



INTERNATIONAL JOURNAL OF
INNOVATION AND
INDUSTRIAL REVOLUTION
(IJIREV)

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**COAL GANGUE AS AGGREGATE IN CONCRETE:
A REVIEW ON PHYSICOCHEMICAL PROPERTIES,
MODIFICATION TECHNIQUES, AND PERFORMANCE
IMPACTS**

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Article Info:

Article history:

Received date: 29.03.2026

Revised date: 15.04.2026

Accepted date: 05.05.2026

Published date: 22.06.2026

To cite this document:

Li, M., Lim, N. H. A. S.,
Awalluddin, M. D. K., & Yoon,
T. C. (2026). Coal Gangue as
Aggregate in Concrete: A
Review on Physicochemical
Properties, Modification
Techniques, And Performance
Impacts. *International Journal of*

Abstract:

This by-product that is produced by the process of coal extraction and washing, is produced in high quantities and is causing some major environmental problems. The use of coal gangue as a concrete aggregate has recently undergone extensive research as one of the strategies to utilize the waste resource. However, past research has mainly focused on either coarse or fine aggregate models, and little has been done to integrate overall performance assessment and adjustment plans. The review is a critical study of the physical, chemical, and mineralogical properties of the coal gangue in different regions of the world, and its effect on the fresh performance, mechanical behavior, and strength of coal gangue aggregate concrete (CGAC). The focus lies on enhancing performance techniques like pre-wetting, calcification, surface coating, and increased the mixture of minerals. The paper also demonstrates the presence of critical performance thresholds so that optimal levels of substitution (usually 20-40%) can result in the enhancement of the durability of CGAC. Further studies must focus on the construction of multi-dimensional models of durability assessment

DOI: 10.35631/IJIREV.825012

Keyword:

Coal Ganguge Aggregate, Concrete Performance, Durability Enhancement, Modification Methods, Sustainable Construction Materials



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Introduction

Coal is a significant worldwide energy source, which is represented by its widespread distribution and huge deposits and is used in many industrial areas. Not only is it a very important source of energy but it is widely applied in power generation, heating and steel making industries. Figure 1 shows the annual growth rate of the world coal consumption each year since 2010, with the key role played by China as an energy market consumer and producer of coal (Hao et al., 2022).

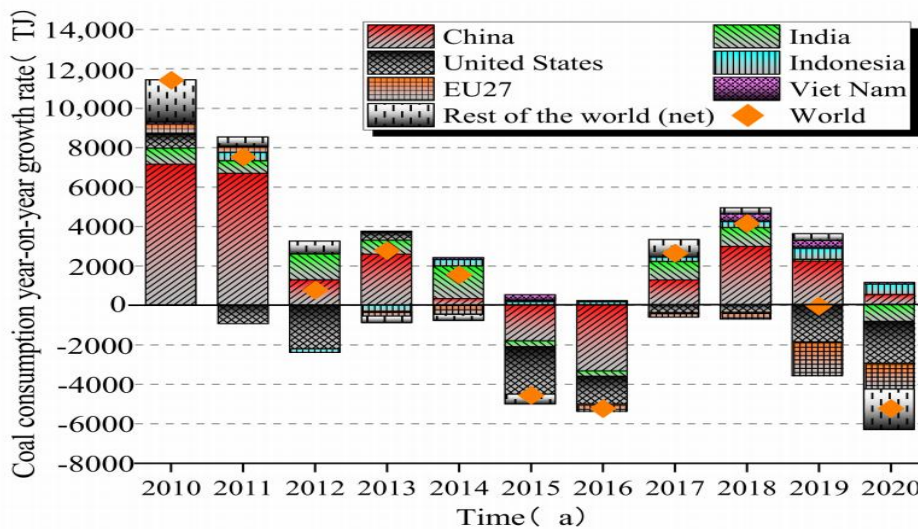


Figure 1: Annual Growth Trend of Global Coal Consumption From 2010 Onward (Wang, 2022).

Nevertheless, mining and use of coal is bound to have negative environmental effects. The coal gangue is mostly produced when coal is extracted as the strata of rock surrounding the coal seam is cut along with the coal seam, with some further gangue as a result of coal washing and beneficiation, extraction of low-grade coal and impurities as compared to high-grade coal. The combination of these processes produces huge amounts of coarse and fine gangue material which are eventually released as solid waste. The coal gangue usually forms a range of 1025 percent of the total output of raw coal and has now become a significant contributor to solid waste in China. (Li & Wang, 2019; Ma et al., 2021). The cumulative figure already stands beyond 6 billion tonnes and has covered over 13,000 hectares of land and the figure is growing year by year at an average of 300 million tonnes. Similarly, the centuries of coal mining in Europe have resulted in about 175 million tonnes of coal gangue that are deposited in dumping places (Wang, 2022; Frías et al., 2012).

In Figure 2, it is possible to identify some of the environmental issues that were caused by the significant amount of coal gangue deposits over the years (Stracher & Taylor, 2004; Long et al., 2019). To start with, coal gangue being a carbonaceous rock would have previously held carbon, sulfides and heavy metals which are capable of polluting soil and ground water. The long-term storage of it could cause the acidification of soils and substantially decrease the arable land and erode ecosystems and plant habitats (Prasad et al., 1996; Querol et al., 2008). Secondly, coal gangue is unstable when deposited because of its porosity and loose structure and uneven size of particles and hence it can be affected by slope failures and geological phenomena such as landslides and debris-flows during severe weather conditions such as heavy rain, wind erosion and earthquakes (Li et al., 2020; Huang et al., 2018). Furthermore, the fine particles of coal gangue can be easily blown away by the winds and thus lead to dust pollution and endanger people and their living conditions. The carbon that is remaining in coal gangue could also spontaneously burn under weathering and oxidation to produce sulfur dioxide, carbon monoxide and other toxic gases (Luo et al., 2022). The preserving of the coal gangue poses significant challenges with regards to the wastage of the resource and pollution of the environment thus necessitating the necessary management and utilization strategies.

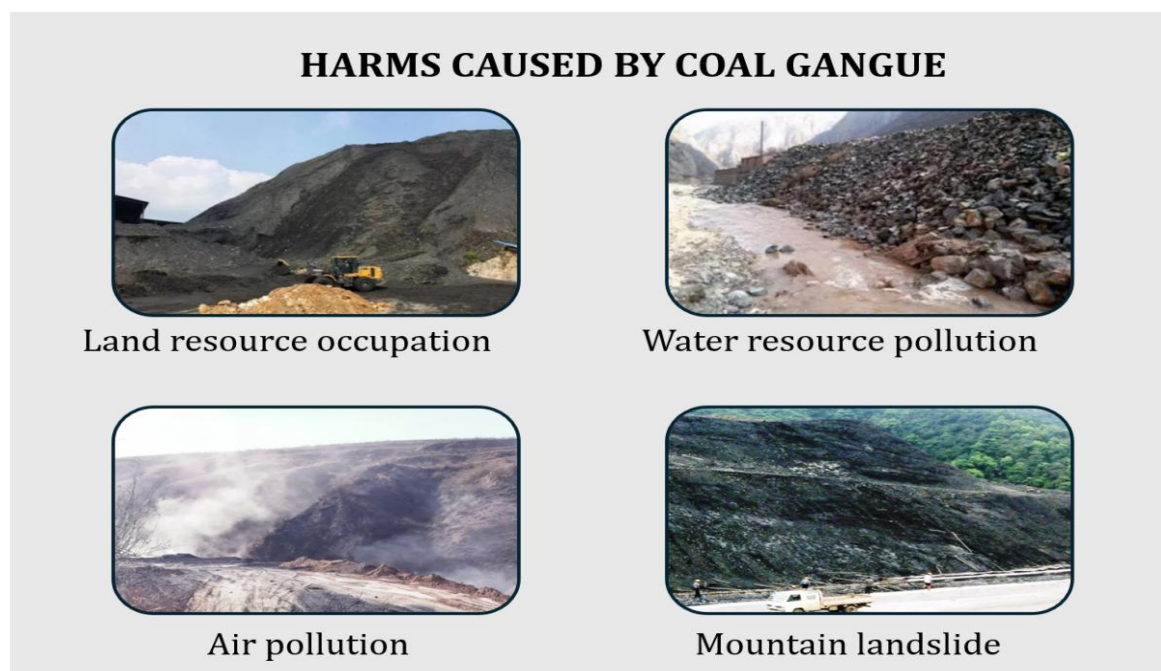


Figure 2: Drawbacks Of Waste Coal Gangue (Huang Et Al., 2018).

Over the past decades, it has received a fair share of attention with consideration to the further introduction of coal gangue into the construction material, mostly as an addition of cementitious materials or as an addition to concrete as an aggregate. It has been reported that coal gangue is likely to exhibit poor compatibility with cementitious systems when used as a mineral admixture in concrete (Liu et al., 2021; Pang et al., 2022). Its mineral structure is mostly made of relatively inert minerals, such as quartz and kaolinite that make it rather unresponsive to chemical reactions and have an adverse impact on the strength of concrete when substituting cement (Wang et al., 2025). On the contrary, the use of coal gangue as a part of the concrete is considered to be one of the possible strategies to use the large resource nowadays. Coal gangue particles are, however, likely to have porous and fragile structure when used as aggregate, with a high level of water demand and it lacks the ability to offer sufficient structural support to the concrete skeleton.

In order to overcome the drawbacks of the use of coal gangue as a concrete aggregate, this paper sequentially reviews the current modification approaches and performance improvement techniques. Regardless of the increased amount of literature on the use of coal gangue in concrete, the current research is still quite fragmented and does not have a multi-dimensional system of evaluation. Most of the past studies concentrate on individual side effects like either mechanical properties, fresh performance or individual indicators of durability without establishing correlations among these performance areas. In addition, there is a large gap of detailed modelling of durability that integrates freeze-thaw resistance, chloride penetration, and carbonation behavior with various ratios of replacement and different methods of modification. Furthermore, the synergistic advantage of the combination of a number of various modification strategies (e.g., pre-treatment, coupling of calcification and mineral admixture, etc.), as well as the variability of coal gangue characteristics in different geographical backgrounds have not been extensively studied. Those gaps do not allow developing coherent design principles and restrict the widespread use of coal gangue aggregate concrete (CGAC) in the engineering world.

Thus, it is necessary that an entire review should not only collect current results, but also develop interrelationships between material properties, methods of modification, and multi-performance results. This kind of an integrated strategy is needed to determine the best design thresholds, make trade-offs between strength and durability, and aid the creation of standardized utilization strategies of coal gangue in sustainable construction.

In order to address the above gaps, the review is thorough and integrative in the sense that it has looked into the physicochemical properties of coal gangue in different locations, their influence on fresh, mechanical, and durability performance, and critically evaluated various ways of alteration. Specific attention is paid to determining performance thresholds and learning coupled mechanisms and outlining the possible ways to practice CGAC and standardize it.

In order to fill these gaps, the following are some of the key points that will be added in this review. Firstly, it provides a combined analysis, which systematically relates the physicochemical characteristics of coal gangue to fresh, mechanical, and durability performance of concrete to understand the material behavior in a more holistic way. Second, it determines the critical performance levels, especially the optimal replacement range of 20-40 percent, by which the coal gangue could help in improving the durability without the effect of strength being greatly affected. Third, the paper summarizes and compares various

improvement techniques including pre-wetting, calcification, coating surface and mineral admixture synergy, how each works, and the synergized effects on improving the concrete performance. This review is more comprehensive in terms of optimizing mixed design, performance and subsequent standardization of coal gangue aggregate concrete (CGAC) through the integration of these areas.

Methodology of Literature Review

The present review is founded on the systematic literature search that will help to represent the latest level of research on coal gangue aggregate concrete (CGAC). Major academic databases, such as Web of Science, Scopus, and ScienceDirect, were searched with the help of the combinations of such keywords as coal gangue concrete, coal gangue aggregate, durability, mechanical properties and modification techniques. Peer-reviewed journals between the years 2010 and 2025 have been used as the major selection criteria with the intention of ensuring that the journals refer to the most recent technological developments. Altogether, nearly 120 articles were filtered; only the most interesting articles in the framework of the current review were selected because of their interest in physicochemical characteristics, performance analysis, and enhancement measures. Review papers and experimental studies also have been considered to provide balance analysis. The literature that was gathered was then divided into major areas of theme, such as material properties, fresh performance, and mechanical behavior.

The Properties of Coal Gangue

The coal gangue is generally loose, porous and possessed many microcracks that cause the low compressive and crushing resistance- way less than that of the natural crushed stone as shown in Figure 3 (Zhang et al., 2023). It has a porous and loose internal structure; therefore, it is likely to have a relatively high-water absorption, ranging between 1.9% and 8.4% (Zhang et al., 2024; Zhang et al., 2024). Moreover, coal gangue has low mechanical integrity, crushing values that lie between 9.9% and 20.6%.

Zhou et al., (2012) conducted systematic research on the crushing strength and failure mechanisms of coal gangue. The findings indicated that the crushing strength of coal gangue particles was between 3.02Mpa and 11.11Mpa with an average of about 6.1Mpa. The high deviation in strength is largely explained by the unavoidable heterogeneity of coal gangue that is formed by various mineral elements e.g. clay mineral, quartz, feldspar, and leftover carbon. Microcracks, pores and weathered surfaces that occur also contribute to the decrease in the integrity of individual particles resulting in premature failure under loads. In addition, variation in the particle size, shape, and mineral compositions can lead to the occurrence of a few particles that will focus the stress on the weak interfaces, leading to low measured values.



Figure 3: Raw Coal Gangue (Yang Et Al., 2022)

The mineralogical composition of coal gangue is quite complex; it includes minerals of the clay group such as kaolinite and illite, the number of which reaches approximately 70 percent; quartz is the second mineral, its amount equals approximately 20 percent, and the rest is feldspar and other impurity minerals (Ma et al., 2020). SiO_2 , Al_2O_3 , Fe_2O_3 , and CaO are the primary chemical compositions of coal gangue (Li et al., 2021). Based on the mineral and oxide compositions in the summation of Table 1, the coal gangue in various regions of the world should mainly be divided into four types: (1) clay-rich coal gangue ($\text{SiO}_2=40\% -70\%$), (2) sandstone-type that contains SiO_2 over 70% of oxide, (3) aluminum-rich coal gangue and (4) calcium-rich coal gangue ($\text{CaO}=\text{more than } 30$) (Wang et al., 2019). Table 1 represents the chemical composition of coal gauge.

Table 1: Chemical Composition of Coal Gangue Samples from Various Regions

Sample (%)	North China	South China	Spain	Africa	Germany
SiO_2	58.82	55.50	56.40	57.31	45.73
Al_2O_3	27.87	18.15	26.34	5.82	25.21
Fe_2O_3	8.31	5.42	6.42	3.12	1.61
CaO	0.78	3.38	1.06	0.53	0.51
MgO	—	1.23	0.17	0.50	0.48
K_2O	1.23	1.67	4.02	0.45	0.21
Na_2O	—	0.64	0.17	0.54	0.35
Ref.	[24]	[25]	[5]	[26]	[27]

Table 1 indicates that the coal gangue of different regions of world is mostly of the argillaceous type that is characterized by high content of SiO_2 and Al_2O_3 and also by the layer structure morphology. With proper treatment in terms of activation, this kind of clay-containing coal gangue has latent pozzolanic activity and therefore has a high potential of being used in terms of its resources. Figure 4 will be the summary of coal gangue modification methods.

Figure 4 gives an idea on the way of modifying the coal gangue aggregates (CGA), their mechanisms and optimization of performance.

Modification Technique	Main Mechanism	Performance Enhancement	Representative Results
Pre-wetting treatment	Pre-saturation reduces water absorption during mixing, preserving free water	Improved workability and flowability, reduced bleeding and segregation	Slump maintained at 163-185 mm; improved homogeneity[33]
Calcination modification	High-temperature dehydroxylation activates reactive phases and removes impurities	Significant increases in compressive and flexural strength	Compressive strength increased by 39.5% (450 °C) and 18.6% (750 °C) [50]
Surface slurry coating	Cement/mineral slurry wraps the aggregate surface, reducing surface defects	10-15% increase in compressive strength; enhanced structural integrity	28-day compressive strength reached 48.3 MPa (+12.1% over control)[53]
Synergistic mineral admixtures	Pozzolanic reactions form additional C-S-H/AFT, filling pores and refining structure	Improved freeze-thaw, carbonation, and chloride penetration resistance	15% FA + 10% GGBS reduced frost-induced mass loss by 32.6%; 7% silica fume improved chloride resistance[34]
Chemical admixture optimization	Chemical additives improve workability, pore structure, and freeze-thaw resistance	Enhanced frost resistance and durability against chloride ingress	0.02% air-entraining agent improved frost resistance by ~50%[70]
Microbially Induced Carbonate Precipitation (MICP)	Bacteria produce CO_3^{2-} reacting with Ca^{2+} to form CaCO_3 filling pores and cracks	Improved aggregate hardness, reduced water demand, enhanced durability	Bacillus LMG 22257 and B. pasteurii showed notable reinforcement effects[55, 56]

Figure 4: Coal Gangue Modification Techniques

Fresh Properties of Coal Gangue Aggregate Concrete

The new performance of CGAC tends to decrease with the growth of the coal gangue aggregate content. This decline in workability can be linked mostly to the coarse and porous surface properties of coal gangue aggregates, which causes increased absorbability of mixing water. Moreover, the friction between aggregates is also increased which decreases the flowability of the concrete mix. Further, coal gangue aggregates also have a more irregular particle shape than natural aggregates, is more likely to create internal resistance, which in turn decreases the cohesiveness and homogeneity of the mix. On the whole, aggregates negatively influence the fresh performance of concrete, and the necessary corrections should be made based on the practice in terms of construction and processing conditions.

Flowability is used as a parameter of evaluating plasticity and workability of coal gangue concrete (CGC) (Qin & Gao, 2019). The declining trend in the slump of CGC tends to be on an increasing trend as the replacement level of natural coarse aggregate by CGA increases. This is depicted in figure 5 which shows that at a 100 percent replacement level of natural aggregate, the slump of CGC reduces by almost 55 percent when natural aggregate is completely replaced by coal gangue (Duan et al., 2014). As Chilkwazi et al., (2023) observed, the addition of coal gangue content in the slump of concrete decreased the slump of concrete to 175mm, 131mm and then 72mm when the proportion of the content was increased to 0percent and 100 percent respectively. With 100 percent coal gangue it is 41 percent of the slump of ordinary concrete, which means a real decrease. Such behavior is primarily connected with the high porosity and rough surface of the particles of coal gangue, which contributes to increased contact with the cement paste. The mixing process will cause these particles to absorb a lot of mixing water, which will decrease the amount of free water in the mixture hence resulting in a loss of workability of the concrete.

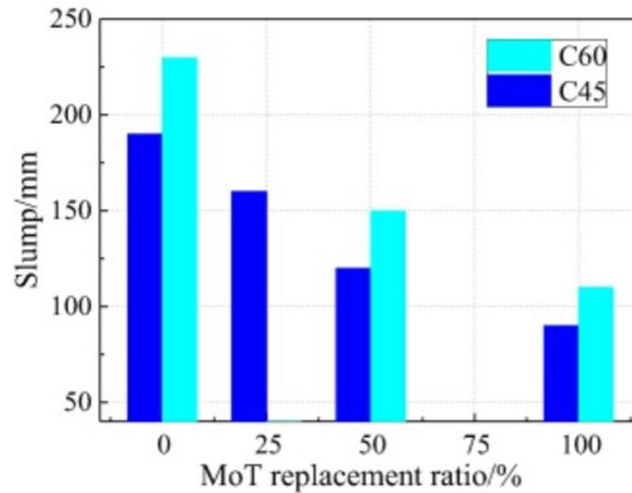


Figure 5: Impact Of Coal Gangue Replacement Ratio on Fresh Concrete Slump (Vo Et Al., 2025)

To minimize the ill effects of the high porosity of the coal gangue, a good method is pre-saturation treatment, whereby the aggregate is first saturated in advance and hence will not take up as much water in mixing, leaving enough free water in the paste of cement. Zhu et al., (2020) sprayed water over coal gangue aggregates one hour before mixing to take the aggregates near to a saturated surface dry (SSD) condition. This treatment was useful in reducing the problem associated with uneven water uptake during mixing. The test results indicated that the initial slump of the treated concrete was with the range of 163-185 mm and was very cohesive and water retentive and could not segregate or bleed and hence, the overall homogeneity significantly enhanced. Zhu et al., (2024) also supported the effectiveness of this pre-wetting method by showing that pre-saturation of the 80 percent of the coarse aggregate of the gangue 10 to 60 minutes before mixing is the best method of producing mixtures that have desirable flowability and stability.

Considering the replacement ratio as constant, particle size is the primary factor in determining the water absorption capacity of the coal gangue coarse aggregates. The reason behind this is that the specific surface area depends on the aggregate particle size as well as the surface texture and hence has a huge influence on the degree to which cementitious materials and mixing water cover the aggregate surface (Cheng et al., 2025).

Fineness modules of coal gangue fine aggregate affect greatly the flowability of concrete. (Gao et al., 2021) found that as fineness modules were 0.62, maximum slump of the concrete was 195 mm but in the case of 0.44 the slump was significantly lower at 140 mm. Gangue fine aggregates of coal have a lubricating effect at high values of fineness modules. The changes in the size of particles are the main cause of this phenomenon which influences the interparticle friction and the extent to which the paste covers the aggregates, and consequently the workability of the concrete mixture is regulated.

As Pan et al. pointed out, the effect of the rise in coal gangue fine aggregate content on the workability of the backfill mixture can be noticed in the decrease in the slump (Zhou et al., 2015). As Figure 6 indicates that within the range of mass concentration of 78 percent to 84 percent, the slump was reduced by 257mm to 184mm at a ratio of 7:3 of fine to coarse aggregate implying a reduction of 28.4 percent. The slump also reduced by 21.1 when a higher proportion

of fine aggregate was used, that is, 4:6, which resulted in the slump of 171 mm. The results indicate that a larger volume of fine aggregates might improve the adhesiveness of the pastes and inter-aggregate friction, which will eventually bring down the flowability. Thus, alterations in the fine aggregate content do not only have a direct impact on the lubrication and filling capacity of the slurry but also on its response to alterations in the mass concentration. To this end, fine aggregates properties have a great effect on the rheological characteristics of backfill system.

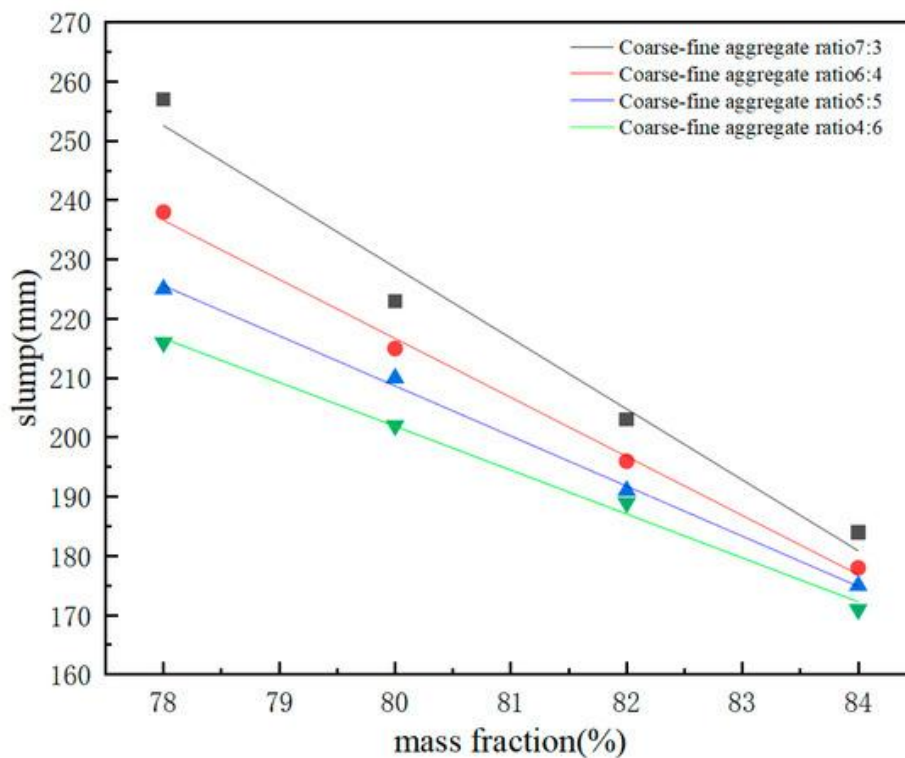


Figure 6: Correlation Between Slump and Mass Content (Minh & Le Phuong, 2018)

According to these results, Wang et al. [39] noticed that the slump of the concrete decreased then increased with the increase in the replacement ratio of the coal gangue aggregate. The coal gangue particularly influenced the flowability of concrete when the replacement level was lower than 45. Coal gangue fine aggregates when added in suitable quantities can be used to enhance the compacting of particles so as to maximize the gradation, hence improving slump. Nevertheless, when the replacement proportion is rather high the high-water absorption and the high specific surface area of the fine aggregates are likely to reduce the workability of the mixture. All in all, the variation of slump shows various trends according to the coarse-fine aggregate ratio. So, the idea of the rational regulation of fine aggregate content is key to the regulation of the rheology of coal gangue-based mixtures and the attainment of the optimal mix design (Zhang et al., 2020; Dong et al., 2015).

Mechanical Performance of Coal Gangue Aggregate Concrete

Coarse aggregates, which are mainly used as the structural framework and load-bearing element in concrete, are the main components. A thinner layer of cement paste usually forms at the interface between coal gangue aggregates and cement paste a strong-encasing-weak structure is formed-where the more strength cement pastes wraps around the weaker coal

gangue aggregate (Pan et al., 2024). Nevertheless, the mechanical strength of aggregate of coal gangue is low, thus it is likely to get fractured when subjected to outside forces and therefore restricts the total load-carrying capacity of the concrete structure (Wang et al., 2018). Figure 7 shows how coarse aggregate in the form of coal gangue affects crack propagation and mechanical behaviour in concrete (Xiao et al., 2020). CGAC, in contrast to ordinary concrete, generally has a dual-channel crack propagation mode, in which cracks propagate parallel to the interface between coarse aggregate and cement paste, i.e., as in Figure 7(a)). The cracks do not just follow the interfacial transition zone (ITZ) but go directly through the aggregate body creating a third-channel pathway of failure. The experimented shift in the crack propagation is important in the reduction in compressive strength of high coal gangue replacement ratios.

This process is also supported by the microstructural differences as shown by figure 7(b). With normal concrete, the cracks are mainly going along the edges of the coarse aggregates leaving the coarse aggregate intact to a significant extent implying that the coarse aggregate gives some type of crack arrest. Conversely, coal gangue concrete has cracks that go through part of the coal gangue aggregates implying the co-occurrence between the aggregate fracture and interfacial failure. This effect is manifested in the inefficiency of coal gangue aggregates to adequately resist shear stress, which eventually reduces the mechanical performance of the complete concrete matrix.

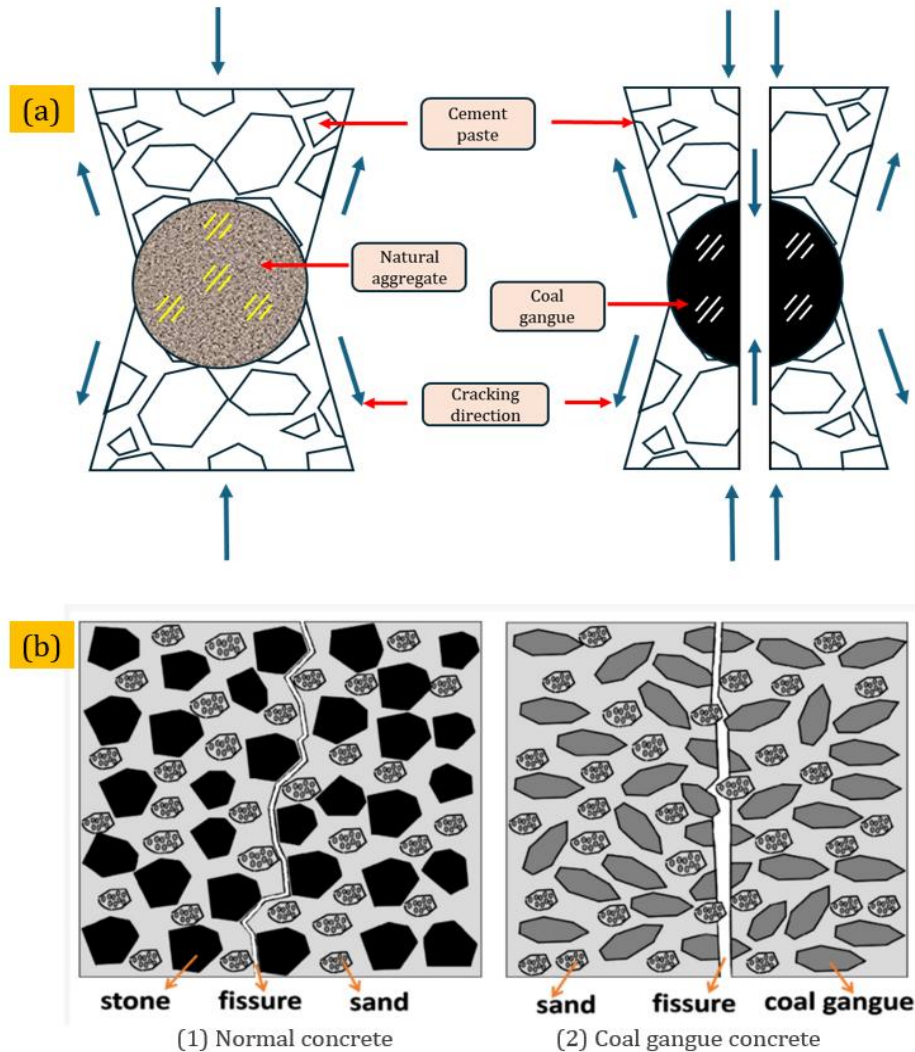


Figure 7: a) Compressive Failure Mechanism of Aggregates b) Failure Trend of Concrete (Reddy & Gupta, 2008)

In cases where CGA is adopted instead of coarse aggregates, there are possibilities of shear planes in the concrete matrix, which leads to a drop in its strength. Past research studies show that the mechanical behavior of the concrete made with coal gangue is highly dependent on the replacement ratio with varying levels of loss in the strength level as the substitution level rises (Song et al., 2025; Zhou et al., 2019). Figure 8 reveals that the higher the content of coal gangue the slower the compressive strength decreasing of CGAC, and it can be seen more clearly when the replacement level is greater than 45%.

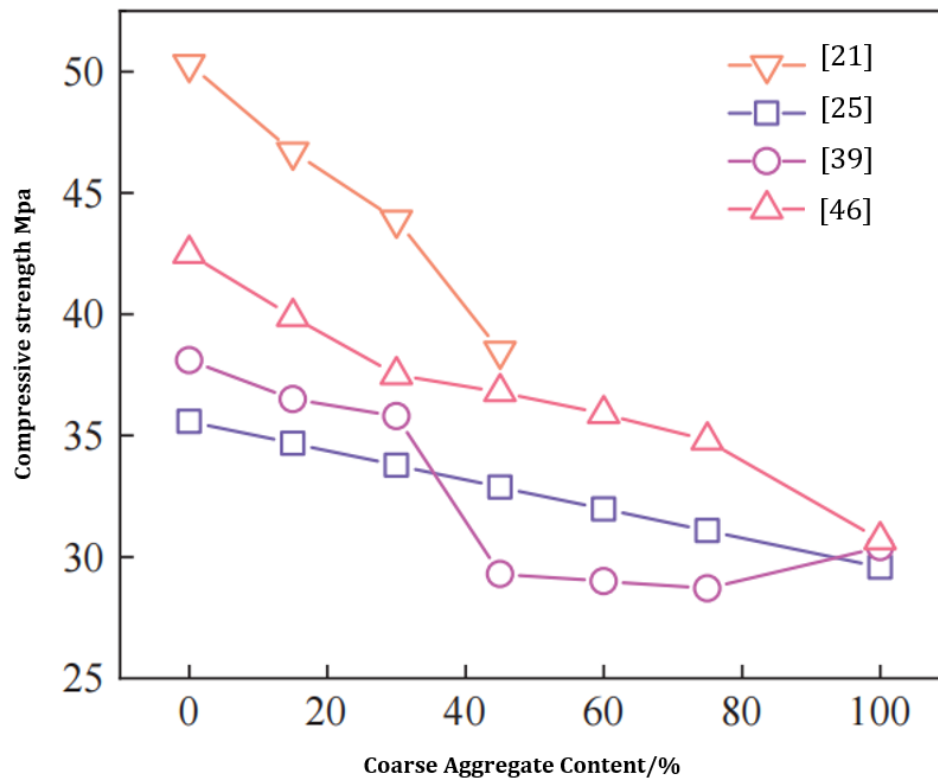


Figure 8: Relationship Between CGA Content and Compressive Strength of Concrete (Wang & Wang, 2018)

The coal gangue needs to be crushed before it can be utilized to substitute natural aggregates. Nevertheless, the crushed coal gangue normally has a higher value of crushing in comparison to natural gravel (Gao et al., 2021; Yu et al., 2022). Also, it has a loose structure and high porosity, which makes it absorb water more. As such there is need to enhance and adjust the characteristics of coal gangue to make it easy to substitute natural aggregates with it.

The treatment of the calcification of coal gangues has proven to enhance the mechanical behaviour of the aggregates and overcome its imperfections. Yang et al., (2013) used the surface thermal activation on the aggregates of coal gangue and noted a steep increase in the performance of these materials in the cement-based materials. The findings showed that the compressive and flexural strengths had improved by 69.2 and 95.3 percent, respectively. Zhu et al., (2021) also verified the efficacy of calcification: the compressive strength of the concrete prepared using a mix of coal gangue aggregates that were calcified at 450 °C and 750 °C reached 39.2 Mpa and 45.9 Mpa respectively, which was an increase of 39.5 and 18.6 Mpa over untreated samples. These findings indicate that not only latent reactive components (silica and alumina) on the surface of the gangue are activated but it also aids in the reaction of these components with the cement hydration product, increasing the number of bonding phases, and increasing the overall strength of the concrete. The morphological development of coal gangue at various temperatures of calcinations at a heating rate of 50 °C/min is shown in Figure 9. The sample without any calcification (Figure 9a) has a clear flaky and layered morphology which does not change significantly when it is calcified at 500 °C (Figure 9b). At high temperatures up to 600-800°C (Figures 9c-e), the particles become irregular porous, which is mainly caused by the dehydroxylation of kaolinite and its transformation into metakaolinite. At 1000 °C, (Figure 9f), the formation of a fully formed crystalline structure indicates the

transition of the phase between metakaolinite and mullite. These observations indicate that the microstructure of coal gangue highly relies on the calcination temperature that consequently controls its reactivity and applicability as an additional cementitious additive.

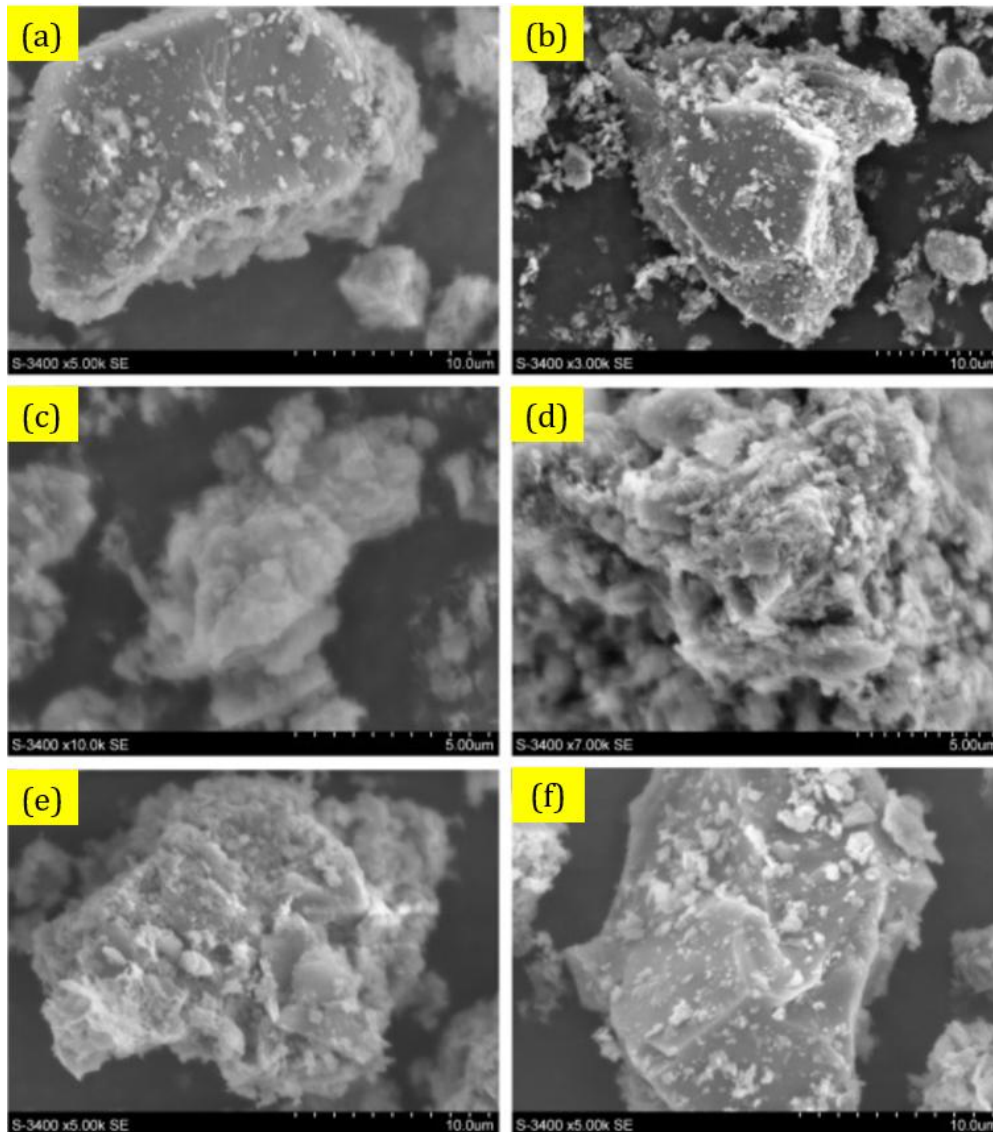


Figure 9: SEM Micrographs of Coal Gangue at Different Temperatures of Calcination (Cao Et Al., 2016): (A) Uncalcined; (B) 500 O C; (C) 600 O C; (D) 700 O C O C; (E) 800 O C; (F) 1000 O C.

Moreover, surface slurry coating methods have been found useful in altering the structure of coal gangue aggregate surfaces and thus enhancing their mechanical attributes greatly. Wu et al., (2022) utilized one of the approaches, which consisted of the coating of the self-igniting coal gangue aggregates with a slurry to create pervious concrete, which led to significant enhancement in compressive strength. Zhang et al., (2023) incorporated the slurry of cement and ultrafine mineral powder as the coating material in their study, which facilitated the evolution of C-S-H gel in the ITZ, allowing the coal gangue concrete to attain a compressive strength of 48.3 MPa at 28 days—an improvement of 12.1% over the untreated control group. These results show that there is positive association between the surface densification treatment and mechanical properties of concrete. To illustrate how the interfacial transition zones (ITZ)

on unmodified coal gangue aggregate (CGA) and cement-based wrapping modification (CM) compare, figure 10 is used to compare the two. In Figure 10(a) that corresponds to the unaltered CGA, the ITZ is quite loose and discontinuous and there are observable micro-cracks that propagate along the aggregate-matrix interface. This means that there is a poor relationship between the aggregate and cementitious matrix, a common feature of untreated gangue aggregates. Conversely, Figure 10(b) reveals that ITZ is clearly more compact and concentrated to create a continuous zone of transition between the aggregate and the surrounding matrix. The coating is effective in alleviating micro-defects as well as enhancing interfacial bonds that enhances structural integrity of the composite. The thicker layer of ITZ in the CM sample implies increased crack initiation and propagation resistance as compared to the unmodified CGA.

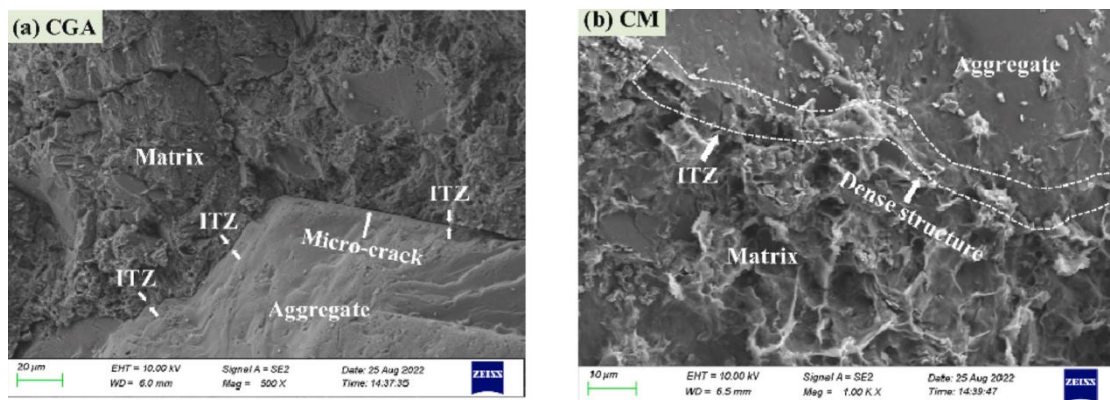


Figure 10: Micromorphology Of Modified Coal Gangue Aggregate Concrete (Zhang Et Al., 2022).

Moreover, the option of introducing *Bacillus* LMG 22257 and *Bacillus pasteurii* has revealed possibilities to enhance mechanical behavior of CGA and respective concrete, and they have showed good reinforcement behavior.

Use of coal gangue as a fine aggregate in concrete is usually restricted to replacement levels of not more than 20% in terms of mass, as affirmed by various researchers (Guo et al., 2024; Sun et al., 2016). When coefficients of water absorption in coal gangue at low replacement ratios (≤ 20 percent) are compared to natural river sand, the former absorbs more water, which further minimizes the ratio of water-to-binder. Furthermore, coal gangue particles that are obtained after crushing and sieving are likely to be of a smaller gradation and are latent pozzolanic. The reactive elements which comprise mainly SiO_2 and Al_2O_3 can undergo a secondary pozzolanic reaction with cement hydration products, creating more C-S-H and Aft phases. These new hydration products refine the pore structure and seal microcracks and this improves the structural integrity of the cementitious matrix.

In order to explain further the effects of the fine aggregates of coal gangue on the compactness and mechanical behavior of concrete, some researchers have focused on the development of slurry-filling structures. Zhang et al., (2023) proposed three representative structural morphologies of fill system based on coal gangue, namely: (a) skeleton-porous structure, (b) skeleton-dense structure and (c) suspended-dense structure, which represent the coarse-to-fine aggregates ratio of 7:3 (or 6:4), 5:5, and 4:6, respectively. As the amount of fine material in the agglomeration increases progressively in content-reflected in a falling ratio of coarse to fine-

the internal structure of the slurry will change to forms of loose packing, firmly stuffed, and finally to uniform suspension.

The Coarse aggregates in the set up as described in Figure 11(a) act as the main load-bearing structure but because of low percentage of fine aggregates, the number of unfilled voids is large, which gives a high-porosity and structurally loose matrix. Conversely, Figure 11(b) shows an optimal coarse-to-fine ratio whereby the augmented existence of fine aggregates augments the packing density and the formation of a more consistent slurry distribution which causes better interlocking of particles and creation of a dense and stable matrix. Further addition of fine aggregate material as indicated in Figure 11(c) results in a system of fine particles whereby the skeletal input of coarse aggregates reduces. It is a suspended structure that helps in enhancing flowability at the cost of structural stability, which underlines the trade-off between the rheological performance and mechanical robustness of high fine-aggregate systems.

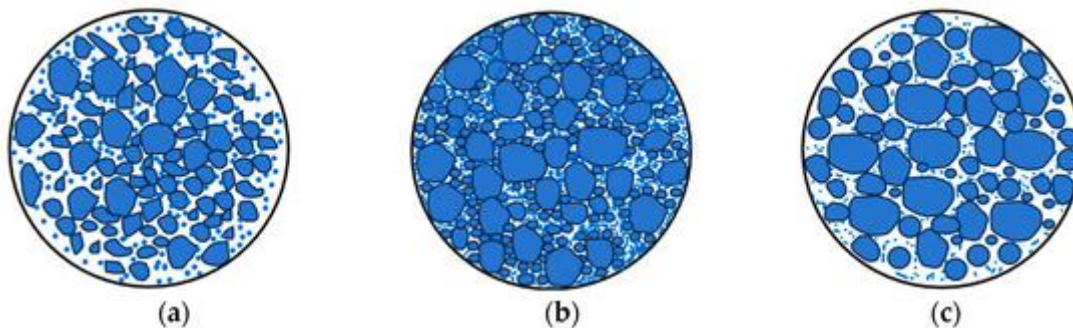


Figure 11: Pore Structure of Gangue Paste Backfill Depending on Coarse-Fine Aggregates Ratio (A) Framework-Pore (7:3, 6:4), (B) Framework-Dense (5:5), And (C) Suspend-Dense (4:6) Structures (Zhao Et Al., 2022).

Compressive strength has been a very important factor in determining structural stability of filling slurry. Figure 12 indicates that the compressive strength of the filling material specimens depends on the ratio of coarse and fine components of coal gangue aggregates, as well as on the mass concentration. The differences in the coarse-fine ratio are basically the alteration in the content of coal gangue coarse aggregates. With a change in the coarse to fine ratio of 7:3 to 4:6, the experimental findings show that the percentage of fine aggregates has an eminent influence on compressive strength at various curing ages. In all ages, the compressive strength tends to peak when the ratio of coarse to fine is 5:5 indicating that a moderate addition of fine aggregates will increase the particle packing density that will boost early and long term strength. This enhancement could be explained mostly by the effect of the void-filling of smaller particles that reduce the total porosity, enhance encapsulation of the paste, and enhance quality of the interfacial transition zone (ITZ). But upon increasing the fine aggregate content (i.e. a ratio between coarse and fine 4:6) there is a decrease in compressive strength that is observed. This implies that the skeleton of fine aggregate is not stable enough, and this may result in inadequate availability of paste, or even higher friction between the particles, which is undesirable in the strengthening process.

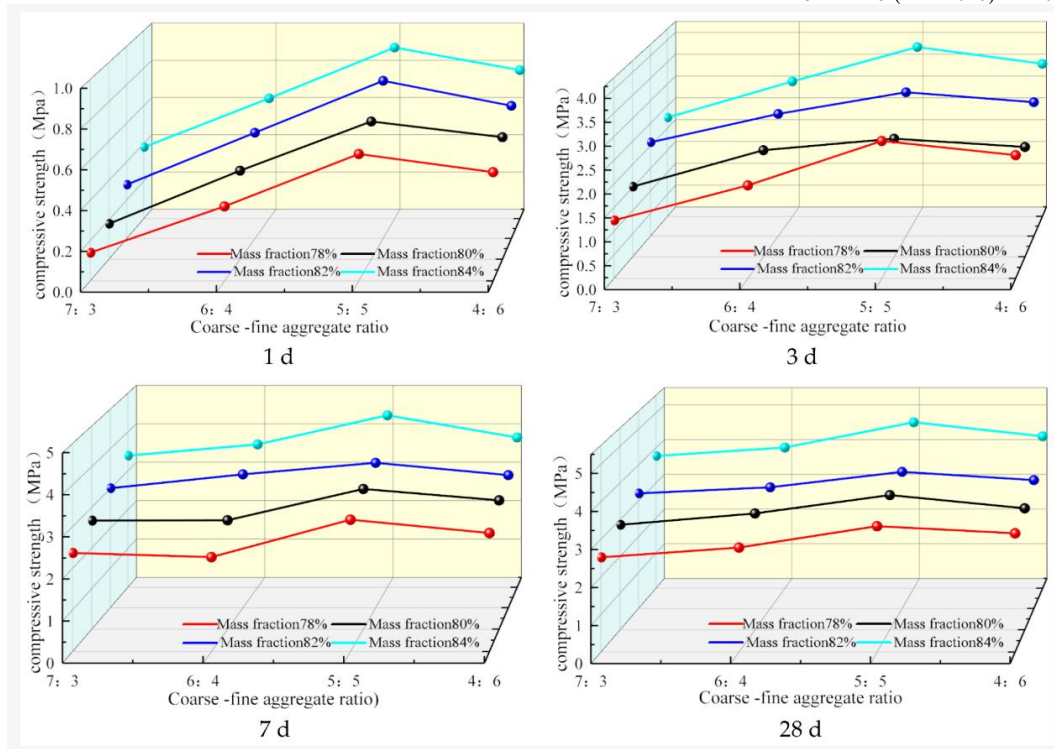


Figure 12: Effect Of Coarse-Fine Ratio of Aggregates on Compressive Strength of Coarse Coal Gangue Filling Paste at Various Curing Ages (Qiu Et Al., 2020).

Durability Of Coal Gangue Aggregate Concrete

Freeze-Thaw Resistance

Frost resistance is one of the indicators to test the capability of a concrete material to resist the damage caused by freeze-thaw cycles and expansion caused by frost in the low-temperature environment (Powers, 1965). The well-known theories on the mechanism of freeze-thaw damage internationally are the hydrostatic pressure hypothesis and the osmotic pressure hypothesis suggested by Power as shown in Figure 13 (Zhu et al., 2022). This problem is especially applicable to the areas in China that lie in the north and where coal gangue resources are vast and freezing-thaw phenomenon are common. Due to the nature of the water absorption capacity which is more usually high in CGAC than in conventional concrete, the expansion pressure generated by the water in the pore structure is more pronounced and therefore the pore structure is more vulnerable to extreme degradation throughout repeated freeze thaw cycles.

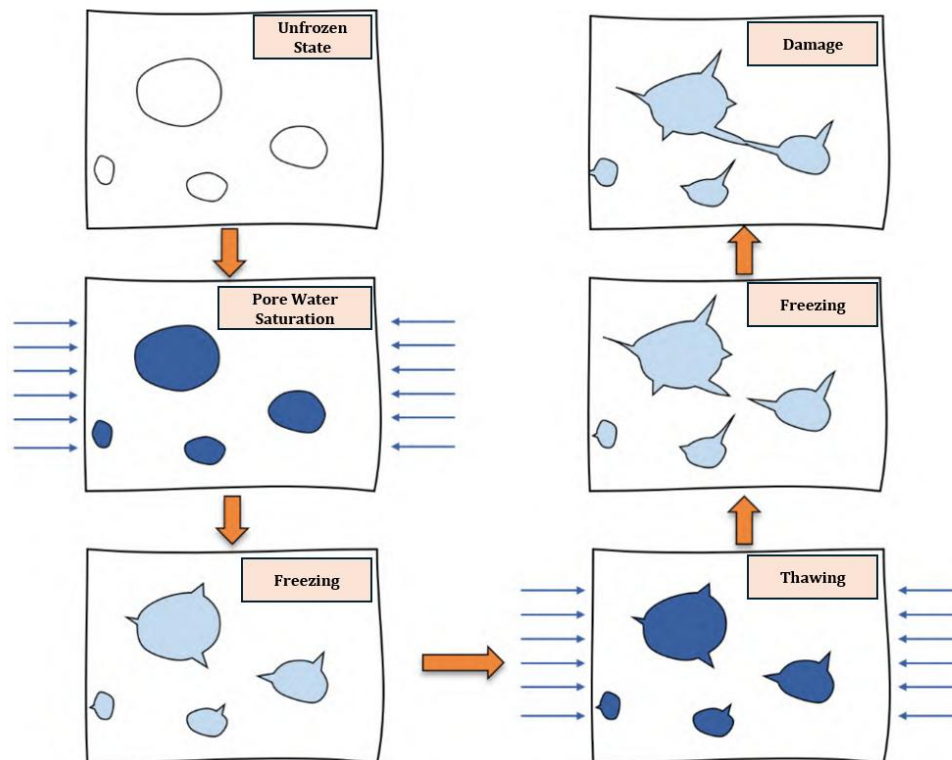


Figure 13 Schematic Diagram of Frost Damage Mechanism in Concrete (Guan Et Al., 2024)

Some studies done in the past show that the frost resistance of concrete is highly dependent on the content of coal gangue. Experimental manipulations with the coal gangue replacement percentage got to the fact that the relative mass, compressive strength, and relative dynamic modulus of elasticity decreased significantly with an increase in the replacement percentage of 0 to 60% (Li & Yan, 2013). The decrease in relative mass of concrete with 40 percent coal gangue after 100 freeze-thaw cycles was less than 97 percent. Nevertheless, replacement levels of more than 40 percent led to quick decay of mass and strength. The use of pre-wetting with extra water, combined use of 15% fly ash and 10% ground granulated blast furnace slag (GGBS) decreased the mass loss of coal gangue concrete caused by frost by 32.6%. In a different study, Huang, (2015) noted that concrete with 30 percent of coal gangue as the aggregate remained above 80 percent of the original compressive strength of the mix in 50 cycles of freezing and thawing whereas control samples with no coal gangue did not losing their strength by about 25 percent. The freeze-thaw behavior of coal gangue concrete both in macro and micro-scale. The findings indicated that the frost resistance as well as mechanical properties were significantly enhanced when the level of coal gangue powder did not exceed 20 percent. The concrete showed a compressive strength of 16.4% reduction, a splitting tensile strength of 26.1% reduction, a rate of mass loss of 1.77% and relative dynamic modulus retained at 91.32 after 300 freeze-thaw cycles, which is a good overall durability. At the microstructural level, it was identified that coal gangue fills the gaps between cement particles and increases compactness of the matrix. Also, the secondary hydration reactions were caused by its pozzolanic reactivity which produced more calcium silicate hydrate C-S-H gel, thus enhancing the mechanical and durability performance of the concrete. In order to satisfy frost resistance demands of CGAC, a replacement ratio of CGA is usually suggested to be maintained at less than 40%.

Other researchers have also done specific optimization studies on the frost resistance of CGAC. Buenfeld et al., (1998) conducted tests in freeze-thaw cycle; coal gangue concrete with the water-to-binder ratio of 0.65 and 0.45. The use of high-performance water-reducing admixtures at the stage of mixing the concrete in their study was a significant advance that enhanced the freeze-thaw resistance of the concrete. The enhancement is mostly connected with the fact that the water reducer can minimize the moisture level in the pores of coal gangue, which reduces the expansive stress that occurs in the freezing-thaw cycles and leads to the reduction of the damage. A one-variable design in a related study that was used to examine the impact of the ratio between coal gangue replacement and frost resistance. The findings demonstrated that the concrete could withstand the freeze-thaw cycles with the replacement level not exceeding 60. In addition, 0.02% air-entraining agent was added to the mix, and this enhanced the frost resistance by about 50 percent. These results suggest that the use of coal gangue concrete can be greatly improved in terms of durability performance by controlling the coal gangue replacement ratio and optimisation of the utilisation of the chemical admixtures.

Chloride Ion Penetration Resistance

Chloride ion penetration resistance can be considered as one of the valuable indices to assess the strength of the concrete and it is usually confirmed by the electric flux method that represents the ability of the material to resist chloride ingress. It has also been found that coal gangue when incorporated at a suitable replacement level can effectively increase chloride resistance in concrete meaning that it has a potential of improving concrete structural durability and thus it can be considered as a promising method in enhancing structural durability. Gu and Zhang, (2019) established that the electric flux was minimal when the replacement ratio of the natural coarse aggregate was manipulated at 45 percent indicating the optimum chloride ion resistance (Jabłońska et al., 2017). The same was extended with examining greater levels of the replacement of coal gangue and noted a great worsening in penetration resistance when the replacement was more than 40. In particular, the electric flux and the chloride diffusion coefficient increased by, respectively, 80N m²/C over conventional concrete at a 50% replacement ratio, and by 0.39 / 10⁻⁹ cm²/s. It was found that the resistance decreased at high replacement levels due to increased porosity and more loosely packed microstructure. In addition, the particle size of the coal gangue, specific surface area and whether the material was calcined or not are also important factors in determining its effects on the performance of permeability.

Researchers have further suggested the idea of using mineral admixtures as a good optimization strategy besides the replacement ratio of the coal gangue. These include silica fume a highly reactive pozzolanic substance, which has proven to be quite effective when used in coal gangue concrete. When 7% silica fume was added to the coal gangue concrete it had a great means of resisting the permeability of chloride ions. This has been enhanced mainly because silica fume is capable of refining the microstructure, which means that it will fill in capillary pores as well as react with calcium hydroxide to create more C-S-H gel, hence making the matrix density higher and permeability lower. Moreover, the joint effect of a variety of factors on chloride ion resistance and identified that the water-to-binder ratio, silica fume content, coal gangue content, as well as the dosage of water-reducing admixtures, had a strong impact on the performance in terms of permeability. In their research, they found the best combination, which is a watertobinder ratio of 0.3, 7 percent silica fume, 40 percent coal gangue, and 0.75 percent water reducer which gives the concrete the most favorable chloride ion penetration resistance.

Carbonation Resistance

The issue of the long-term stability of concrete is sensitive to carbonation, especially in situations whereby the continuity of the concrete is in constant contact with the atmosphere. CO₂ enters the concrete via pores and any other routes as shown in Figure 14 and reacts with hydration products like calcium hydroxide (Ca(OH)₂). The result of such a reaction is a decrease in alkalinity and the breakdown of the passive film that causes the formation of cracks and the deposition of carbonation products. More so, the carbonation products that are generated during this process precipitate in the pore structure leading to the volumetric expansion and creating microcracking. These fissures in turn enable the additional infiltration of CO₂ which forms a self-accelerating decay cycle, which further increases the process of carbonation. This eventually poses a serious threat to corrosion and structural failure of steel reinforcements.

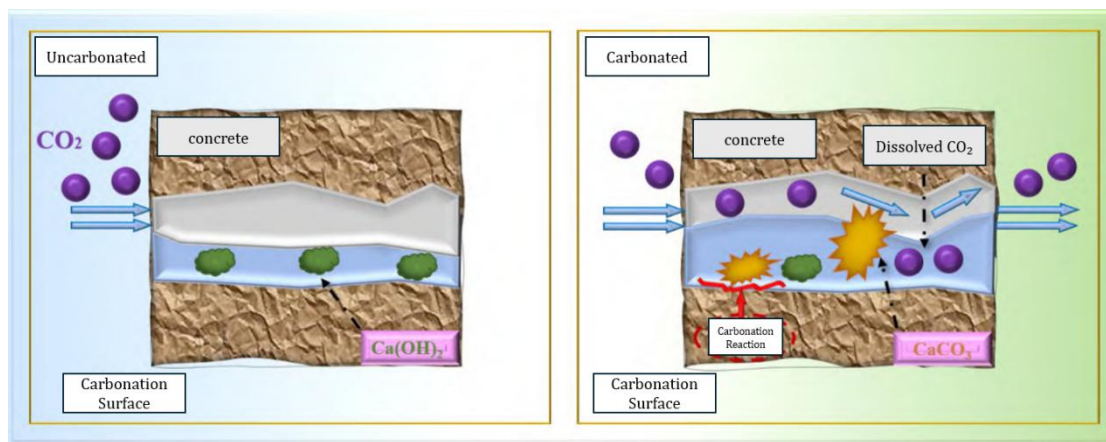


Figure 14: Carbonation Reaction of Concrete (Zhang & Ling, 2020).

It has been established in many studies that the type of raw material, replacement ratio, the ratio of water to binder, and curing conditions, have a strong effect on the carbonation resistance of coal gangue concrete. Li et al., (2023) managed to optimize pore structure of concrete with the help of coal gangue aggregates, which were thermally activated at 700 C, and the replacement ratio of 30-40, the water-to-binder ratio was kept between 0.35-0.40. Their experiment resulted in the fact that the depth of the carbonation after 28 days of the experiment was only slightly higher than they were at the start of the experiment, namely 6.8 mm and 7.5 mm respectively (Wang et al., 2016). Nevertheless, the growth of the carbonation depth at 100% replacement was 66.2% suggesting that over substitution speedily intensifies CO₂ diffusion. In addition, to investigate the measures to make the carbonation resistant by changing the nature and dosages of added cementitious materials as well as by the minimization of the ratio of water to binder. The findings indicated that with a constraint of the content of fly ash, slag, and coal gangue to 15, 25, and 20 percent respectively, the depth of carbonation decreased by 10.5% to 35.4. Any time these limits were exceeded, however, accelerated the hydration of cement and thereby favored carbonation (Sadati et al., 2016).

Moreover, the carbonation of coal gangue concrete at different stipulated curing periods and the water-to-binder ratios (Ballim & Lampacher, 1996). The findings indicated that carbonation depth grew with longer curing period with a tendency of rapid growth early on, which then slowed down gradually and thereafter stabilized. Concerning the water to binder ratio, when the ratio was below 0.50, a decline in the carbonation depth with the ratio occurred but at a

ratio above 0.50, the carbonation depth started rising (Dong, 2016). This shows that there is a critical threshold effect on the ratio of water to binder on carbonation behavior where the lowest level of carbonation was recorded at a ratio of 0.50. Additional evidence on this finding the phenomenon of carbonation is the result of the interaction of a number of variables. In their study, they found that comparatively greater design strength, water content, and dosage of cement add to enhanced compactness of concrete and thus prevents the ingress of CO₂ and diffusion which slows down the carbonation process.

To conclude, resistance to carbonation of the coal gangue concrete depends on a complex of factors, such as the mix composition, the concrete type, and curing conditions. The objective application of the rationalization of these parameters is highly important in increasing the long-term performance of coal gangue concrete.

Conclusion

Being a waste common in industry in the solid form of coal gangue, coal gangue has a potential high level of sustainable use in the concrete. The rational integration not only facilitates the resource recycling of industrial by-products and minimizes the environmental pollution, but also offers new information in the development of green building materials.

This review has come up with the following key conclusions:

- 1) Coal gangue normally has a loose form and porous and expansive of water. These characteristics adversely affect the new performance of concrete and lead to a decrease in mechanical strength and durability.
- 2) The performance of coal gangue concrete with regard to the durability performance tends to show a first improvement and then degradation trend as the gangue content in concrete is increased. The replacement range of 20-40 percent is generally the optimal range of performance.
- 3) Pre-wetting treatment, addition of supplementary cementitious materials, optimization of the chemical admixtures, surface slurry coating, and modification of the calcification can be effectively used to alter the surface morphology and interfacial behavior of coal gangue aggregates resulting in higher compactness and strength of the concrete.

In a more comprehensive viewpoint, coal gangue when used as a concrete aggregate has immense environmental and socio-economic advantages to it. The wide use of coal gangue can reduce drastically the amount of the industrial solid waste produced, reduce the occupancy of land and the amount of pollution to the environment brought about by disposal of gangue. In the meantime, its application in concrete construction is useful in conserving natural aggregate resources which enables more sustainable construction. The findings of this review in the case of the construction industry would provide some useful guidelines on how to obtain the most appropriate mixed design, improve durability, and ensure that performance is reliable that would aid in moving towards more resource-saving and environmentally friendly materials. Besides, the establishment of the performance limits and change plans indicate the imperative of the establishment of the uniform design requirements and technical specifications to assist

in the establishment of safety and unregulated use of coal gangue aggregate concrete (CGAC) in the engineering works.

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- Acknowledgements:** The authors appreciate their supervisors and their co-workers who have guided them on this research, given them constructive ideas, and supported them through this research.
- Funding Statement:** This research received no external funding and was self-funded by the authors.
- Conflict of Interest Statement:** The authors declare that there is no conflict of interest regarding the publication of this paper. All authors have contributed to this work and approved the final version of the manuscript for submission to the International Journal of Innovation and Industrial Revolution (IJIREV).
- Ethics Statement:** This article is a review study and does not involve any human participants, animals, or identifiable personal data. Therefore, ethical approval was not required.
- Author Contribution Statement:** Minghao Li contributed to the conceptualization, literature review, data collection, analysis, and original draft preparation. Nor Hasanah Abdul Shukor Lim contributed to the supervision, manuscript review, and editing. Mohamad Dinie Khalis Bin Awalluddin contributed to the technical review and manuscript revision. Yoon Tung Chan contributed to literature screening, data organization, and manuscript proofreading. All authors have read and approved the final version of the manuscript.
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