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Current status of research on the mechanical properties of gangue concrete with different mixing amounts

Xiaorui Jia, Juannong Chen and Bo Liu *

School of College of Civil and Architectural Engineering, North China University of-Science and Technology, Tangshan 063210, China.

Abstract

Coal gangue is an industrial waste with high calorific value, mainly generated from the gangue removed during coal washing and the waste rocks discharged during tunnel excavation, causing serious environmental pollution. However, it is also a valuable mineral resource. Adding coal gangue to concrete can improve its strength, workability, durability, and resource utilization. At present, there is not much research on the mechanical properties of coal gangue concrete with different dosages. This article studies the physical and mechanical properties and working performance of coal gangue concrete, and summarizes the mechanical properties of slurry/mortar/concrete mixtures containing coal gangue powder with different dosages as cement substitutes, including compressive strength, tensile strength, drying shrinkage, and workability. In order to provide reference for the research of coal gangue concrete, and to prospect its future development prospects.

Keywords

Coal gangue; Concrete; Mechanical properties; research status.

1. Introduction

Sustainable development refers to the practice of human production, lifestyle, and creative activities that do not compromise the needs of future generations. This model was first recognized as a global development approach in 1987 [1]. China has also been engaged in ecological and environmental protection work since 1972 [2]. In China, coal gangue accounts for 15-20% of coal production, with an annual discharge exceeding 7 billion tons. Due to its long-term persistence in the soil, coal gangue has severely impacted the atmosphere and soil, and has even led to geological disasters [3,4]. The comprehensive utilization of coal gangue has become a significant challenge globally [5-8].

The construction industry is rapidly developing, with the production of one ton of Portland cement (PC) emitting 800-1,000 kilograms of carbon dioxide [9,10]. Achieving low-energy, low-consumption, and low-emission cement-based composites has become a current research hotspot. In 1940, Purdon [11] was the first to utilize sodium hydroxide to activate volcanic ash to produce a new type of alkali-activated cementitious material. Research findings indicate that this composite cementitious material exhibits a dense structure [12-14]. Therefore, utilizing organic silicon represents a green and environmentally friendly approach for the efficient recovery of industrial solid waste.

A portion of researchers have used mechanically or thermally activated coal gangue as an additive in concrete [15]. This paper provides a systematic introduction to coal gangue and its powder in general, and reviews domestic and international research on the use of coal gangue powder to replace cement in concrete preparation. It focuses on its compressive strength, tensile strength, workability, and drying shrinkage rate. Additionally, it outlines future research

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trends and directions for developing new types of concrete with various dosages of coal gangue powder.

2. General Characteristics of Coal Gangue

2.1. Physical Properties

Coal gangue (Fig 1) is a type of rock formed during the coal formation process, resulting from the combination of organic matter and inorganic substances that settle alongside coal. It typically occurs in thin layers and appears black or dark gray. Most coal gangue that has not undergone spontaneous combustion is predominantly black, with a relatively dense structure. In its natural state, it may exhibit a slight reddish hue and tends to have a more porous structure.

Coal gangue comprises various types, including clay minerals, sandstone, carbonate rocks, and aluminum-rich rocks. It is rich in clay minerals such as kaolinite, illite, and montmorillonite, while its primary components include quartz, calcium carbonate, pyrite, and carbonaceous materials. However, the exact mechanisms of its formation remain unclear. The hardness of coal gangue varies depending on the mineral composition and sediment characteristics, but it is generally soft and prone to cracking.

The surface of coal gangue is often covered with coal mud and fine particles, making it loose with many flaky particles and pores, resulting in considerable variability in its properties. Coal gangue can self-combust at certain temperatures after being stored for a long time, forming natural coal gangue. The bulk density of natural coal gangue typically ranges from 900 kg/m^3 to 1300 kg/m^3, with high porosity, low carbon content, and certain pozzolanic properties [16].

(a) Flaky gangue (b) Raw gangue

Fig. 1 Picture of gangue

2.2. Chemical composition

Coal gangue is a mixture of many kinds of rock mass, its chemical composition is according to the rock type and mineral composition changes. For example, clay rock type gangue is mainly SiO_2, and Al_2O_3, SiO_2 fluctuates in 30~60%, Al_2O_3 fluctuates in 15~40%.

Yanbing Zhao et al. [17] conducted laboratory experiments on coal gangue in the Ordos region of Inner Mongolia, China, using S95-grade fine slag as a supplementary cementitious material. This resulted in a cementitious material with a specific surface area of 450 kg/m^2 and a density of 2.9 g/cm^3, which was characterized and compared to Ordinary Portland Cement (OPC).

X-ray fluorescence analysis was performed to assess the primary compositions of coal gangue, slag, and OPC (Table 1). The study found that the hydration products differed significantly due to the lower calcium oxide content in coal gangue and relatively higher levels of SiO_2 and Al_2O_3.

Di Wu et al. [18] obtained mature coal gangue (C-CG) powder (Table 2) through a sintering process at 800°C for 2 hours, with both heating and cooling rates set at 2°C/min. The results indicate that the particle size distribution of CG and C-CG is comparable to that of cement, while the calcined powder exhibits higher pozzolanic activity.

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Table 1 Chemical compositions of the materials (%)

Components	SiO2	Al2O3	Fe2O3	SO3	MgO	CaO	Na20	K2O	Others	LOI
Coal gangue	55.14	40.96	1.23	0.43	0.30	0.41	0.09	0.20	1.24	15.33
OPC	21.08	7.10	3.45	3.85	2.11	60.2	0.21	1.16	0.84	2.10%
Blast furnace slag	36.10	16.32	-	-	11.32	35.58	-	-	0.68	2.30

Table 2 Chemical composition and physical properties of cement, silica fume (SF), CG and C-CG (wt%)

	Cement	SF	C-CG	CG
CaO	67.78	0.69	0.17	1.47
SiO_2	18.55	95.56	53.01	35.53
Fe_2O_3	3.71	0.18	0.46	1.43
Al_2O_3	4.34	0.34	45.61	57.69
MgO	1.85	0.89	0.07	0.36
SO_3	2.82	1.52	-	0.64
K_2O	0.7	0.53	0.1	0.24
P_2O_5	0.1	0.52	0.06	0.12
Na_2O	0.09	0.11	-	0.11
Specific gravity	3.15	2.2	2.6	2.82
Loss of ignition	2.45	1.73	0.07	0.14
Specific surface area (m^2/kg)	350	18,816	3816	10,184

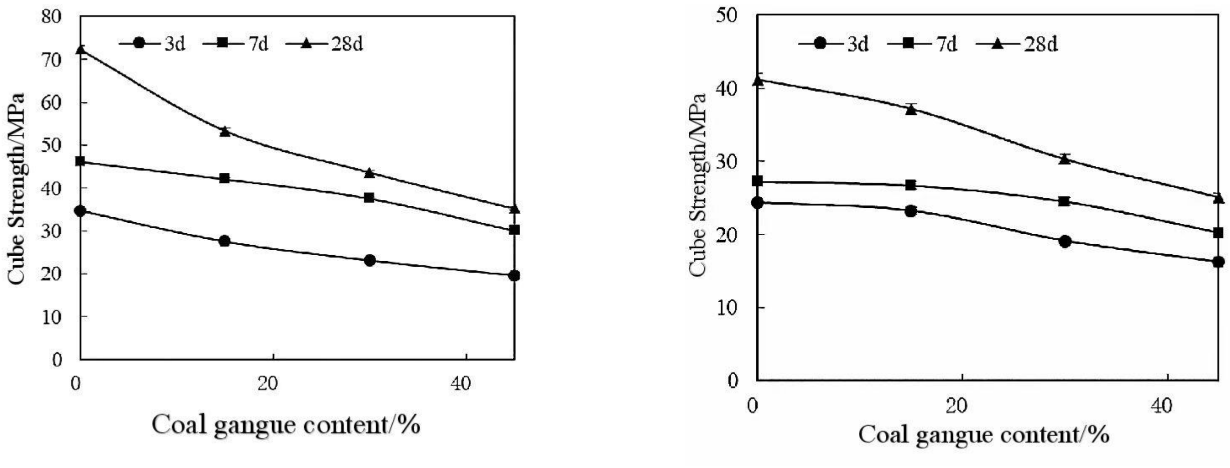
3. Current status of research on the mechanical properties of concrete with different gangue admixtures

3.1. Compressive strength

The study investigated the preparation method for coal gangue concrete cubic samples, which included stages of pre-wetting the coal gangue, mixing it with the cement matrix, combining the materials, preparing the mix, and curing. A new process was introduced for preparing a mixture of coal ash, and experimental research was conducted.

According to the standards specified in GB/T50081-2019 [19] for testing the physical and mechanical properties of concrete, compressive strength tests were performed, applying a uniform load at a rate of 0.5 MPa/s. During the tensile tests, an initial uniform load was applied until all samples failed, and their failure behavior was recorded using the load F, followed by a constant-speed loading. The three experiments were conducted using two sets of parallel specimens, and the average values were calculated as the experimental results.

Xuan Chen [20] experimentally determined the compressive strength and splitting tensile strength of gangue concrete with admixture of 15%, 30% and 45% respectively, and analyzed the effect of gangue admixture on the compressive strength of gangue concrete under different conditions (water cement ratio, age of curing), and the results of the test are shown in Fig 2.



(a) Water cement ratio 0.3 (b)Water cement ratio 0.3

Fig. 2 Compressive Strength of Concrete with Different Proportions of Coal Gangue

Fig 2(a) shows that both ordinary concrete and coal gangue concrete exhibit an increase in cubic compressive strength with age, and the rate of growth is relatively rapid. However, the strength of coal gangue concrete is lower compared to that of ordinary concrete, and the compressive strength decreases as the proportion of coal gangue increases. Furthermore, the strength growth rate for ordinary concrete and coal gangue concrete (at 15%, 30%, and 45% replacement levels) decreases from 2.8 MPa/day to 3.6 MPa/day during the 3d to 7d period, dropping to 0.43 MPa/day to 0.78 MPa/day from 7d to 28d.

Di Wu et al. [18] also conducted experiments to investigate the relationship between compressive strength changes and coal gangue content at different curing ages, as illustrated in Fig 3. The inclusion of coal gangue tends to reduce early strength, with the exception of CG20, where the addition of 20% coal gangue powder results in a strength increase of 15.9%.

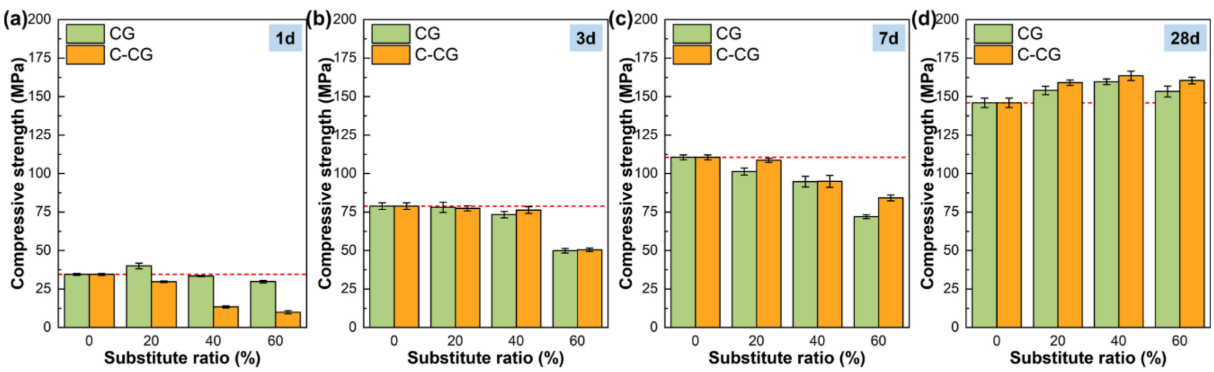


Fig. 3 Compressive Strength of Concrete with Different CG and C-CG Contents at (a) 1d, (b) 3d, (c) 7d, and (d) 28d

Gradually, the strength increases, and the strength gap between coal gangue modified concrete and the control group narrows. At 28 days, the concrete containing coal gangue demonstrates comparable strength, indicating that coal gangue has significant pozzolanic activity. Moreover, concrete with a high dosage of coal gangue (60%) can reach a strength of 150 MPa, confirming the feasibility of using a large amount of coal gangue in concrete production.

It is also noted that even using a calcination activation process, the actual water cement ratio increases after replacing cement with calcined coal gangue, resulting in lower 1-day strength for concrete containing calcined coal gangue compared to that with uncalcined coal gangue. In the later stages, the strength of CCG60 shows only a slight increase (4.6%) compared to the concrete with uncalcined coal gangue powder, indicating that coal gangue powder can be directly used to prepare concrete. Therefore, considering the energy consumption of the calcination process, it is recommended to use concrete containing 60% coal gangue powder from a strength perspective.

Lidong Qiao [21] also pointed out in his research that the compressive strength of coal gangue concrete over time was explored at both macro and micro levels. Under the condition of incorporating 10% silica fume, the study derived the variation laws of compressive strength influenced by the age, water cement ratio, and different dosages of coal gangue, as shown in Fig 4.

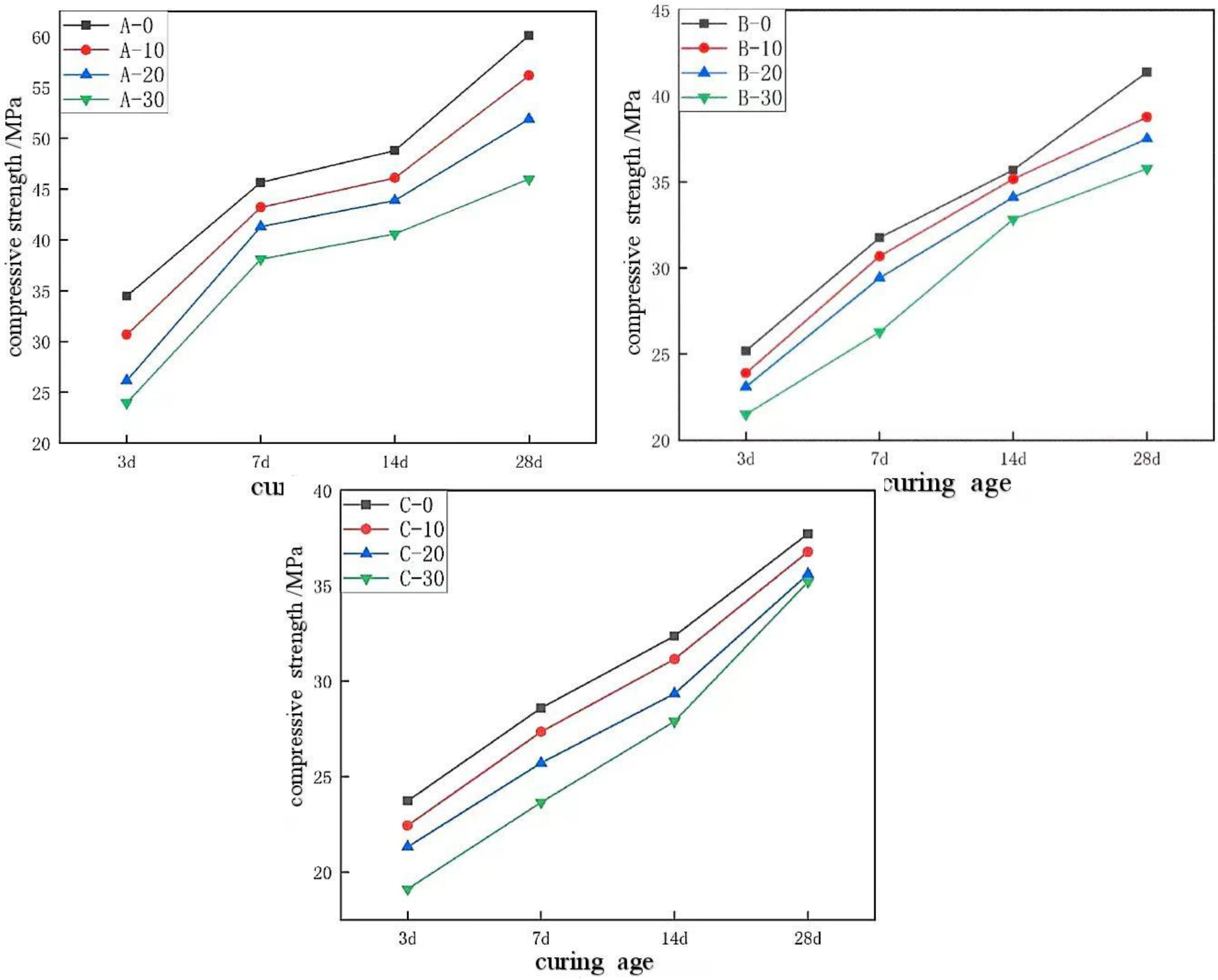


Fig. 4 The relationship between compressive strength and age for groups A (water cement ratio 0.35), B (0.40), and C (0.45)

As the amount of coal gangue increases, the compressive strength of the cement gradually decreases, displaying a trend similar to that of ordinary concrete at all ages. When the water-to-binder ratio is 0.35, the maximum allowable amount of coal gangue reaches 30%, achieving a strength of 45 MPa. Under a water-to-cement ratio of 0.35, the proportion of coal gangue has a significant impact on the compressive strength of the concrete; however, as the water-to-cement ratio increases, the effect of coal gangue incorporation diminishes. Notably, when the incorporation level is at 30%, the influence is less pronounced, indicating good compatibility between the coarse aggregate and the matrix strength. The study results indicate that with a 30% incorporation level, the maximum water-to-cement ratio is 0.45, and the compressive strength of the specimens exceeds 35 MPa.

3.2. Splitting Tensile Strength

Zuochao Dong [22] conducted experimental research on the split tensile strength of coal gangue concrete with varying dosages. It was found that under the same load conditions, as the amount of coal gangue increased, the deformation of the crack surfaces also increased.

Therefore, the crack opening displacement is primarily influenced by the content of coal gangue, the calcination characteristics of the coal gangue, and the water cement ratio. Specifically, concrete with a high content of coal gangue, high crushing value, and a high water cement ratio exhibits greater crack opening displacement under the same load, as illustrated in Fig 5.

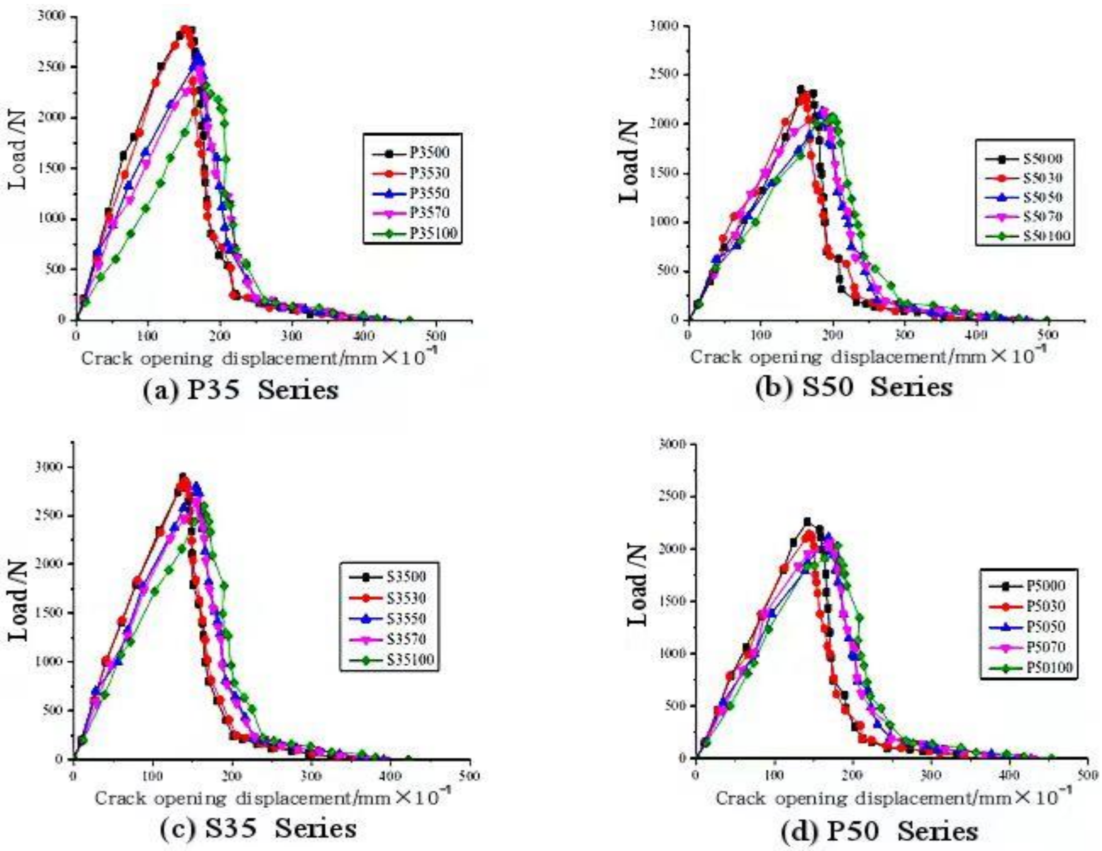
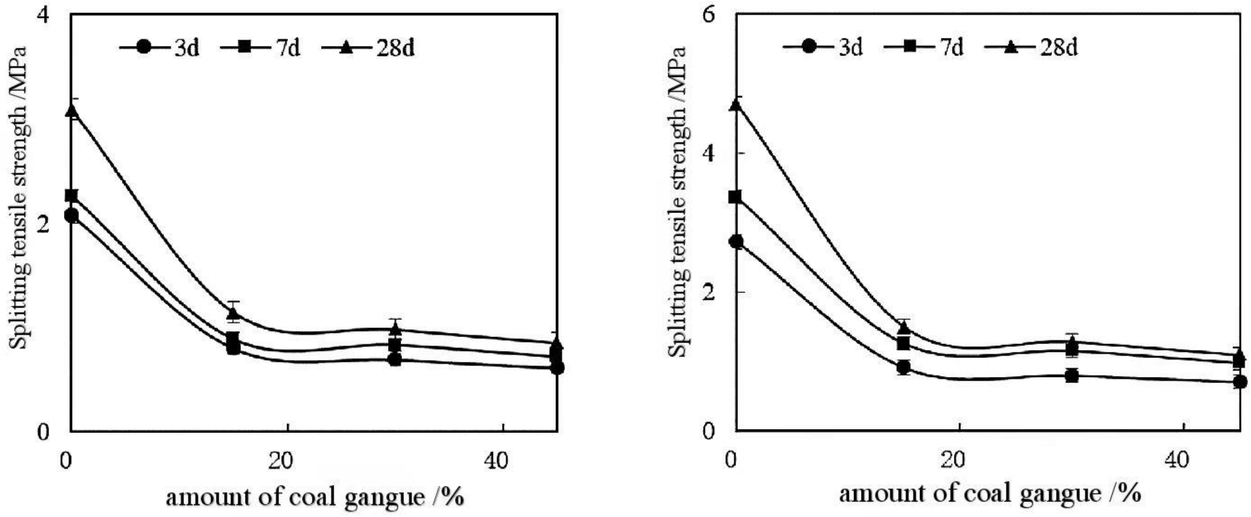


Fig. 5 Comparison of load opening displacement under different coal gangue content

In summary, the tensile and flexural strength of coal gangue concrete is related to the content of coal gangue coarse aggregate, the calcination characteristics of the coarse aggregate, and the water cement ratio. The flexural performance of coal gangue concrete deteriorates with a higher content of uncalcined coarse aggregate and a higher water cement ratio.

Moreover, Xuan Chen [20] also reported the effect of different conditions (water cement ratio, curing age) and varying coal gangue contents on the splitting tensile strength of coal gangue concrete (Fig 6).



(a) Water cement ratio 0.3 (b)Water cement ratio 0.3

Fig. 6 Splitting Tensile Strength of Coal Gangue Concrete with Different Coal Gangue Contents

In the results above, both ordinary and coal gangue concrete exhibit an increase in split tensile strength with age when the water-to-cement ratio is 0.3. However, compared to ordinary concrete, their tensile strength shows varying degrees of decrease, which continues to decline as the proportion of coal gangue increases. This trend aligns with the observed changes in cubic compressive strength.

3.3. Workability of Concrete

Workability refers to the ease with which concrete mixtures can be handled to achieve a uniform and dense final product. It is a comprehensive technical property that encompasses flowability, cohesiveness, and water retention. Workability is critically important in the production and transportation of concrete in civil engineering.

According to Hongqiang Ma [23], the slump of concrete is a key indicator of its workability and plasticity. Experiments measuring the slump values of concrete samples with varying amounts of coal gangue showed that as the amount of coarse coal gangue increased, the slump of the concrete gradually decreased. The slump reduction was more significant with the addition of calcined coal gangue, largely due to the water absorption characteristics of the coal gangue.

Zhao Zhenqing's [24] research also illustrates that, based on experimental data, the slump of concrete decreases as the proportion of coal gangue increases, indicating reduced flowability of the mixture. The size of the slump changes in relation to the amount of water used; when coal gangue is incorporated into the concrete, its water absorption rate exceeds that of the aggregate. This results in a relative decrease in free water within the mixture. As the amount of coal gangue increases, it adsorbs more mixing water, thereby reducing the amount of water available to enhance the fluidity of the cement paste, ultimately leading to a greater loss in slump.

Furthermore, as the replacement ratio of unwashed coal gangue increases, the slump of the concrete decreases linearly, indicating a rapid change in the workability of the mixture.

Di Wu et al. [18] conducted a study on the impact of varying amounts of coal gangue powder on the workability of concrete using slump flow tests, the results of which are illustrated in Fig 7(a).

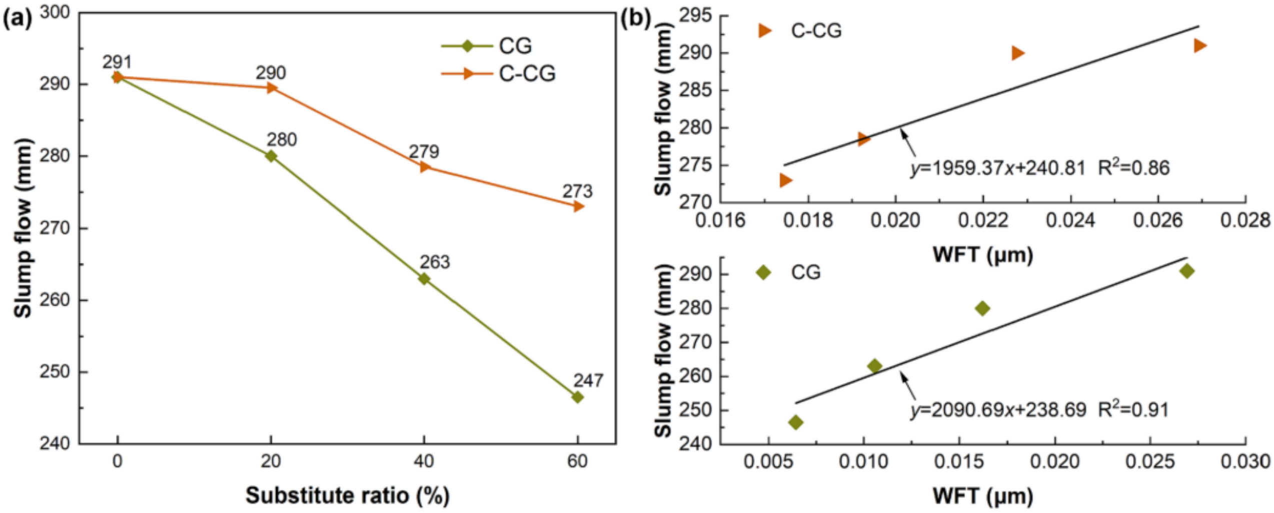


Fig. 7 (a) the slump of concrete with varying contents of coal gangue and calcined coal gangue, and (b) illustrates the relationship between slump and WFT (Water-to-Fines Ratio)

4. Drying Shrinkage

In the process of application, concrete can undergo phenomena such as chemical reactions, internal water content changes, and temperature fluctuations, leading to a reduction in volume. The primary modes of shrinkage deformation in concrete include drying shrinkage, self-shrinkage, and carbonation shrinkage.

Di Wu et al. [18] reported that self-drying shrinkage typically causes micro-cracking in the early stages, which subsequently leads to a drastic decline in the material's strength and durability. Fig 8 illustrates the self-drying shrinkage of concrete containing coal gangue and calcined coal gangue.

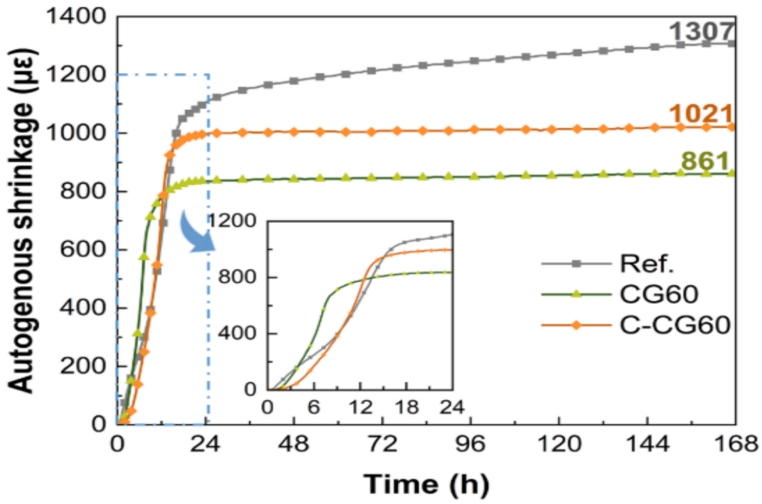


Fig. 8 Self-drying shrinkage of concrete with 60% CG and C-CG

Due to the lower volume of hydration products, the hydration process within the first 24 hours is minimal. However, in the later stages, as the concrete hardens and its resistance to shrinkage increases, the chemical shrinkage is alleviated. Subsequent hydration reduces the humidity within the system, leading to shrinkage. The addition of coal gangue delays the hydration process within the first 24 hours, thereby reducing chemical shrinkage.

Additionally, because of the difference in density between coal gangue and cement, its volumetric displacement can increase the effective water-to-binder ratio, mitigating the self-drying effect caused by reduced humidity. The shrinkage rates are reduced by 21.4% and 34.1% compared to normal concrete. Moreover, the deformation of concrete with burned coal gangue is greater than that of concrete mixed with coal gangue, primarily due to its denser packing structure, which results in finer capillary pores.

Most shrinkage occurs in the early stages; the shrinkage rates for ordinary concrete, CG60, and C-CG60 after one day account for 85%, 97%, and 83% of the total shrinkage after seven days, respectively. After 24 hours, all samples with coal gangue and calcined coal gangue show stable deformation, whereas the reference samples continue to exhibit a slow increase in deformation.

Zhenqing Zhao [24] presented research findings indicating that as the dosage of coal gangue increased, the shrinkage strain of concrete decreased.

Table 3 Shrinkage strain values of coal gangue concrete

养护龄期(d)	混凝土收缩应变(10^{-6})			
	M_1(0%)	M_2(30%)	M_3(40%)	M_4(50%)
3	90.032	80.915	76.8776	73.332
5	113.843	100.358	90.478	89.323
7	120.784	115.408	113.674	102.893
10	158.883	145.026	143.789	139.542
14	187.994	178.236	141.894	140.554
20	278.342	258.091	210.289	180.654
28	300.834	280.024	270.478	230.543
35	350.954	330.267	310.033	270.653
48	370.883	340.718	335.783	300.006
60	390.975	360.238	350.061	320.113
80	392.732	375.234	360.028	340.209
90	400.821	354.897	348.083	333.842
100	460.833	402.782	380.229	350.221
120	480.987	450.432	436.093	380.992

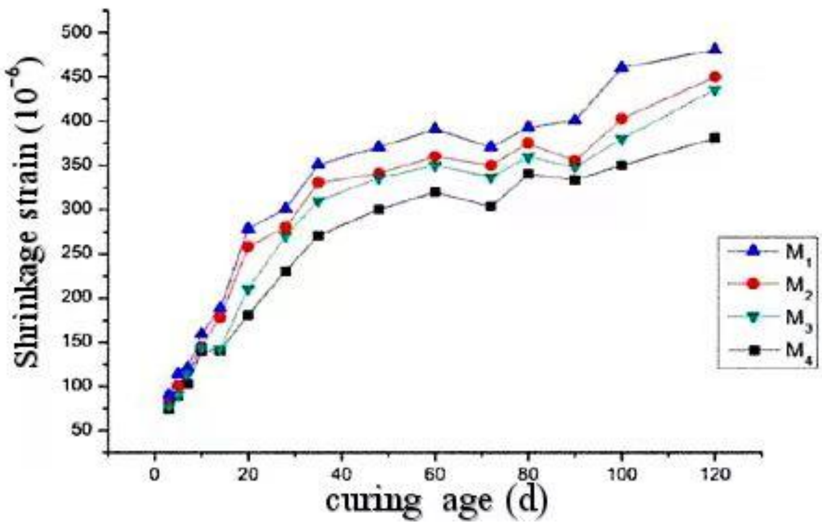


Fig. 9 The effect of coal gangue content on concrete shrinkage

From Table 3 and Fig 9, it can be observed that the variation in concrete shrinkage follows a similar pattern under different curing ages. When the proportion of coal gangue is between 30% and 50%, the shrinkage values gradually decrease, showing no significant effect in the early stages. However, after 14 days, a noticeable increase occurs, although the magnitude of shrinkage is much less compared to concrete without coal gangue.

Compared to concrete without coal gangue, at dosages of 30%, 40%, and 50%, the shrinkage deformation at 120 days was reduced by 6.4%, 9.3%, and 20.8%, respectively. As the coal gangue content increases, the packing density and volumetric content of the aggregate also rise. However, the aggregates themselves provide some restraint against the shrinkage of the concrete, thereby reducing the overall shrinkage deformation. When the coal gangue content exceeds 60%, the mechanical properties of concrete may not meet design requirements, thus a content of around 50% is considered optimal.

Shrinkage is a phenomenon of volume reduction during the hydration process of concrete throughout its entire age, but the changes in shrinkage become minimal after a certain age. When the water cement ratio is constant, as the coal gangue content increases from 10% to 40%, the shrinkage will initially increase and then decrease [25].

From the analysis above, the higher water-cement-ratio leads to a larger maximum shrinkage at a greater coal gangue content. The primary reason for this phenomenon lies in the high reactivity of coal gangue. During the hydration process of cement, $Ca(OH)_2$ reacts with coal gangue, leading to shrinkage [26]. When the water-to-cement ratio is low, the presence of unreacted cement is more significant, resulting in fewer pozzolanic reactions. Consequently, the maximum autogenous shrinkage of the concrete occurs with a small amount of coal gangue.

Concrete is prone to shrinkage due to its high content of binding materials and low water-to-cement ratio. This shrinkage occurs when moisture does not diffuse outward, leading to capillary forces and volume changes caused by hydration reactions as the material dries out.

5. Conclusion

Based on the research conducted on the mechanical properties of concrete with varying amounts of coal gangue, including compressive strength, splitting tensile strength, and workability, the following conclusions can be drawn:

Compressive Strength: There is a specific relationship between the compressive strength of coal gangue concrete and the amount of coal gangue added. The results indicate that a moderate addition of coal gangue can enhance the compressive strength of concrete, although the strength tends to gradually decrease with an increasing coal gangue content.

Splitting Tensile Strength: The addition of coal gangue can increase the aggregate content in the concrete and strengthen the interfacial adhesion, thereby improving the splitting tensile strength. However, when the content of coal gangue is excessively high, the particle shape and distribution may adversely affect the internal structure of the concrete, leading to a reduction in tensile strength.

Workability: A small amount of properly treated coal gangue can enhance the workability and fluidity of concrete, improving its plasticity. However, when the coal gangue content is too high, the water absorption and moisture retention properties of coal gangue can negatively impact the workability of the concrete, increasing construction difficulties.

Drying Shrinkage Rate: The drying shrinkage rate of coal gangue concrete is also influenced by the amount of coal gangue added. As the coal gangue content increases, the water cement ratio rises, and the $Ca(OH)_2$ generated from cement hydration reacts with the reactive material, coal gangue. This interaction contributes to increased shrinkage, which mainly occurs in the early stages of concrete molding. Therefore, when adding coal gangue, it is crucial to adjust the concrete mix design and consider additional admixtures to reduce the drying shrinkage of the concrete.

6. Summary and Outlook

In summary, it is crucial to maintain an appropriate dosage to balance the various mechanical and workability performance characteristics of the concrete. Future research can further optimize the mix design, explore the use of supplementary materials, and conduct long-term performance evaluations and environmental impact assessments to enhance the effectiveness and sustainability of coal gangue concrete applications. The following areas can be focused on in future research:

Optimizing Mix Design: Investigate different proportions of coal gangue concrete to explore the best combinations that can enhance the mechanical properties of the concrete.

Objective Evaluation of Reactivity: To achieve a more objective assessment of the reactivity of coal gangue aggregates, it is recommended to use alternative evaluation methods in comparison with existing ones to leverage the strengths of each.

Theoretical Design Aspects: Much of the current research on coal gangue aggregate concrete is limited to basic physical and mechanical properties. Future work should extend to the theoretical design aspects of fundamental components such as beams, columns, and slabs, as well as further investigate the overall structural performance of coal gangue aggregate concrete.

By deepening research in these areas, a better understanding of the mechanical properties of coal gangue concrete with varying proportions can be attained, leading to optimized mix designs and application techniques. This will enable coal gangue concrete to perform more effectively in engineering practices and provide a scientific basis for the comprehensive utilization of coal gangue resources.

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