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Thermodynamic Analysis of Thermal Stability in Recycled Concrete Derived from Building Solid Waste

Yong Pan[1*], Gao Chen[1], Chunshui Huang[2]

[1] Zhejiang Communications Construction Group Co., Ltd., Hangzhou 310000, China
[2] School of Civil Engineering, Xuchang University, Xuchang 461000, China

Corresponding Author Email: 12015042@xcu.edu.cn

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ABSTRACT

With the acceleration of urbanization, the amount of construction solid waste has increased dramatically. How to effectively deal with and utilize these wastes has become a major challenge in environmental management and resource recycling. Transforming these wastes into recycled concrete is a feasible way to solve this problem, where the thermal stability of concrete is a key attribute to ensure its structural safety. This study, based on thermodynamic principles, delves into the thermal stability of building solid waste recycled concrete. Firstly, the multiphase heat conduction behavior of recycled concrete is analyzed, and a thermodynamic model is used to simulate the heat exchange process between different phases; secondly, through the grey relational analysis method, the thermal stability performance of recycled concrete under different conditions is comprehensively evaluated. Previous studies mostly relied on simplified physical models or empirical formulas to predict the thermal stability of recycled concrete, which cannot fully reflect the impact of the material's microstructure and complexity on its thermal behavior. To overcome these shortcomings, this study proposes a new method combining multiphase heat conduction analysis with grey relational evaluation, aiming to provide a more accurate and practical model for predicting thermal stability. The research results verify that the proposed method can effectively reveal the contribution of each constituent phase to the thermal stability in recycled concrete, which is of great significance for the realization of high-performance, sustainable recycled concrete material design.

1. INTRODUCTION

As global industrialization and urbanization continue to advance, the construction industry has developed rapidly, generating a large amount of building solid waste [1, 2]. If these wastes are not properly treated, they will exert significant pressure on the environment. However, if the resources contained in these wastes are properly recycled and reused, not only can the environmental burden be reduced, but also new resource channels can be provided for the construction materials industry [3-5]. Against this backdrop, transforming building solid waste into recycled concrete has become an important technical route. In this process, the thermal stability of concrete has become a key indicator to ensure its structural reliability and durability, and studying the thermal stability of recycled concrete based on thermodynamic principles is of great significance for promoting the development of sustainable building materials [6-8].

In past research, the thermal stability of recycled concrete was mostly estimated through empirical models or simplified physical models, which have achieved certain results in terms of practicality and accuracy [9-13]. However, due to the complex composition of building solid waste and the significant differences in the properties of waste from different sources, these models often fail to fully capture the impact of material multiphase nature on thermal stability [14-16]. Therefore, it is particularly urgent to develop an analysis method that can effectively reflect the thermal behavior of recycled concrete under actual complex conditions.

Existing methods are limited in dealing with material complexity, especially in predicting the heat conduction behavior of multiphase materials. The common homogenization approaches usually ignore the impact of microstructure, which is crucial for accurately simulating and predicting the thermal stability of concrete under extreme temperatures [17-20]. In addition, studies on the systematic thermal stability evaluation of building solid waste recycled concrete are scarce, and there is a lack of a reasonable evaluation system [21-23].

This paper first discusses the multiphase heat conduction behavior of building solid waste recycled concrete, using a thermodynamics-based model to meticulously analyze the heat exchange and conduction mechanisms between phases. Secondly, the grey relational analysis method is used to conduct a comprehensive system assessment of the thermal stability of recycled concrete. This method not only considers the actual composition and structural complexity of the material but also reveals the degree of influence of different factors on thermal stability, providing a scientific basis for the design and optimization of recycled concrete. The results of this study will provide new theoretical and practical paths for the research of sustainable building materials, and have significant practical significance for environmental protection and resource recycling and reuse.

2. ANALYSIS OF MULTIPHASE HEAT CONDUCTION IN BUILDING SOLID WASTE RECYCLED CONCRETE

The effective utilization of building solid waste is an effective way to alleviate the shortage of natural resources and reduce environmental pollution. This article focuses on the multiphase heat conduction analysis of building solid waste recycled concrete. The thermal stability of concrete is a key factor affecting its service life and safety in extreme temperature environments. Through in-depth study of the multiphase heat conduction characteristics of recycled concrete, theoretical support and technical guidance can be provided for the resource utilization of these wastes, thereby increasing the recycling rate of construction waste and promoting the development of the circular economy.

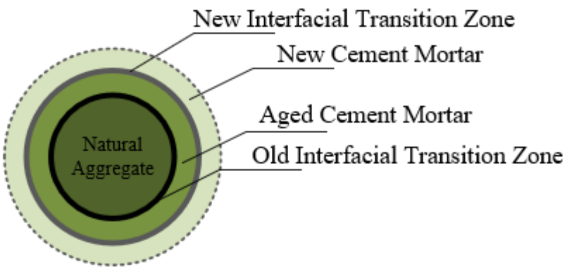


Figure 1. Structure of building solid waste recycled concrete

Figure 1 provides a simplified schematic diagram of the structure of building solid waste recycled concrete. In treating recycled concrete from building solid waste as a multiphase composite material, this study specifically focuses on the following constituent phases.

(1) Cement Matrix: The cement matrix is the binding component of recycled concrete, containing cement paste and hydration products, providing strength and stability to the concrete. The cement matrix is the dominant continuous phase in multiphase composite materials, usually with a higher thermal conductivity. The heat conduction capability of the cement matrix acts as a foundation in the overall thermal performance of recycled concrete. The efficiency of heat transfer in the cement matrix is high but can be affected by the degree of hydration, distribution of hydration products, and internal microcracks.

(2) Aggregates: In recycled concrete, aggregates usually consist of two parts: natural aggregates and recycled aggregates. Natural aggregates are traditional materials obtained from natural sources such as river sand, limestone, etc. Recycled aggregates, on the other hand, come from construction waste and may consist of concrete blocks, bricks, tiles, glass, and other various waste building materials after crushing and processing. The thermal conductivity of these aggregates is usually related to the mineral composition of the source. Natural aggregates like natural stone have a consistent thermal conductivity, while recycled aggregates show greater variability due to the diversity of their original building materials. Aggregates in concrete are usually discretely distributed, and their thermal performance significantly influences the overall thermal conductivity.

(3) Interfacial Transition Zone: The interfacial transition zone refers to the microscopic area between the cement matrix and the surface of aggregate particles. The equivalent interfacial transition zone is a key component in multiphase materials, as its physical and chemical properties are usually different from both the cement matrix and aggregates, and this is often a weak point in strength and durability and also an important factor affecting heat conduction. Being a microscopic area between the cement matrix and aggregates, it has a higher porosity rate than both, resulting in lower thermal conductivity. The presence of the equivalent interfacial transition zone causes the heat flow in multiphase composite materials to be non-homogeneous, potentially forming thermal bridges or thermal resistance, affecting overall thermal stability. Figure 2 shows a schematic diagram of the evolution process of the interfacial transition zone.

(4) Pore Structure: The pore structure of recycled concrete includes capillary pores formed by unreacted cement particles due to hydration reactions, and air voids formed by air entrainment or expulsion. These pores can be seen as another phase in the multiphase material, having complex effects on the thermal performance of the concrete. A higher porosity means more air gaps in the thermal conduction path, which may lead to a lower overall thermal conductivity coefficient, affecting the material's thermal stability. The impact on thermal conductivity is twofold. On one hand, a higher porosity implies more air gaps, reducing thermal conductivity; on the other hand, the connectivity and distribution of the pore structure also affect the thermal flow path, thereby influencing the efficiency of heat transfer.

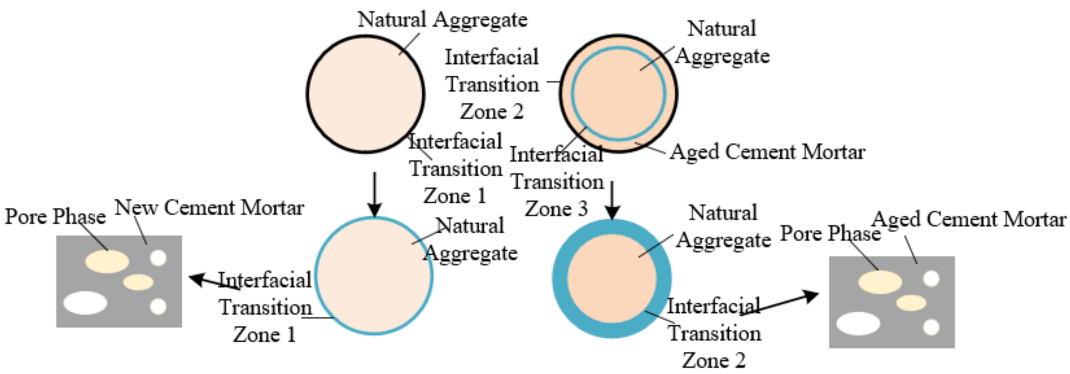


Figure 2. Evolution process of the interfacial transition zone

(5) Additives and Admixtures: These substances are used to improve the workability, strength, durability, and other properties of concrete. For example, admixtures like fly ash, slag powder, and diatomaceous earth can improve the microstructure of concrete, reducing porosity and thereby influencing the material's multiphase heat conduction behavior.

In this paper, the *Maxwell* model is chosen to predict the thermal conductivity coefficient of building solid waste recycled concrete. The *Maxwell* model provides an effective way to assess the overall thermal conductivity of composite materials, especially when the material consists of multiple phases with different thermal conductivities. The core principle of the *Maxwell* model is based on the following assumption: the aggregates (discrete phase) in recycled concrete are considered to be uniformly distributed within the cement matrix (continuous phase), and the aggregate particles are idealized as spherical, with unhindered thermal interaction between them. In this model, the recycled aggregate particles are imagined as small spheres suspended in the cement matrix as a continuous phase, and the heat transfer through these two materials is influenced by their respective thermal conductivities. Figure 3 presents the principle of multiphase heat conduction analysis of building solid waste recycled concrete.

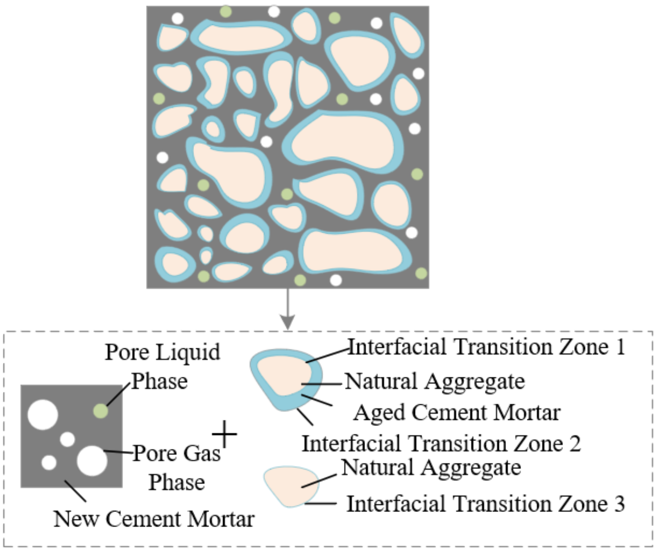


Figure 3. Principle of multiphase heat conduction analysis in building solid waste recycled concrete

Specifically, the *Maxwell* model starts by considering the thermal conductivities of the cement matrix and aggregates separately. Then, it's essential to determine the volume fraction of aggregates in the composite material. The volume fraction of aggregates is crucial for calculating the overall thermal conductivity coefficient, as it directly reflects the proportion of aggregates in the concrete. The *Maxwell* model takes into account the interaction between aggregates and the cement matrix, that is, how aggregate particles affect the heat transfer within the cement matrix. Due to the different thermal conductivities of aggregates and the cement matrix, there will be varying degrees of transfer efficiency when heat crosses these two materials. The model combines the thermal conductivities of aggregates and the cement matrix with the volume fraction of aggregates in a specific way to calculate the overall thermal conductivity. This calculation method considers the scenario of aggregate particles suspended in the cement matrix and the thermal conductive properties of both materials.

The pore liquid phase and the pore gas phase differ fundamentally in their heat transfer behavior. The thermal conductivity of liquids is generally higher than that of gases, so the presence of liquid in the pores leads to an increase in the overall thermal conductivity of concrete. In contrast, gases, due to their low thermal conductivity, reduce the material's conductive ability when present. Also, inside concrete, pore liquids might undergo phase changes, like freezing or melting during freeze-thaw cycles, while pore gases do not. The phase change process absorbs or releases a significant amount of heat, thereby affecting the material's thermal stability. Therefore, this paper considers the pore liquid phase and the pore gas phase separately in a first-order model to more accurately assess the impact of phase changes on thermal stability. Assuming that the calculated value of the second-order multiphase model of recycled concrete is represented by η_z, the thermal conductivity coefficient of the pore liquid phase by η_t, the volume fraction of the pore liquid phase by n_z, and the thermal conductivity coefficient of recycled concrete containing pore gas phase by η_{DR}, then the following formula is obtained:

$$\eta_z = \eta_{DR} \frac{2\eta_{DR} + \eta_t - 2n_t(\eta_{DR} - \eta_t)}{2\eta_{DR} + \eta_t + n_t(\eta_{DR} - \eta_t)} \quad (1)$$

In building solid waste recycled concrete, the porosity and the presence of gas within the pores significantly impact thermal conduction. By focusing on the pore gas phase, the study can more accurately explore and quantify the impact of pore gas on the overall thermal conductivity, which is vital for optimizing the material's thermal stability. Moreover, actual recycled concrete is a material comprising multiple components and complex structures. Treating it as a composite material consisting of an equivalent solid phase and pore gas phase simplifies the analysis without losing generality, aiding in establishing a practical and operational model for the thermal conductivity coefficient. Therefore, this paper further analyzes building solid waste recycled concrete as a composite material composed of an equivalent solid phase and pore gas phase, and constructs a model for the thermal conductivity coefficient of recycled concrete containing the pore gas phase. Assuming the thermal conductivity coefficient of the pore gas phase is represented by η_h, the volume fraction (%) of the pore gas phase by n_h, the volume fraction (%) of the equivalent solid phase by η_{to}, and the thermal conductivity coefficient of the equivalent solid phase by n_{to}, the following formula is obtained:

$$\eta_{DR} = \eta_{to} \frac{2\eta_{to} + \eta_h - 2n_h(\eta_{to} - \eta_h)/(n_h - \eta_{to})}{2\eta_{to} + \eta_h + n_h(\eta_{to} - \eta_h)/(n_h - \eta_{to})} \quad (2)$$

In building solid waste recycled concrete, the newly hardened cement matrix and coarse aggregates are the primary mediums for heat conduction. By focusing on these two components, one can more directly examine how they affect the overall thermal conductivity of the concrete. Additionally, in building solid waste recycled concrete, coarse aggregates are often made by crushing different sources of construction waste, and their thermal properties may differ from natural aggregates. Considering coarse aggregates as a separate dispersed phase helps to evaluate the unique properties of recycled materials. Therefore, this paper further treats building solid waste recycled concrete as a composite material composed of a newly hardened cement matrix (continuous phase) and coarse aggregates (dispersed phase), constructing a model for the thermal conductivity coefficient of the equivalent solid phase of building solid waste recycled concrete for analysis. Assuming the thermal conductivity coefficient of the newly hardened cement matrix is represented by η_{zl}, the volume fraction (%) of coarse aggregates by n_{zx}, and the thermal conductivity coefficient of coarse aggregates by η_{FC}, then, there is:

$$\eta_{to} = \eta_{sl} \frac{2\eta_{sl} + \eta_h - 2n_h(\eta_{sl} - \eta_h)/(n_h - \eta_{sl})}{2\eta_{sl} + \eta_h + n_h(\eta_{sl} - \eta_h)/(n_h - \eta_{sl})} \tag{3}$$

Ordinary and recycled aggregates, as dispersed phases, often cannot achieve a completely uniform distribution in building solid waste recycled concrete. Their contact or proximity can cause local thermal properties to differ from the expected uniform distribution, thus affecting overall heat conduction behavior. The *Maxwell* model adopted in this paper typically assumes uniform spherical particles for the dispersed phase, but in reality, the shapes and sizes of ordinary and recycled aggregates can be very irregular and varied. This irregularity affects heat flow paths and thermal exchange efficiency, causing the predictions of the *Maxwell* model to deviate from actual conditions. To address this, the paper chooses to define the thermal conductivity coefficient of coarse aggregates in building solid waste recycled concrete based on the average values calculated using series and parallel models. Assuming the thermal conductivity coefficients of coarse aggregates under series and parallel models are represented by η_{FC1}, η_{FC2}, and the volume fractions (%) of recycled and ordinary aggregates by n_{RC}, n_{NC}, and the thermal conductivity coefficients of recycled and ordinary aggregates by n_{RC}, n_{NC}, the following formulas are obtained:

$$\eta_{FC} = (\eta_{FC1} + \eta_{FC2})/2 \tag{4}$$

$$\eta_{FA1} = 1/(n_{RC}/\eta_{RC} + n_{NC}/\eta_{NC}) \tag{5}$$

$$\eta_{FC2} = n_{RC}\eta_{RC} + n_{NC}\eta_{NC} \tag{6}$$

At the mesoscopic level, defining and analyzing the equivalent interfacial transition zone is crucial for understanding and predicting the thermal conductivity coefficient of building solid waste recycled concrete. The equivalent interfacial transition zone is the microscopic area between the cement paste and aggregates, typically having a higher porosity than the cement matrix and aggregates. These pores are filled with air or moisture, and their thermal conductivity is much lower than that of solid materials. The high porosity results in thermal insulation properties of the equivalent interfacial transition zone, significantly affecting the overall thermal conductivity of the concrete material. Moreover, the structure of the equivalent interfacial transition zone in building solid waste recycled concrete is more complex, as the surfaces of recycled aggregates may be rough, uneven, and possibly coated with aged cement paste or other attachments. This complexity needs to be accurately described and quantified in the model. To address this issue, this paper defines the thermal conductivity coefficient λ of the equivalent interfacial transition zone. Assuming the volume of the interfacial transition zone in recycled concrete is represented by N_{VUSC}, and the volume of natural aggregates in recycled concrete by N_{xh}, the definition is as follows:

$$\lambda = \frac{N_{VUSC}}{N_{xh}} \tag{7}$$

Assuming the thickness of equivalent interfacial transition zone 1 is represented by s_1, and the thickness of equivalent interfacial transition zone 2 by s_2, the specific calculation process is as follows:

$$N_{VUSC} = (1-E)N_{VUSC1} + EN_{VUSC2} \tag{8}$$

$$N_{VUSC_1} = \frac{\pi}{6}D^3 - \frac{\pi}{6}(D-2s_1)^3 \tag{9}$$

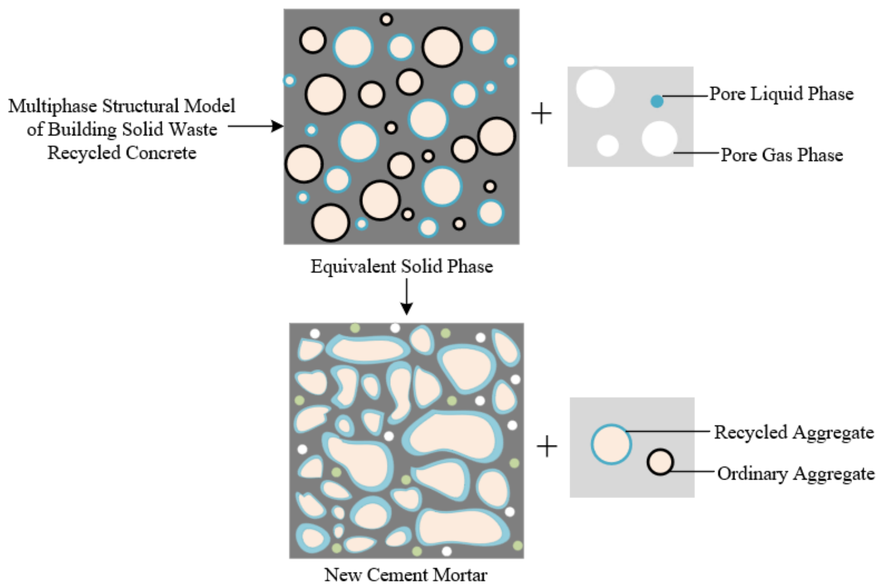


Figure 4. Theoretical model of thermal conductivity coefficient for building solid waste recycled concrete

$$N_{VUSC_2} = \frac{\pi}{6} D^3 - \frac{\pi}{6} \left(D - 2s_2 \right)^3 \tag{10}$$

Since the porosity and material composition of the equivalent interfacial transition zone might differ significantly from ordinary concrete, these differences directly affect the material's thermal behavior. Through influence coefficients, the theoretical model can be adjusted to better match experimental data, thus improving the model's accuracy in predicting actual material behavior. Assuming the thermal conductivity coefficient of recycled concrete is represented by η, the calculated value of the second-order multiphase model of recycled concrete by η_z, and the deviation of the fitting formula by $d(\lambda)$, this paper constructs the following theoretical model for the thermal conductivity coefficient of building solid waste recycled concrete considering influence factors:

$$\eta = \eta_z + d(\lambda) \tag{11}$$

The specific model is provided in Figure 4. By combining Formula 1 with the above formula, we can get:

$$\eta = \eta_{DR} \frac{2\eta_{DR} + \eta_t - 2n_t \left(\eta_{DR} - \eta_t \right)}{2\eta_{DR} + \eta_t + n_t \left(\eta_{DR} - \eta_t \right)} + 0.074\lambda + 0.139 \tag{12}$$

3. GREY RELATIONAL ANALYSIS OF THERMAL STABILITY IN BUILDING SOLID WASTE RECYCLED CONCRETE

The study of the thermal stability of building solid waste recycled concrete is of great research value for improving its application performance and environmental sustainability. Grey relational analysis, as a data analysis method, shows its unique advantages in dealing with uncertainty and incomplete information in system analysis. Grey relational analysis can help evaluate the thermal stability of recycled concrete under different temperature conditions, and thus determine its performance in extreme climatic or high-temperature working environments. By analyzing the impact of different components on thermal stability, guidance can be provided on how to choose suitable recycled aggregates and admixtures, and how to adjust the proportions of cement matrix and aggregates to improve the thermal stability of the concrete.

To effectively evaluate the thermal stability of building solid waste recycled concrete, it is necessary to establish a comprehensive and reasonable evaluation system. This system should be able to fully reflect the performance of recycled concrete under various thermal environments, including its durability, resistance to thermal stress, and thermal conduction behavior.

(1) Basic Performance Parameters: Thermal conductivity coefficient measures the ability of thermal energy to transfer within the material; specific heat capacity reflects the heat storage capacity of the material as the amount of heat absorbed per unit mass for a unit temperature rise; thermal expansion coefficient affects the generation of thermal stress by indicating the material's capacity for volume change under thermal action.

(2) Durability Performance Indicators: Freeze-thaw resistance, reflecting the material's ability to resist damage under freeze-thaw cycles; high-temperature resistance, the ability to maintain structural integrity and functionality under high temperatures; fire resistance, performance in extreme thermal environments like fires.

(3) Thermal Stress Evaluation Indicators: Thermal stress crack resistance, the material's ability to resist crack formation and expansion under temperature differences; thermal fatigue performance, the material's ability to resist fatigue under long-term thermal cycling.

(4) Microstructural Evaluation Indicators: Pore structure analysis, including porosity, pore size distribution, and connectivity; characteristics of the equivalent interfacial transition zone, namely its microstructure and physical properties; microcrack development, the formation and expansion of microcracks under thermal action.

(5) Environmental Adaptability Performance Indicators: Thermal environmental stability, performance changes under different temperature and humidity conditions; thermal cycle stability, the ability to recover performance under freeze-thaw cycling.

(6) Sustainability Evaluation Indicators: Energy consumption analysis during production, use, and disposal phases; carbon footprint, assessing greenhouse gas emissions over the entire lifecycle; resource recycling rate, the proportion and efficiency of recycled aggregate usage.

The specific steps of grey relational analysis are as follows:

(1) First, design a series of experiments to test the thermal stability parameters of recycled concrete. The experimental design should consider variables such as different proportions of recycled aggregates, different curing conditions, and different environmental factors. Determine thermal performance indicators such as thermal conductivity, thermal expansion coefficient, and specific heat capacity through experiments. Use standardized testing methods to ensure data reliability and comparability. Classify, code, and establish a database of experimental results. Record related environmental conditions and specific concrete formulations for each test indicator. Conduct quality checks on the collected data, including completeness, consistency, and outlier handling, to ensure accuracy in subsequent analyses.

(2) The reference sequence represents the ideal or optimal thermal stability performance. Choose a set of recycled concrete data with the best thermal stability performance as the reference sequence. The comparison sequences are the thermal performance data of recycled concrete under various conditions obtained in the experiments. Each set of data will serve as a comparison sequence for analysis against the reference sequence.

(3) Normalize all data using the selected method to eliminate the effects of different dimensions and scales, allowing direct comparison between data. Assuming the number of influencing factors is u=0,1,...,v, with each factor comprising l levels, the normalization formula is given as:

$$a_u(j) = \frac{a_u'(j)}{a_u'(1)} \tag{13}$$

(4) Calculate the absolute value differences between each comparison sequence and the corresponding elements of the reference sequence, i.e., $|a_p(j)-a_u(j)|$. These differences reflect the deviation of actual data from the ideal state. Analyze the distribution of absolute value differences to identify under which conditions the thermal stability of recycled concrete deviates significantly from the optimal state. Further, identify the maximum and minimum values among all calculated absolute value differences. These two extremes are crucial for

subsequent calculation steps, as they will be used for normalization and evaluation of the grey relational coefficients. Analyze the sensitivity of the maximum and minimum values to determine their stability under different experimental conditions. This helps evaluate the model's response to extreme data.

(5) Using the previously identified maximum and minimum values, calculate the grey relational coefficient for each data point according to the formula for grey relational coefficients. Assume the resolution coefficient, which takes values in the range (0,1), is represented by ϑ. The calculation formula is given below. The grey relational coefficient reflects the relative relationship between the comparison sequence and the reference sequence, and typically includes a resolution coefficient in the formula to adjust the sensitivity of the grey relational coefficient.

$$\varsigma_u(j)=\frac{\underset{u}{MIN}\,\underset{j}{MIN}\left|a_0(j)-a_u(j)\right|+\vartheta\,\underset{u}{MAX}\,\underset{j}{MAX}\left|a_0(j)-a_u(j)\right|}{\left|a_0(j)-a_u(j)\right|+\vartheta\,\underset{u}{MAX}\,\underset{j}{MAX}\left|a_0(j)-a_u(j)\right|} \tag{14}$$

(6) For each comparison sequence, calculate the average of all the grey relational coefficients to obtain a comprehensive degree of association. This value will comprehensively reflect the similarity of the comparison sequence as a whole to the reference sequence, and its calculation formula is:

$$e_u=\frac{1}{l}\sum_{j=1}^{l}\varsigma_u(j) \tag{15}$$

In the study of building solid waste recycled concrete, once the degree of association is obtained through grey relational analysis, it can be used to assess the impact of different factors on the material's thermal stability.

Firstly, sort the degrees of association of all comparison sequences. The varying degrees of association between all sequences will reveal the similarity of the material's thermal stability under different test conditions to the ideal state. By comparing the said degree of association, the factors that most significantly affect thermal stability can be identified. For example, if a particular mix of recycled concrete has a high degree of association, this indicates that it performs close to the ideal state in terms of thermal stability. Conversely, sequences with low degrees of association may expose factors that negatively impact thermal stability.

By analyzing the sequences with high degrees of association, determine the material components or proportions that are favorable for improving thermal stability, such as adding specific admixtures or changing the content of recycled aggregates. Analyze the process conditions that lead to increased degrees of association, such as curing time and temperature-humidity conditions, to optimize the production process. Improve sequences with low degrees of association, for example, by refining the microstructure within the concrete, reducing porosity, or enhancing the performance of the interfacial transition zone.

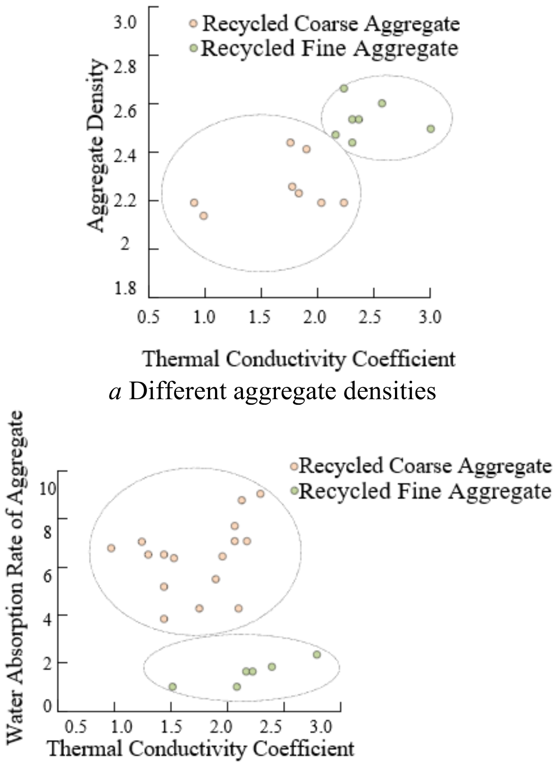
Based on the results of the degree of association, recommendations can be made for establishing or revising standards and guidelines for the use of recycled concrete, to ensure the material's thermal stability meets engineering requirements. Combined with grey relational analysis, the performance of recycled concrete under different environmental conditions can be evaluated, thereby providing guidance for its application in specific climates and usage environments.

4. EXPERIMENTAL RESULTS AND ANALYSIS

Table 1 shows the mix proportion design of building solid waste recycled concrete used in the experiments. Specimen numbers 1 to 12 represent different mix proportion schemes. The main components involved in the mix proportion include water-cement ratio, cement, fly ash, recycled aggregate, natural aggregate, medium sand, water, and the proportion of water reducer used. The mix proportion design includes three different water-cement ratios: 0.55, 0.50, and 0.45. Concrete with a lower water-cement ratio usually has better durability and compressive strength because a low water-cement ratio helps to form a denser cement paste. All specimens used cement and fly ash. Fly ash, as an admixture, can improve the workability of concrete, reduce the amount of cement used, and also enhance the strength and durability in the later stages. Specimens 1, 5, and 9 did not use recycled aggregates but used entirely natural aggregates. Specimens 4, 8, and 12 completely replaced natural aggregates with recycled aggregates. The intermediate specimens 2, 3, 6, 7, 10, and 11 used a mix of different proportions of recycled and natural aggregates. The experiment aims to find the optimal proportion of recycled aggregates by comparing the impact of different recycled aggregate ratios on concrete performance, balancing environmental benefits and material properties. The quantities of medium sand and water in all mix proportions were kept constant, facilitating the observation of the impact of water-cement ratio and recycled aggregate proportion variations on concrete performance exclusively. All specimens used 1% water reducer, which helps to improve the pumpability and flowability of the concrete, and also reduces the water-cement ratio to some extent, thus enhancing the concrete strength.

Table 1. Design of mix proportions for building solid waste recycled concrete

Specimen Number	Water-Cement Ratio	Cement	Fly Ash	Recycled Aggregate	Natural Aggregate	Medium Sand	Water	Water Reducer
1	0.55	442	115	0	1000	750	275	1%
2	0.55	442	115	300	700	750	275	1%
3	0.55	442	115	500	500	750	275	1%
4	0.55	442	115	1000	0	750	275	1%
5	0.50	478	132	0	1000	750	220	1%
6	0.50	478	132	300	700	750	220	1%
7	0.50	478	132	500	500	750	220	1%
8	0.50	478	132	1000	0	750	220	1%
9	0.45	424	124	0	1000	750	150	1%
10	0.45	424	124	300	700	750	150	1%
11	0.45	424	124	500	500	750	150	1%
12	0.45	424	124	1000	0	750	150	1%



a Different aggregate densities

b Different aggregate water absorption rates

Figure 5. Thermal conductivity coefficient of building solid waste recycled concrete

Figure 5 presents a scatter plot of the thermal conductivity coefficients of building solid waste recycled concrete. From Figure 5-a, it can be seen that there are two groups of data, each identified with different colored dots: "Recycled Coarse Aggregate" and "Recycled Fine Aggregate". The thermal conductivity coefficients for Recycled Fine Aggregate (green dots) are in the higher range of aggregate density, roughly between 2.5 and 3.0, with thermal conductivity coefficients ranging from 2.6 to 2.8 *W/(m·K)*. The recycled coarse aggregate (orange dots) has thermal conductivity coefficients distributed over a wider range of aggregate densities, varying from about 2.0 to 3.0, with coefficients ranging approximately from 2.2 to 2.6 *W/(m·K)*. For lower aggregate density values, the thermal conductivity coefficients for recycled coarse aggregate are lower, indicating that materials with lower density have lower thermal conductivity. The distribution of the points suggests that for both types of aggregates, the thermal conductivity coefficient of recycled concrete slightly increases with the increase in aggregate density. It can be concluded that aggregate density is a factor influencing the thermal conductivity coefficient of recycled concrete, and this influence shows different trends in different types of aggregates (coarse and fine aggregates). Additionally, the clear distinction between the two types of aggregates in these data points validates the feasibility and rationality of the models represented by these points in assessing the thermal conductivity performance of materials. Setting appropriate model parameters and boundary conditions can provide relatively accurate predictions for real-life situations, thus proving the effectiveness of constructing the model.

A similar analysis can be applied to the data points in Figure 5-b. Recycled fine aggregates (green dots) have thermal conductivity coefficients concentrated in a lower range, roughly between 1.5 and 2.0 *W/(m·K)*, in the lower water absorption rate range (about 0-2%). Recycled coarse aggregates (orange dots) show more scattered thermal conductivity coefficients in the higher water absorption rate range (about 2-10%), but most are concentrated between 1.0 and 1.5 *W/(m·K)*. Overall, as the water absorption rate of the aggregate increases, the thermal conductivity coefficient tends to decrease, especially for recycled coarse aggregates. The two groups of data points are concentrated at different positions in terms of water absorption rate, indicating that water absorption rate is a distinct parameter affecting the thermal conductivity coefficient of recycled concrete with different types of aggregates. Based on the performance of the data points, it can be concluded that the water absorption rate of the aggregates significantly influences the thermal conductivity coefficient of recycled concrete, and this influence exhibits different characteristics in fine and coarse aggregates. Lower water absorption rates are associated with lower thermal conductivity coefficients, particularly noticeable in recycled coarse aggregates.

Table 2 demonstrates the impact of different pretreatment methods on the thermal conductivity coefficients of recycled coarse aggregates from building solid waste and natural coarse aggregates. From the table, it is evident that natural coarse aggregate has the lowest porosity (3.18%) and the highest thermal conductivity coefficient (1.55 *W/mK*). Since it undergoes no pretreatment, its thermal conductivity coefficient can be used as a reference benchmark. Untreated recycled coarse aggregate has a higher porosity (18.98%), leading to a reduced thermal conductivity coefficient of 1.14 *W/mK*, a change rate of 25.8% compared to natural coarse aggregate. This indicates that higher porosity reduces the material's thermal conduction capability. Pretreatment significantly improves the thermal conductivity performance of recycled coarse aggregates. Particularly, the washing and iron removal treatment brings the thermal conductivity coefficient of recycled coarse aggregate close to that of natural coarse aggregate, with almost no loss in thermal performance.

Table 2. Thermal conductivity coefficients of recycled concrete from building solid waste with different pretreatments

Aggregate Type	Pretreatment Method	Aggregate Porosity	Thermal Conductivity Coefficient	Change Rate of Thermal Conductivity Coefficient
Natural Coarse Aggregate	None	3.18	1.55	/
Recycled Coarse Aggregate	None	18.98	1.14	25.8
	Washing	15.23	1.21	15.2
	Washing + Iron Removal	12.36	1.52	0.6
	Acid Pickling	14.59	1.23	24.8
	Acid Pickling + Sieving	14.87	1.42	14.2
	Acid Pickling + Pre-soaking	14.97	1.38	18.9

Washing and iron removal significantly reduce the porosity of recycled aggregates, where iron removal helps to remove metal particles that conduct heat more effectively, thereby increasing the overall thermal conductivity coefficient of the concrete. Acid pickling, although it can increase the roughness of the aggregate surface and improve its bond strength with cement stone, does not enhance thermal conductivity as significantly as physical methods (such as washing and iron removal). It can be concluded that the thermodynamics-based model constructed in this paper can meticulously analyze the impact of different pretreatment methods on the heat exchange and conduction mechanisms between different phases of recycled coarse aggregates. By comparing with experimental data, the model can effectively predict the thermal conductivity coefficients of recycled aggregates with different pretreatments, proving its reliability and accuracy in practical applications.

Table 3. Ranking results of the degree of association for thermal stability evaluation indicators of building solid waste recycled concrete

Evaluation Item	Degree of Association	Ranking
Basic Performance Parameters	0.885246	1
Durability Performance Indicators	0.858256	2
Thermal Stress Evaluation Indicators	0.853247	3
Microstructural Evaluation Indicators	0.849923	4
Environmental Adaptability Performance Indicators	0.842689	5
Sustainability Evaluation Indicators	0.835479	6

Table 3 provides the degree of association and ranking results for the thermal stability evaluation indicators of building solid waste recycled concrete. As shown in the table, the design of the evaluation indicator system comprehensively covers various aspects affecting the thermal stability of building solid waste recycled concrete. The high degree of association for each evaluation item indicates that the selected indicators are both reasonable and effective. Basic performance parameters, being the most crucial factor affecting thermal stability, should be given the highest priority in optimizing the formula and improving the processes of recycled concrete. Durability and thermal stress evaluation indicators are also very critical, suggesting that in addition to considering the initial physical properties, the long-term performance and resistance to thermal stress of recycled concrete should be emphasized in its design. The influence of microstructural characteristics indicates that optimization at the micro-level is also an important way to improve thermal stability. The relatively lower degree of association for environmental adaptability and sustainability indicators does not mean these factors are unimportant, but rather that their direct impact on thermal stability is less than that of basic physical and durability properties. However, given the increasing importance of sustainability, these factors remain an indispensable part of the overall evaluation system. It is evident that the evaluation indicator system constructed in this paper demonstrates its effectiveness through empirical data, reasonably reflecting the impact of each evaluation indicator on thermal stability and providing a scientific basis for practical applications. Through the ranking of degrees of association, this evaluation system can also help decision-makers identify key areas for improving the thermal stability of recycled concrete, enabling more precise material design and process improvements.

Table 4. Stress-strain relationship test results for building solid waste recycled concrete

Strain	Stress		
	Recycled Aggregate Content 10%	Recycled Aggregate Content 20%	Recycled Aggregate Content 30%
0.5	2.1	2.3	2.4
1	3.8	4.2	4.6
1.5	5.2	5.8	6.2
2	6.8	7.1	8.2
2.5	7.7	8.2	10.2
3	8.1	9.4	11.8
3.5	10.2	11.4	12.4
4	11.7	12.9	14.5

Table 4 provides the stress-strain relationship test results of building solid waste recycled concrete with different contents of recycled aggregates. From the table, it is observed that as the strain increases, the stress of all concrete specimens shows a growing trend, which is typical stress-strain behavior for concrete materials. At the same level of strain, the higher the content of recycled aggregates, the greater the stress the concrete can withstand. This indicates that under the conditions of this test, the increase in recycled aggregate contributes to enhancing the load-bearing capacity of the concrete. Concrete with 10% recycled aggregate content sustains the lowest stress at each level of strain, while the concrete with 30% content sustains the highest stress. This suggests that increasing the proportion of recycled aggregate in the specimens can improve the compressive stress capacity of the concrete, which is related to the higher hardness and compressive strength of the recycled aggregates. The relationship between stress and strain is not entirely linear, especially at higher levels of strain, where the rate of increase in stress becomes larger. This nonlinear behavior is associated with the formation and development of microcracks in the concrete and the changes in the material's compactness at different levels of strain. Based on the stress-strain relationship test results, it can be inferred that the thermal stability of concrete would also improve with an increase in recycled aggregate content. This is because higher compressive strength usually implies higher thermal stability. If the recycled aggregates themselves have a lower coefficient of thermal expansion, then increasing their content would reduce the overall thermal expansion of the concrete, thereby enhancing thermal stability.

Figure 6 presents the stress-strain curves of building solid waste recycled concrete. From the figure, it is evident that at lower temperatures (0℃ and -5℃), the concrete withstands higher stress under the same strain conditions. This is because materials become more brittle and harder under low-temperature conditions, thus exhibiting higher resistance to deformation in the initial stage. As the temperature decreases, the initial elastic modulus of the concrete increases, indicating that the material is more resistant to initial loads at lower temperatures. Under all temperature conditions, as the strain increases, the stress also increases, but the rate of increase slows down, indicating the formation and expansion of cracks. Particularly at -5°C, at higher strain (15%), the stress rapidly rises to a high value (50 MPa), indicating rapid crack propagation under low temperature and high strain conditions. At 15°C and 10°C, as the strain increases, the stress begins to decrease after reaching a peak value, indicating that the material has reached its limit strength and is beginning to fail. At 0°C and -5°C, the stress continues to increase or reaches a high value at the highest strain value; due to the incompleteness of the data, the downward trend after the peak is not visible.

The experimental data indicate that as the temperature decreases, recycled concrete exhibits higher initial compressive stress but becomes more brittle under high strain, which is crucial for the assessment of the thermal stability of structures. To ensure the safety and reliability of structures under different temperature conditions, the design of recycled concrete needs to be optimized based on its mechanical performance within the anticipated range of environmental temperatures.

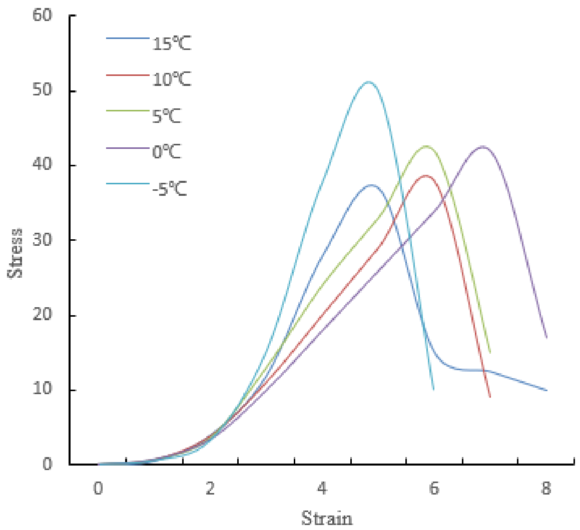


Figure 6. Stress-strain curve of building solid waste recycled concrete

Table 5. Elastic modulus values of building solid waste recycled concrete under different temperature conditions

Recycled Aggregate Replacement Rate	Temperature	Compressive Strength	Elastic Modulus
	15	36.2	32.1
	10	37.8	31.5
0	-5	41.2	32.8
	-0	43.5	33.6
	-5	46.8	31.5
	15	31.2	32.5
	10	33.9	33.8
50	-5	37.2	32.4
	-0	38.9	31.5
	-5	43.2	32.2
	15	28.6	28.9
	10	28.9	29.5
100	-5	36.5	32.1
	-0	41.2	31.5
	-5	43.6	32.8

Table 5 provides the compressive strength and elastic modulus values of building solid waste recycled concrete with different replacement rates of recycled aggregates under various temperature conditions. The table shows that at 0% replacement rate (no recycled aggregates), the elastic modulus of concrete varies little at different temperatures, generally staying between 32.1 and 33.6 GPa. When the replacement rate of recycled aggregates increases to 50%, the elastic modulus slightly rises, particularly at 10°C, reaching a peak of 33.8 GPa. At a 100% replacement rate (completely using recycled aggregates), the elastic modulus decreases, especially at 15°C and 10°C, with values of 28.9 GPa and 29.5 GPa, respectively. For different replacement rates of recycled aggregates, the elastic modulus increases under cold conditions (-5°C). This is because the material becomes harder and more brittle at lower temperatures, thus showing higher resistance to deformation under initial strain. However, this trend is not as pronounced at a 100% replacement rate due to the complete use of recycled aggregates altering the internal structure of the concrete, affecting its response to temperature changes. At the same temperature, as the replacement rate of recycled aggregates increases, the compressive strength generally shows a declining trend. This is because the bond between recycled aggregates and fresh cement stone is not as good as that with natural aggregates, or the recycled aggregates may have more defects. It can be concluded that the thermal stability of recycled concrete is influenced by its material composition and environmental temperature. These factors should be considered comprehensively in design and evaluation. Structures become more brittle at low temperatures, which requires special attention, especially at high replacement rates of recycled aggregates. For concrete composed entirely of recycled aggregates, although the elastic modulus increases at low temperatures, the overall modulus is lower, which affects its performance under thermal stress.

Table 6. Peak strain of building solid waste recycled concrete under different temperature conditions

Recycled Aggregate Replacement Rate	Temperature	Compressive Strength	Peak Strain
	15	34.5	5.7
	10	37.8	6.1
0	-5	41.2	6.2
	-0	43.6	6.5
	-5	46.7	5.8
	15	31.2	4.3
	10	33.6	4.3
50	-5	37.5	6.2
	-0	38.9	6.5
	-5	43.2	6.2
	15	27.3	5.3
	10	28.9	4.6
100	-5	36.5	5.7
	-0	41.2	6.1
	-5	43.5	4.7

Table 6 presents the compressive strength and peak strain of building solid waste recycled concrete with different recycled aggregate replacement rates under various temperatures. The table indicates that at a 0% recycled aggregate replacement rate, the peak strain slightly increases as the temperature decreases. This is because the material becomes harder at lower temperatures, allowing it to withstand greater strain before failure. At a 50% replacement rate, the peak strain is lower at 15℃ and 10℃, but increases at -5℃ and 0℃, suggesting that a moderate amount of recycled aggregate can increase the toughness of concrete under certain conditions. At a 100% replacement rate, the peak strain is lower at 15℃ but reaches a higher value at 0℃. This suggests that a high proportion of recycled aggregate can provide additional toughness at certain temperatures, although this trend is not consistent. Temperature changes have varying impacts on the peak strain of concrete with different replacement rates. In pure natural aggregate concrete, low temperatures increase the peak strain, while in high replacement rate concrete, the impact of temperature on peak strain is less pronounced. In all cases, compressive strength generally increases as the temperature decreases due to the material becoming more brittle and stronger at the initial load-bearing capacity. However, peak strain does not always increase with increased compressive strength, indicating no direct linear relationship between strength and toughness and depending on the proportion of recycled aggregate and environmental temperature. It can be concluded that the thermal stability of recycled concrete should consider its peak strain and compressive strength at different temperatures. Low temperatures increase compressive strength, but the impact on peak strain is complex and depends on the proportion of recycled aggregate. When designing recycled concrete structures, the formula should be optimized based on the anticipated temperature range and recycled aggregate replacement rate to achieve the best mechanical performance and thermal stability.

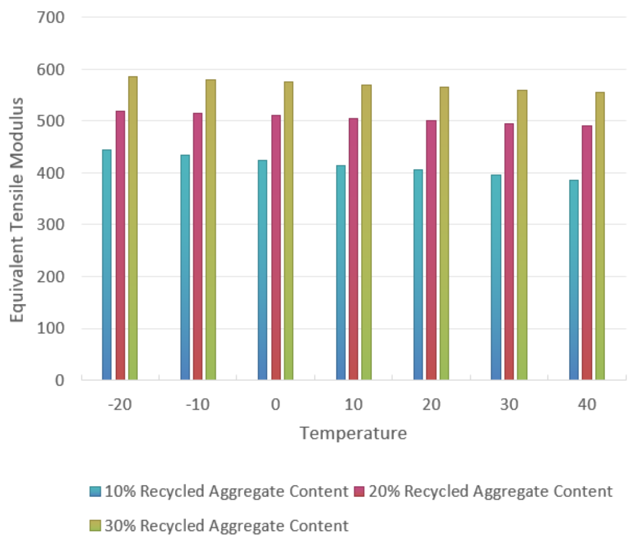


Figure 7. Equivalent tensile modulus and temperature relationship of building solid waste recycled concrete

Figure 7 shows the equivalent tensile modulus of concrete with 10%, 20%, and 30% recycled aggregate content over a temperature range of -20℃ to 40℃. The figure indicates that the equivalent tensile modulus of all samples decreases as the temperature rises. This suggests that recycled concrete becomes softer with increasing temperature, and its resistance to tensile forces weakens. The impact of temperature on the equivalent tensile modulus is consistent across all samples, showing that higher temperatures result in lower modulus values. With the increase in recycled aggregate content, the equivalent tensile modulus also increases. This is likely because recycled aggregates themselves have higher hardness or can provide greater modulus contribution. At all temperature conditions, concrete with 30% recycled aggregate content exhibits the highest equivalent tensile modulus, while that with 10% content shows the lowest. It can be concluded that in cold environments, recycled concrete demonstrates higher equivalent tensile modulus, indicating good thermal stability. However, in high-temperature environments, the reduction in the equivalent tensile modulus leads to a decline in structural performance, especially under tensile stress. This trend suggests that recycled concrete structures should be designed according to the anticipated temperature range, optimizing the concrete mix with an appropriate amount of recycled aggregate to enhance thermal stability.

5. CONCLUSION

This paper explored the multiphase heat conduction behavior of building solid waste recycled concrete and employed a thermodynamics-based model to meticulously analyze the heat exchange and conduction mechanisms between different phases. Furthermore, the thermal stability of recycled concrete was comprehensively and systematically assessed using grey relational analysis. Experimentally, concrete mix designs with varying water-cement ratios, cement, fly ash contents, and recycled coarse aggregate replacement rates were proposed. The experiments explored the impact of these variables on the performance of recycled concrete. It was found that reducing the water-cement ratio helps enhance the mechanical strength and durability of the concrete, while the addition of fly ash improves workability and later-stage strength.

Various pretreatment methods for recycled coarse aggregate, including washing, iron removal, acid pickling, sieving, and pre-soaking, were employed. These pretreatments aimed to reduce the porosity of recycled aggregates, improve their bond strength with cement stone, and enhance the overall performance of concrete. The experimental results showed that pretreatment significantly improved the thermal conductivity performance of recycled aggregates, especially washing combined with iron removal, bringing the thermal conductivity coefficient of recycled coarse aggregate close to that of natural coarse aggregate. The study of thermal conductivity coefficient changes in recycled aggregates subjected to different pretreatment methods demonstrated that pretreatment not only reduced the porosity of recycled aggregates but also reduced the thermal conductivity coefficient in most cases, enhancing insulation. The grey relational analysis indicated that basic performance parameters are the most critical factors affecting thermal stability, followed closely by durability performance and thermal stress evaluation indicators.

This paper confirmed that carefully designed mix proportions and appropriate aggregate pretreatment methods could significantly enhance the thermal stability and other performances of recycled concrete. The methods and conclusions of this study provide a scientific basis for the effective utilization of building solid waste and the performance enhancement of recycled concrete, contributing to the advancement of sustainable building materials.

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