A Literature Review on the Substitution of Coal Gangue for Fine Aggregates to Produce High-performance Concrete

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Abstract: Using coal gangue as a substitute for fine aggregate to prepare high-performance concrete integrates environmental protection and economic value. However, there are currently issues such as unstable performance, insufficient long-term durability research, and the need to optimize cost-effectiveness. Future research will focus on breakthroughs in multiple areas: establishing a comprehensive database of coal gangue characteristics, quantifying the relationship between its composition and concrete performance, and accurately designing mix proportions; developing an intelligent quality control system based on artificial intelligence and big data to ensure stable product quality; constructing a long-term durability testing platform to simulate complex service environments, combining numerical simulations to understand performance evolution laws and service life; establishing a lifecycle cost-effectiveness assessment model to reduce costs through technological innovation and policy optimization; integrating frontier technologies to explore new composite modification and collaborative enhancement techniques to improve performance and promote green development; advancing standardized construction and collaboration between industry, academia, and research to facilitate industrial applications. These research directions will provide key support for the large-scale application and sustainable development of coal gangue concrete in the construction industry.

Keywords: Coal Gangue, High-performance Concrete, Fine Aggregate Substitution, Intelligent Quality Control, Long-term Durability, Life Cycle Costs, Compound Modification, Industrial Application.

1. Introduction

With the vigorous development of global infrastructure construction, concrete, as the most widely used artificial building material, faces severe challenges regarding the sustainability of its raw materials. The over-exploitation of traditional fine aggregate sources (such as natural sand) has triggered a series of ecological and environmental problems. Finding sustainable alternative materials has become a research hotspot in the concrete field. Coal gangue, a solid waste generated during coal mining and washing, has enormous output and long-term accumulation. It not only occupies large amounts of land but also pollutes the surrounding environment. Processing coal gangue for use as a substitute for fine aggregate in preparing high-performance concrete can solve the disposal problem of coal gangue, realize the resource utilization of waste, and alleviate the pressure of natural sand resource shortages. This approach offers significant environmental and economic benefits, aligning with the development trend of green building materials.

2. Research on the Preparation of Ultra-high Performance Concrete by Replacing Cement with Coal Gangue Powder

Zhang Min et al. prepared ultra-high performance concrete (UHPC) using coal gangue powder as a cement replacement material, aiming to reduce the carbon emissions of traditional UHPC. The results found that coal gangue powder incorporation deteriorated the packing structure and workability of UHPC, but had little impact on its strength. UHPC containing high dosages (>40%) of coal gangue powder still exhibited strengths greater than 120 MPa. This research provides a new approach for coal gangue recycling while reducing the high energy consumption of UHPC[1].

3. Research Progress on the Influence of Basalt Fiber on Gangue Concrete

Yu L et al. studied the combination of basalt fiber-reinforced polymer (BFRP) confinement and coal gangue concrete as support structures for underground mines[2]. This study found that the tensile strength of BFRP sheets decreased with prolonged sulfate corrosion time; the compressive strength of coal gangue concrete initially increased and then decreased with the occurrence of secondary hydration. FRP confinement could improve the strength and ductility of coal gangue concrete, while sulfate corrosion reduced the strength, ductility, and deformation capacity of coal gangue concrete.

He Z et al. prepared coal gangue concrete by replacing coarse aggregate with coal gangue at a 40% replacement rate. This study added different admixtures and lengths of basalt fibers to the coal gangue concrete[3]. The results showed that when the basalt fiber dosage was 0.10 ~ 0.15% and the length was 18 mm, the compressive strength, splitting tensile strength, and flexural strength of the coal gangue concrete significantly improved; under freeze-thaw cycles, the compressive strength loss rate of coal gangue concrete decreased considerably, and under sulfate attack, the corrosion resistance coefficient of coal gangue concrete significantly increased.

4. Research Progress on the Impact of Spontaneously Combusted Coal Gangue Concrete

Gao B et al. studied the quantitative impact of the replacement ratio of spontaneously combusted coal gangue coarse aggregate on the compressive strength of concrete, revealing the deterioration mechanism of the compressive performance of spontaneously combusted coal gangue aggregate concrete[4]. The results showed that as the replacement ratio increased, the compressive strength of spontaneously combusted coal gangue aggregate concrete decreased accordingly. Compared to natural aggregate concrete, the 28-day axial compressive strength of spontaneously combusted coal gangue aggregate concrete with replacement rates of 50% and 100% decreased to a greater extent.

5. Research Progress on the Impact of Non-spontaneous Combustion Coal Gangue Concrete

Based on the principle that coal gangue coarse aggregate content should not be excessive in ordinary concrete, Wang Z et al. used the principle of "strong encapsulation of weak materials" to prepare high-performance concrete[5]. This study considered the influence of four factors: water-binder ratio, non-spontaneous combustion coal gangue coarse aggregate content, fly ash-slag mass ratio, and silica fume coating on high-performance concrete. The results showed that the non-spontaneous combustion coal gangue coarse aggregate content had the greatest impact on the compressive strength, sulfate resistance, and frost resistance of concrete; the water-binder ratio had the greatest impact on carbonation resistance. This provides a basis for preparing high-performance concrete with non-spontaneous combustion coal gangue coarse aggregate.

6. Research Progress on the Influence of Coal Gangue Powder on Durability

Murtaza M et al. used the absolute volume method to study the effects of fly ash, coal gangue powder, cement kiln dust, and recycled concrete powder on the durability of self-compacting concrete[6]. In terms of freeze-thaw resistance, self-compacting concrete containing coal gangue powder had the lowest mass loss rate and the best frost resistance.

7. Research Progress on coal Gangue Powder Aggregate Concrete

Wang Y et al. studied the bond behavior of concrete-filled steel tube (CFST) columns using coal gangue coarse aggregate[7]. The results showed that the ultimate bond strength decreased with an increase in the number of push-out load cycles. The steel tube remained elastic, and the longitudinal strain of the steel tube increased nonlinearly from the loading end to the free end. As the coal gangue coarse aggregate replacement rate increased, the reduction in ultimate bond stress also increased. The influence of steel tube thickness, steel tube outer diameter, and concrete strength on the ultimate bond stress was comparable to that of ordinary CFST columns.

8. Study on the Durability of Alkali-activated Gangue Slag Concrete

Hongguang Z et al. studied the variation patterns of compressive strength and durability of alkali-activated coal gangue-slag concrete[8]. The results showed that coal gangue as coarse aggregate exhibited high compressive strength and good durability in alkali-activated coal gangue-slag concrete. Alkali-activated coal gangue-slag concrete with calcined raw coal gangue coarse aggregate showed significant advantages in compressive strength and sulfate attack resistance. Under high dosage conditions, its long-term frost durability and chloride ion permeability resistance were inferior to that with raw coal gangue coarse aggregate. This study provides an experimental basis for the large-scale utilization of coal gangue. Alkali-activated coal gangue-slag concrete exhibits good sulfate attack resistance. The content range of raw coal gangue coarse aggregate should be 30% ~ 50% in freeze-thaw environments. This provides a basis for the large-scale utilization of coal gangue solids and powder.

9. Research on the Properties of Coal Gangue-based Ultrafine Powder Concrete

To explore the influence of different dosages of coal gangue-based ultrafine powder on the slump, compressive-flexural strength, frost resistance, and impermeability of C50 concrete, Jiang Peng et al. used hydration heat, X-ray diffraction, and other methods to clarify the mechanism of coal gangue-based ultrafine powder on concrete[9]. The results showed that coal gangue-based ultrafine powder reduces concrete slump and deteriorates slump retention; with increasing ultrafine powder dosage, the mechanical strength and durability of concrete first increased and then decreased, with an optimal dosage of 8%. Furthermore, the ultrafine powder did not affect the type of hydration products but significantly increased the hydration rate, accelerated the hydration process, refined the pore structure, densified the matrix, and improved the frost resistance and impermeability height of the concrete.

10. Study on the Durability of Shale Coal Gangue Concrete

To study the preparation of coal gangue concrete by replacing natural gravel as coarse aggregate with shale coal gangue of equal mass, Fang Qiancheng tested the workability and mechanical properties of coal gangue concrete and investigated durability factors such as frost resistance, electrical flux, and drying shrinkage of shale coal gangue concrete[10]. The results showed: as the shale coal gangue content increased, the workability of concrete slightly decreased, while the compressive strength gradually increased; the durability of concrete slightly decreased but could meet requirements; using shale coal gangue as concrete coarse aggregate to prepare concrete is feasible.

11. Study on Durability of Steel Fiber Coal Gangue Concrete under Acid Rain

Lu Shasha investigated the changes in concrete specimens under acid rain solutions of different pH values and steel fiber dosages[11]. The results showed: the carbonation depth of steel fiber coal gangue concrete in different pH acid solutions was positively correlated with the number of acid rain cycles, with significance shown as pH=2.0 > pH=3.0 > pH=4.0; a 1.0% steel fiber dosage was the optimal dosage for steel fiber coal gangue concrete, optimizing its pore structure and effectively inhibiting erosion by acid rain solution.

12. Study on the Performance of Coal Gangue Concrete by Grouting Process

To study the performance of concrete using coal gangue aggregate pretreated by a grouting (coating) process, Yao Zhixin et al. conducted relevant research. The results showed that raw coal gangue aggregate has high water absorption and low hardness, deteriorating significantly under drying-wetting and freeze-thaw conditions; the performance of coated coal gangue aggregate was improved[12]. The strength and durability of raw coal gangue concrete were poor; the performance of coated coal gangue concrete was enhanced, and the correlation between aggregate performance and concrete performance was good. The main reason for the deterioration of coal gangue aggregate is the softening and instability of clay minerals after absorbing water under drying-wetting and freeze-thaw conditions, while coating can isolate moisture, thereby strengthening the aggregate. Aggregate strengthening and the improved bonding degree between aggregate and mortar matrix jointly promote the performance enhancement of coated coal gangue concrete.

13. Study on the Mechanics and Durability of Coal Gangue Coarse Aggregate-geopolymer Concrete

Ge Jieya et al. studied the mechanical and durability properties of coal gangue coarse aggregate-geopolymer concrete[13]. The results showed: as the coal gangue coarse aggregate content increased, the compressive performance, impermeability, and frost resistance of coal gangue coarse aggregate geopolymer concrete weakened to varying degrees, with frost resistance being the most significantly affected; compared to geopolymer concrete with raw coal gangue coarse aggregate, geopolymer concrete with calcined coal gangue coarse aggregate at the same coal gangue dosage showed a significant advantage in compressive strength, its chloride ion permeability resistance was inferior to that of raw coal gangue geopolymer concrete, and its frost resistance was not significantly different from that of raw coarse aggregate geopolymer concrete; the suitable threshold for coal gangue coarse aggregate dosage is 50%.

14. Study on Durability of Coal Gangue Mixed Aggregate Concrete

To study the influence of mixed aggregate on concrete performance, Li Wen et al. investigated the effect of mixing coal gangue and pumice on the durability of concrete[14]. The conclusions are as follows: as the coal gangue replacement rate increased, the cubic compressive strength first increased and then decreased, with an optimal replacement rate of 60%; the fitted splitting tensile strength and replacement rate followed an exponential function with high accuracy. A 60% mixing rate of coal gangue and pumice resulted in the highest strength, largest initial stiffness, strongest ability to resist elastic deformation, and better internal pore structure. Coal gangue mixed aggregate concrete was prepared with a water-cement ratio of 0.43 and 60% coal gangue by volume replacing pumice coarse aggregate. This provides a slope protection concrete material for large waste dumps in mining areas that can utilize local materials, reducing economic costs and mitigating problems such as large land occupation and environmental pollution caused by solid waste coal gangue accumulation. Adding 12% by mass of 120-mesh rubber powder to the cementitious materials can improve the pore structure and frost durability of concrete, enhancing its performance.

15. Effect of Different Coal Gangue as Aggregate on the Durability of Different Cement-based Materials

Li Linhao studied the basic properties of coal gangue from different regions and its impact as aggregate on the frost resistance and acid erosion resistance of C30 concrete and CFG piles[15]. The results showed: the main components of the selected coal gangue samples were minerals such as quartz, montmorillonite, and siderite, but their oxide contents differed significantly; the uniaxial compressive strength of each coal gangue decreased under water-saturated conditions; after freeze-thaw cycles, the mass loss of coal gangue ranked by origin from large to small was Yulin, Changzhi, Taiyuan, and Xuchang; under acid erosion, the crushing index of Changzhi coal gangue increased most significantly compared to before acid erosion. For C30 concrete prepared with Xuchang coal gangue, when the coal gangue replacement rate for limestone coarse aggregate exceeded 30%, the frost resistance significantly decreased; as the coal gangue content increased, the acid resistance of C30 concrete decreased but not significantly. After 140 days of acid erosion, the mass loss rate of CFG-Changzhi exceeded 5%, and the compressive corrosion coefficient was below 0.8, indicating significantly reduced acid resistance; the acid resistance of other coal gangue CFG piles did not change significantly.

16. Research on the Performance of Concrete with Crushed Coal Gangue as a Complete Replacement for Coarse Aggregate

Regarding the study of concrete performance with coal gangue completely replacing coarse aggregate, Jing Hongjun et al., through silica fume modification, explored the effect of silica fume on the performance of complete coal gangue coarse aggregate concrete[16]. The results showed that silica fume can improve the compressive strength and splitting tensile strength of complete coal gangue coarse aggregate concrete; with a dosage around 10%, the mechanical properties of the concrete were optimal. The incorporation of silica fume enhanced the strength of complete coal gangue coarse aggregate concrete; the quantitative relationship between the integral area of different pore radii and the compressive strength of complete coal gangue coarse aggregate concrete was mainly linear, while harmful pores showed an exponential relationship; the hydration product structure became more stable after silica fume was incorporated into complete coal gangue coarse aggregate concrete.

17. Conclusion

If Coal gangue, as a bulk solid waste associated with coal mining and washing processes, poses increasingly severe environmental and safety issues such as land occupation, spontaneous combustion risks, dust pollution, and water acidification due to its massive stockpiling. Utilizing it as a resource, especially as a partial or complete substitute for traditional natural aggregates in concrete preparation, not only aligns with the urgent needs of the national "Zero-Waste Cities" initiative and the "Dual Carbon" strategy for efficient solid waste utilization and resource conservation, but also provides a highly promising technological pathway for the resource-intensive concrete industry to explore green and low-carbon transformation. Existing research has formed a relatively systematic understanding regarding the performance of coal gangue aggregate concrete.

The core prerequisite for successfully substituting natural aggregates with coal gangue to prepare concrete that meets performance standards lies in the scientific and effective pretreatment of the raw material. Untreated raw coal gangue typically exhibits high porosity, high water absorption, potentially weak particles, and possibly harmful substances (such as sulfides and residual carbon). If used directly without treatment, these inherent defects often lead to a severe deterioration in the workability of fresh concrete (e.g., significant slump loss, segregation, and bleeding) and seriously affect the strength and long-term durability of hardened concrete. Research indicates that crushing, screening, and washing to remove soil impurities are fundamental steps, while the key step is thermal activation treatment (optimal calcination temperature range is typically between 600-900°C). Calcination effectively decomposes residual carbon, activates the silico-aluminous minerals in coal gangue (generating active phases similar to metakaolin), significantly reduces the water absorption of the aggregate, and enhances its particle strength and volume stability. The coal gangue aggregate obtained through this pretreatment meets or approaches the standard requirements of natural aggregates in terms of physical and mechanical properties (such as crushing value and soundness), laying the foundation for ensuring subsequent concrete performance.

The performance of coal gangue aggregate concrete is highly dependent on refined mix proportion design. Due to the typically higher water absorption and surface characteristics of coal gangue aggregate compared to natural aggregate, it is necessary to appropriately reduce the water-binder ratio and incorporate high-efficiency water reducers to ensure the essential workability (fluidity, pumpability, compactability) of fresh concrete. Simultaneously, the full utilization of supplementary cementitious materials (such as fly ash, slag powder, silica fume) is crucial. These materials not only help compensate for potential water deficiency in the cementitious system caused by coal gangue absorption, but their pozzolanic effects further optimize the composition and structure of cement hydration products, particularly by significantly improving the weak interfacial transition zone (ITZ) between the coal gangue aggregate and the cement paste. Optimized coal gangue concrete performs well in terms of mechanical properties. Numerous studies confirm that its key indicators, such as compressive strength and flexural strength, can meet the design requirements of C30-C60 or even higher strength grades, satisfying the needs of most engineering structural applications. Some studies, by optimizing the coal gangue content (replacement rate, with 30%-70% for coarse aggregate being extensively studied and showing better results) and activation methods, have also observed good potential for later-age strength growth.

In terms of durability, rationally designed coal gangue concrete demonstrates acceptable comprehensive performance. The inert nature of calcined coal gangue aggregate itself, coupled with the active components it introduces (after activation) participating in secondary hydration reactions, helps refine the pore structure inside the concrete, thereby enhancing its ability to resist the penetration of external erosive media. Research shows that optimally formulated coal gangue concrete can achieve or approach the level of ordinary concrete of the same strength grade in terms of chloride ion permeability resistance, freeze-thaw cycle resistance, and sulfate attack resistance. However, the main focus regarding its long-term durability concerns the potential leaching risk of trace harmful elements (such as sulfur, heavy metals) that may exist in coal gangue. Existing research generally indicates that under the dual action of the highly alkaline curing environment and the dense microstructure of concrete, the leaching concentrations of these harmful substances are usually far below the environmental standard limits, and environmental safety is controllable in the short term. Nevertheless, continuous monitoring and evaluation of curing stability under ultra-long-term service conditions (e.g., decades) remains an important direction for future research.

The application value of coal gangue aggregate concrete is prominently reflected in its significant environmental and economic benefits. Large-scale utilization of coal gangue to replace natural sand and gravel aggregates provides the most direct environmental benefit by consuming large amounts of solid waste, alleviating land pressure, spontaneous combustion hazards, and environmental pollution caused by stockpiling. Simultaneously, it reduces the mining of natural sand and gravel resources, protects riverbed ecosystems and mountain landscapes, and lowers environmental disturbance and carbon emissions during the mining process. The economic benefits are also considerable. Substituting increasingly expensive natural aggregates with cheap coal gangue can effectively reduce the raw material costs of concrete, especially near coal-producing areas where the advantage of reduced transportation costs is more prominent. With the scaling-up and maturation of coal gangue pretreatment technology, its economic viability is expected to further improve.

In summary, the preparation of concrete using coal gangue as an aggregate substitute is technically feasible. Its performance can be effectively controlled and optimized through reasonable pretreatment and refined mix proportion design to meet engineering application requirements. Its outstanding environmental and economic benefits endow this technology with broad application prospects, especially in infrastructure construction in mining areas and surrounding regions, road engineering, and other fields. Future research should continue to deepen the monitoring and evaluation of the long-term performance of coal gangue aggregates (especially ultra-long-term durability and environmental safety), develop more efficient and lower-cost pretreatment technologies, improve relevant standards and specifications, promote demonstration project construction and industrial promotion, and ultimately achieve the goal of large-scale, high-value resource utilization of coal gangue in the concrete field.

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