figure 21 shows the details.

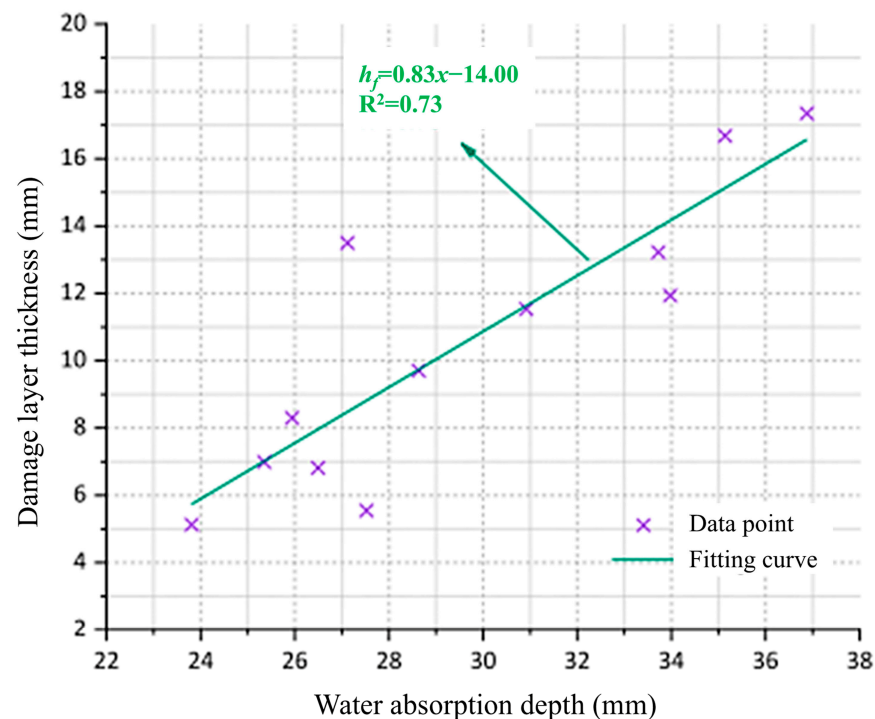


Figure 21. Fitting curving relationship ($R^2 = 0.73$) between damage layer thickness and water absorption depth [124].

Xiao et al. [125] believe that concrete materials are frequently subjected to external loads and environmental factors simultaneously in actual engineering and that focusing solely on the freeze–thaw effect does not describe the deterioration properties of gangue concrete, preventing the application and popularization of gangue. The researchers examined the MLR, damage layer thickness, relative dynamic elastic modulus, and compressive strength of gangue concrete with a 40% replacement rate, as well as the degradation properties of the pore structure and the interfacial transition zone. They also discussed the impact of varying levels of stress on the pore grade ratio, pore size distribution, pore fluid properties, and interfacial zone properties. The findings revealed that the higher the bending stress ratio, the faster the relative dynamic elastic modulus and compressive strength of gangue concrete degraded, the faster the damage layer thickened, the larger the proportion of large pores within the sample, and the pore connectivity increased. Furthermore, the interface zone between the mortar and gangue aggregate is the weakest component of gangue concrete, with thickness and microhardness increasing and decreasing as the stress level increases. The sample approaches failure as the interfacial area deteriorates. Figure 22a–d depict the apparent shape of gangue concrete following 40 FTCs with varying bending stress ratios. The surface of gangue concrete without bending force was sparsely

distributed, with some holes induced by cement paste separation. The number of holes and defects on the sample surface increased as the stress ratio was set to 0.2. The specimens deteriorated substantially as the stress ratio approached 0.4, and aggregate exposure became more noticeable. At the same time, there are little microcracks between the loading points. As the applied bending stress ratio approached 0.6, the specimen surface spalled further, the width of the crack between the loaded bearings expanded and lengthened, and the lower and the top surfaces of the sample were pierced along the faults disclosed in the aggregate. Figure 22e,f illustrate the microstructures of the transition zone at the interface of specimens with varying stress ratios. When the stress level equals zero, the damage in the specimen's interface zone is minimal, the bond between the gangue aggregate and the mortar matrix is strong, the structure of the interface zone is dense, a few microcracks extend to the bonding zone of the mortar matrix, and there is no cracking in the closed pores incorporated by the air-entraining agent. As the stress level rises to 0.2, microcracks appear in the interfacial area of the specimen, and the crack width margins are longer compared to those of the specimen with a zero stress ratio. At the same time, there are larger connecting holes, and a few closed bubbles have burst. At this point, the specimen is slightly more damaged than the unloaded specimen. When the stress level reaches 0.4, the micropores in the matrix section expand, the pore size rises dramatically, the crack extension widens, and many fractures link. The link between the mortar matrix and the aggregate becomes slack, and the interfacial area expands dramatically. The damage to the specimens rose dramatically when the applied stress level was raised to 0.6. Cracks formed within the mortar matrix are linked and staggered with those at the interface. The interfacial structure is loosened, scattered particles emerge on the surface, closed pores rupture and flow via fractures, pore size and diameter grow dramatically. Scanning electron microscopy analysis of the structure revealed that increasing the stress level hastened the degradation of gangue concrete, weakening the link between the mortar matrix and the aggregate, as well as loosening the structure of the interfacial area. Figure 22 shows the details.

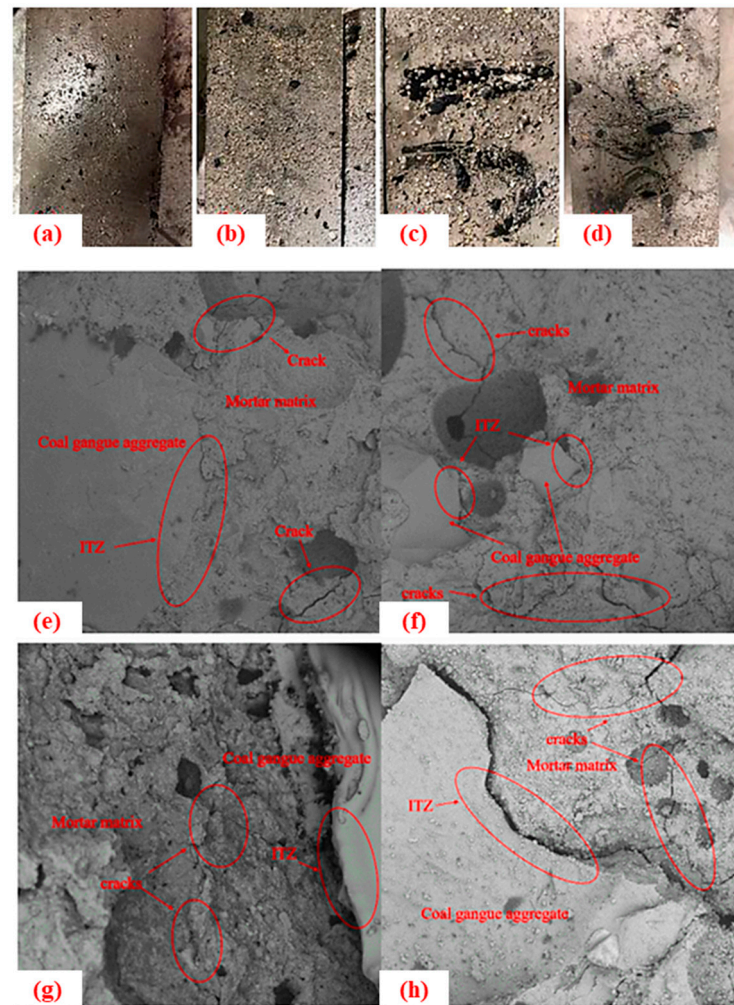


Figure 22. The apparent morphologies of CG concrete for various stress ratio ((a–d) S0, S2, S4, S6) and the micromorphology of ITZ between the mortar matrix and the CG aggregate ((e–h) S0, S2, S4, S6) [125].

6. Economic Viability

Wu et al. [71] concluded that it is viable and practicable to entirely replace natural aggregates with CG aggregates and produce CGPC in collaboration with WSAC. As manufacturers increasingly emphasize the economic value of building materials based on solids, it is critical to compare the manufacturing costs of conventional PC and CGPC in order to determine the commercial viability of novel products. A comparison of the economic and technical performance parameters of CGPC with the standard PC is provided in Table 3. The cost per cubic meter of CGPC is just CNY 155.67, offering a 50.6% saving in comparison to conventional PC (costing CNY 314.9), implying that the adoption of CGPC can produce significant profit margins and positive market competitiveness for firms. Furthermore, based on the low carbon emission features of CGS and WSAC in manufacturing engineering, the CO₂ emissions per cubic meter of CGPC produced are estimated to be 114 kg, which is only 43% of the emission produced by conventional PC (265 kg CO₂ emissions). More importantly, the manufacturing of CGPC does not require energy-intensive silicate cement or mined NA. Also, the utilization rate of solid waste is close to 100%, highlighting its high social and economic value as well as development space and diverse application prospects in conserving natural resources, lowering costs, and alleviating the environmental pressures of CG emissions and storage.

Table 3. Economic viability analysis of CGPC [71].

Raw Materials	Unit Price CNY (USD)/t	Traditional PC		CGPC	
		Mix Proportion t/m ³	Cost CNY (USD)/t	Mix Proportion t/m ³	Cost CNY (USD)/t
Water	4.1 (0.61)	0.12	0.49 (0.07)	0.14	0.57 (0.08)
NA	110 (16.35)	1.48	162.8 (24.19)	/	/
CGAs	35 (5.20)	/	/	1.48	29.6 (4.40)
Portland cement	450 (66.87)	0.33	148.5 (22.07)	/	/
WSAC	375 (55.73)	/	/	0.33	123.7 (18.39)
Fly ash	90 (13.37)	0.04	3.6 (0.53)		
SCGP	45 (6.69)			0.04	1.8 (0.27)
Total cost CNY (USD)/m ³		314.9 (46.79)		155.67 (23.13)	
CO ₂ emissions t/m ³		0.265		0.114	

Wu et al. [73] evaluated the production cost of LCPEC and the findings are displayed in Table 4. The production cost of 1 m³ of LCPEC and standard eco-concrete is CNY164.85 and CNY286.97, respectively. It has been discovered that the primary component contributing to the reduced overall price of LCPEC is the availability of cheap raw materials, which is caused by low energy consumption during the manufacturing phase of the primary raw material WSAC and the usage of solid waste. The LCA [126,127] and economic evaluations reveal that LCPEC has a less severe impact on the environment compared to conventional eco-concrete. It is more cost-effective in lowering raw energy utilization and material costs. The greenhouse gas emissions and cost of making 1 cubic meter of LCPEC are 32.5% and 57.4% lower than conventional eco-concrete, respectively.

Table 4. Economic viability analysis of LCPEC [73].

Items		Unit Price CNY (USD)/t	Traditional Eco-Concrete		LCPEC	
			Dosages t/m ³	Cost CNY (USD)/t	Dosages t/m ³	Cost CNY (USD)/t
Raw material cost	NA	110 (18.95)	1.47	161.7 (23.56)	/	/
	SCGAs	40 (5.82)	/	/	1.47	58.8 (8.57)
	PO-42.5	346 (52.17)	0.26	90.1 (13.13)	/	/
	LACM	235 (35.65)	/	/	0.36	84.6 (12.33)
	GBFS	220 (32.07)	0.04	8.4 (1.28)	/	/
	Fly ash	90 (13.12)	0.1	9 (1.31)	0.04	3.6 (0.56)
	Water	4.1 (0.64)	0.12	0.49 (0.08)	0.14	0.57 (0.09)
Electricity costs	Concrete mixing	USD 0.14/kwh	2.5 kwh	2.4 (0.35)	2.5 kwh	2.4 (0.35)
Shipping costs	Transport diesel	USD 1.16/t	1.87	14.88 (2.17)	1.87	14.88 (2.17)
	Total cost CNY (USD)/m ³		286.97 (41.84)		164.85 (24.03)	

Zhang et al. [82] discovered that the replacement rate of CG was negatively correlated with environmental impacts and willingness to pay (considering transportation costs) but positively correlated with willingness to pay (without considering transportation costs) using a life cycle evaluation. The environmental effect of CG concrete defines the equilibrium point where the desire to pay (after accounting for transportation costs) is equal at different replacement rates. Based on the experimental findings, the researcher suggested a prediction formula for the equilibrium point for various transit distances.

When the continuous transit distance between CG and natural sand reaches 140 km, using CG can provide significant environmental advantages.

7. Existing Problems with CG as Concrete Aggregate

Although CG aggregate concrete has several benefits and application, there are some obstacles and limits, which are mostly expressed in the following characteristics (as illustrated in Figure 23):

- (1) The main factors that prevent CG from being used as aggregate for high-performance concrete are its high porosity, high water absorption, and low strength, and the impact of the pore size distribution of CG aggregate, the connectivity of the pores, and its rate of water absorption and return on the performance of the concrete has yet to be determined. CG aggregate is presently mostly employed in the manufacture of low strength grade concrete, and its utilization rate remains low. The practicality of CG aggregate for high performance concrete is currently being investigated, and there are no comparable CG aggregate standards to use as a reference.
- (2) The influence of carbonaceous matter in CG on its own strength has been a difficult problem to solve in the utilization of CG as an aggregate, whereas the combination of carbonaceous matter in the surface layer of gangue with the cement–matrix interface has been reported in a few studies. And CG in the minerals and chemical composition is more complex, the distribution of minerals in the CG is also difficult due to statistically different origins of CG performance fluctuations, and even within the same region of the CG’s performance, there are differences in the utilization of CG aggregate, which requires targeted in-depth research.
- (3) Calcination is a common means of removing carbon from CG, high temperature calcination of CG in the mineral composition may change, it has been suggested that calcination of CG can make its kaolinite minerals transformed into reactive biotite kaolinite, the secondary hydration reaction can improve the interface between the aggregate and the cement matrix, but high temperature and changes in the mineral phase on the gangue aggregate microstructure of the impact are not clear. Gangue for aggregate utilization or to improve the performance of gangue aggregate, whether or not calcined treatment is required, needs to be further explored. The study of economic and low-energy consumption gangue aggregate pretreatment and performance enhancement technology is to realize the key to the bulk utilization of gangue aggregate.
- (4) The CG contains significant quantities of dust and hazardous materials, which may have an adverse effect on the durability and mechanical qualities of concrete and must be improved using appropriate means. The unpredictable quality of CG aggregate can cause changes in the quality of concrete, necessitating stringent quality control and proportioning design. Furthermore, the development and maintenance of CG aggregate concrete need careful management and operation in actual engineering applications.

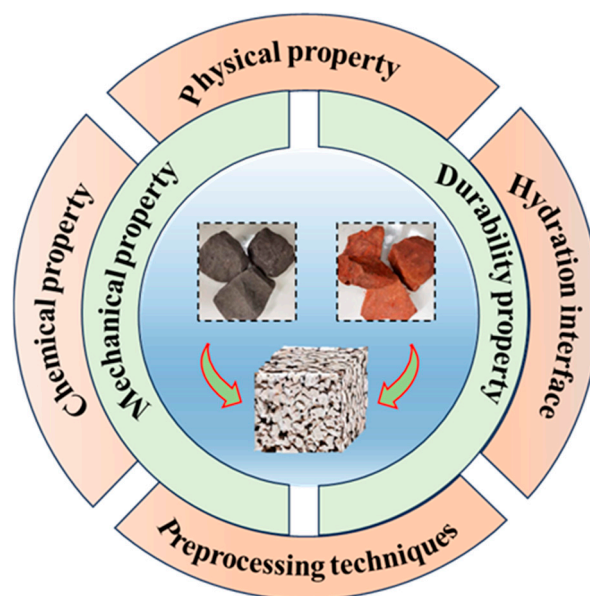


Figure 23. Challenges and research directions in the application of CG aggregate concrete.

8. Conclusions

CG is already one of the main solid wastes released in China due to the country's essential national status of being both a coal producer and a coal consumer. The research on the resource utilization of CG has never stopped, but the CG can still not be used efficiently and in large quantities, while the consumption of non-renewable resources, such as natural sand and gravel, has caused some problems in infrastructure construction. CG concrete uses gangue as an aggregate, which may effectively minimize natural resource mining, which is beneficial to resource conservation and environmental preservation, as well as to improve the compactness and durability of concrete by providing superior mechanical qualities. CG aggregate concrete is also less expensive than normal concrete, lowering overall building costs. Although CG has great potential for use as concrete aggregate, and its treatment and large-scale use as aggregate is of great strategic significance, the carbonaceous gangue's porous water-absorbent, low-strength, and other characteristics present obstacles to its application, and there is a long way to go to find ways to improve its performance. Considering China's coal-producing areas are very fragmented, the performance of CG differs widely among regions. Therefore, research on CG aggregate must be targeted. In summary, gangue concrete, as a novel form of concrete material, has a wide range of applications and development opportunities after a thorough evaluation of its feasibility and practicability in terms of mechanical qualities, durability, mechanism, and economy. However, when applied to a specific project, it must be conducted by using scientific and technical methods to assure the project's quality and safety while taking into account all of its features and constraints.

Author Contributions: L.C. (Liang Cheng) generated the initial ideas of this work and developed the theory and the design approach. L.C. (Liang Cheng), L.Z. and L.C. (Linfeng Cheng) performed the experiments and analyzed the data. Y.G. and H.G. guided the research, and Y.C. performed the device characterization and measurements. L.C. (Liang Cheng) and H.F. wrote the manuscript. L.C. (Liang Cheng) supervised the project. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Open Project of Collaborative Innovation Center of Mine Major Disaster Prevention and Environmental Restoration (CXZX-2024-10), Basic Research Project of

Liaoning Provincial Department of Education (524053230/24-1089), and Doctoral Research Initiation Project of Liaoning Technical University (636000116/24-1011).

Data Availability Statement: Not applicable.

Acknowledgments: The authors thank Z. Ma for help with this research.

Conflicts of Interest: L.C. (Liang Cheng) was employed by Liaoning Technical University and the Collaborative Innovation Center of Mine Major Disaster Prevention and Environmental Restoration. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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