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V. Dzhedzhula
Guo Zhiyong

RESEARCH ON HEAT TRANSFER MECHANISM AND THERMAL PERFORMANCE OF WHEAT STRAW FLY ASH CONCRETE

Vinnytsia National Technical University

A large number of rural residential buildings in the world did not take effective thermal insulation measures. The poor thermal insulation performance of the envelope led to low indoor temperatures in winter, and energy consumption was huge. The purpose of this study was to explore the effect of wheat straw and fly ash incorporated into concrete on its thermal properties, and to provide a low-cost and energy-efficient solution for rural building wall materials. The experiment involved preparing concrete block samples containing different doses of fly ash and straw, building an experimental platform to determine compressive strength and thermal conductivity, and simulating different humid environments using a saturated saline solution to analyse the effect of moisture content on thermal conductivity. The effect of moisture content on thermal conductivity was analysed by simulating different humidity environments with saturated salt solution. Combined with data fitting and comparative analysis, the mechanism of straw admixture, morphology and humidity on the material properties was revealed. The study showed that the thermal conductivity of wheat straw fly ash concrete decreased gradually as the content of fly ash and straw increased, and the larger the content, the smaller the thermal conductivity. The thermal conductivity of wheat straw fly ash concrete increased significantly with the increase in air humidity, and the relationship between moisture content and thermal conductivity was closely related to the content of straw and fly ash. The incorporation of fly ash and straw in concrete effectively improved the thermal insulation performance of building materials, and was an effective alternative for improving building energy efficiency and reducing carbon emissions

Keywords: *building envelope; straw content; air humidity; thermal conductivity ; hygrothermal performance, building energy efficiency*

Introduction

Globally, rural residential buildings were characterized by poor envelope thermal insulation and high energy consumption in winter, which were rooted in the high thermal conductivity of traditional wall materials and the lack of low-cost energy-saving retrofit solutions. Despite the attention that was paid to the resource utilization of agricultural and industrial wastes, most of the existing studies focused on the optimization of the mechanical properties of straw ash as a substitute for cement, while the mechanism by which larger quantities of powdered or striped straw affected the thermal properties of concrete remained unclear. Rural buildings were often located in high humidity environments, and most existing studies were based on dry conditions, ignoring the dynamic effect of humidity on thermal conductivity, which led to deviations between theoretical models and real working conditions.

Agricultural crops generate a large number of agricultural wastes all over the world, Including a large amount of wheat and corn straw (Yang *et al*., 2022). According to the Food and Agriculture Organization of the United Nations (FAO), the total global wheat production in 2022 exceeded 800 million tons, and the burning of large quantities of wheat straw was harmful to the environment. Thermal power generation and industrial production also produced a large amount of fly ash (Ghanim *et al*., 2023), of which more than 30% was landfilled and stockpiled because it could not be comprehensively utilized (Yang *et al*., 2021). Plant fibers as concrete admixtures had a very good prospect for future application (Manniello *et al*., 2022). The rational application of agricultural straw and industrial waste fly ash in the exterior wall materials of rural residential buildings was conducive to improving the thermal performance of traditional building materials, promoting the comprehensive utilization of straw, improving the comfort of the living environment, and reducing the energy consumption of rural residential buildings (Yin *et al*., 2023). A number of scholars studied the application of agricultural wastes to building wall materials. F. Benmahiddine *et al*. (2020) applied hemp straw to concrete and found that hemp concrete had good durability properties. N. Bheel *et al*. (2021) studied the engineering properties of concrete with ternary mixtures of fly ash, wheat stover ash, and corn cob ash, and the results proved that wheat straw ash and corn cob ash could be well used as binders for cementitious composites. B. Niu & B.H. Kim (2022) investigated an innovative method for the preparation of cementitious composites from corn stover plants, providing a new and important technological measure to solve the problem of high energy consumption in rural dwellings. Amin et al. (2022) used rice straw ash and palm leaf ash as partial cement replacement and found that 50% cement replacement could be achieved with agricultural wastes. J. Ahmad *et al*. (2023) showed that wheat straw ash is an agricultural waste with potential for concrete utilization, and the durability performance of concrete was improved. K. Khan *et al*. (2022) utilized wheat straw ash and silica fume as a cement replacement for the production of high-performance and sustainable concrete, and found that these two types of wastes were used to produce high-performance concrete. It was also found that both mixtures had lower CO_2 equivalent strength per MPa. X. Zhang *et al*. (2023) concluded that straw fiber concrete had a low thermal conductivity and was a promising insulating material. E.M. Elbashiry *et al*. (2023) designed a new type of straw-filled bionic concrete hollow blocks, which showed excellent compression and insulation properties and could be used as a new type of non-load-bearing wall material to replace the traditional type. Y. Li *et al*. (2023) concluded that green building materials made of straw could replace energy-intensive and polluting materials such as asbestos and polystyrene, and that straw was an effective alternative for improving energy efficiency and reducing carbon emissions in buildings.

Although many scholars have achieved relatively mature research results in utilizing straw ash as a cement substitute for concrete, there is still a lack of discussion on how the high content of powdered and striped straw affects the thermal properties of concrete. This paper was focused on the combined effect of wheat straw and fly ash on the thermal properties of concrete, and systematically investigate the specific effects of straw content and its particle size on the thermal conductivity of concrete by incorporating a specific proportion of wheat straw and fly ash in conventional concrete, and further analysed the effects of different humidity conditions on the thermal conductivity of straw-fly ash composite concrete. This study aimed to provide a scientific basis for the application of wheat straw in concrete to optimize the thermal insulation performance of building walls.

Materials and Methods

2.1 Research on heat transfer mechanism of straw concrete wall

From the second law of thermodynamics, it can be seen that under the influence of no external work, the heat is always transferred from the high temperature part to the low temperature part, and for the building envelope, its heat transfer process also follows the same law. When there is a temperature difference between the indoor and outdoor air of a building, the heat transfer phenomenon will occur in the outer envelope. In winter, as the indoor temperature is higher than the outdoor temperature, heat will be transferred from indoor to outdoor through the exterior walls, doors, windows and roofs, etc., while in summer, the opposite is true. Heat transfer through exterior walls consists of two main types, i.e., convective heat transfer between interior and exterior surfaces and structural heat transfer. Taking the heat transfer process of wheat straw fly ash concrete (WSC) exterior wall in winter as an example, the heat transfer process includes three processes, namely heat absorption on the inner surface, heat conduction in the flat-wall material layer and heat release on the outer surface, as shown in Figure 1.

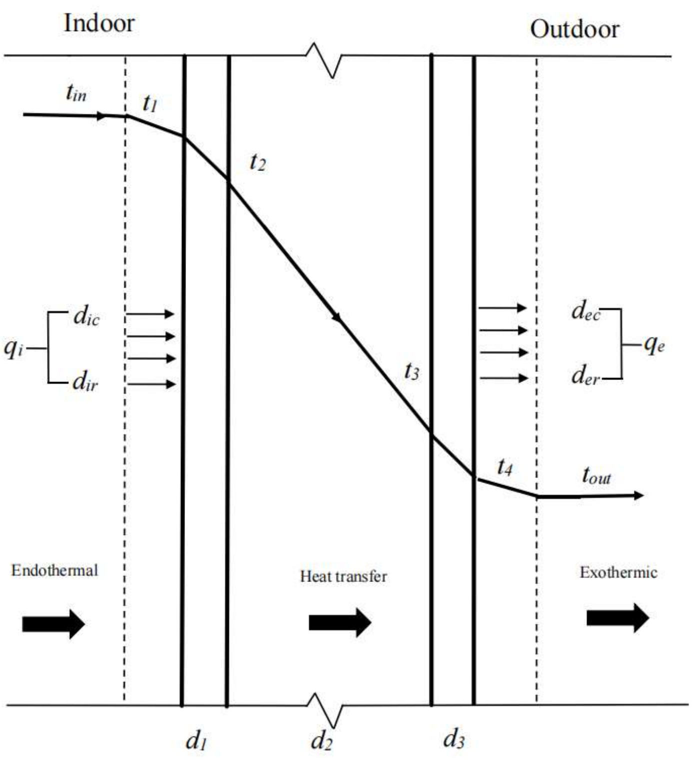

Figure 1. Steady state heat transfer schematic for WSC wall

2.1.1 Convective heat transfer on the inner surface

The inner surface of the straw concrete facade was heated by the combination of convective heat transfer and radiative heat transfer, and the heat flow intensity q_i was expressed as follows:

$$q_i = q_{ic} + q_{ir} = (\alpha_{ic} + \alpha_{ir})(t_{in} - t_1); \quad (1)$$

$$a_i = \alpha_{ic} + \alpha_{ir}; \quad (2)$$

$$q_i = a_i(t_{in} - t_1), \quad (3)$$

where q_i was the intensity of heat flow absorbed by the inner surface of the wall (W/m^2); q_{ic} was the intensity of heat flow transferred from the indoor air to the inner surface of the wall in the form of convective heat transfer (W/m^2); q_{ir} was the intensity of heat flow transferred from the other surfaces of the room to the inner surface of the wall in the form of radiant heat transfer to the inner surface of the wall in the form of convective heat transfer (W/m^2); a_i was the heat transfer coefficient of the inner surface（W/m^2-K）, which was the sum of the convective heat transfer coefficient α_{ic} and the radiative heat transfer coefficient α_{ir}, which represents the difference of the temperature of the inner surface and the indoor air temperature of 1K. This parameter represents the amount of heat transfer through the unit area of the envelope in 1h when the difference between the internal surface temperature and the indoor air temperature is 1K; t_{in} was the indoor air temperature (°C); t_1 was the internal surface temperature of the wall (°C).

2.1.2 Flat-wall material layer heat conduction

Most of the general building materials had pores inside, and the heat transfer within the pores contained two forms of convective and radiative heat transfer in addition to thermal conductivity. However, the heat transferred by convective and radiative heat transfer accounted for a very small proportion of the heat transfer, so the heat transfer of the WSC wall was considered as a single thermal conductive process. As shown in Fig. 1, the WSC wall was a multilayer flat wall composed of three layers of materials. Each layer of materials, from the inside out, were cement mortar, WSC, and cement mortar, and the layers were tightly bonded to each other. The thermal conductivity calculation formula for the flat wall material layers of the WSC wall is shown below:

$$q_\lambda = (t_1 - t_2)/(d_1/\lambda_1 + d_2/\lambda_2 + d_3/\lambda_3), \quad (4)$$

where q_λ was the intensity of thermal conductive heat flow through the straw concrete wall (W/m^2); t_1 was the internal surface temperature of the wall (°C); t_2 was the external surface temperature of the wall (°C); d_i was the thickness of each material layer of the wall (m); λ_i was the thermal conductivity of each material layer of the wall (W/(m-K)).

2.1.3 Convective heat transfer on the exterior surface

The exterior surface of the WSC facade dissipates heat under the combined effect of convective heat transfer and radiative heat transfer, and its heat flow intensity q_e was expressed as follows:

$$q_e = q_{ec} + q_{er} = (\alpha_{ec} + \alpha_{er})(t_4 - t_{out}); \quad (5)$$

$$a_e = \alpha_{ec} + \alpha_{er}; \quad (6)$$

$$q_e = a_e(t_4 - t_{out}), \quad (7)$$

where q_e was the intensity of heat flow from the exterior surface of the wall in the form of heat dissipation (W/m^2); q_{ec} was the intensity of heat flow from the exterior surface of the wall in the form of convective heat transfer to the outdoor air (W/m^2); q_{er} was the intensity of heat flow (W/m^2) transferred to the outdoor air in the form of radiant heat transfer from the external surface of the wall; a_e was the external surface heat transfer coefficient(W/m^2-K), i.e., the convective heat transfer coefficient α_{ec} and the sum of the radiative heat transfer coefficient α_{er}, which indicates the amount of heat transfer through the unit area of the envelope in 1h when the difference between the external surface temperature and the indoor air temperature is 1K; t_4 was the temperature of the external surface of the wall (°C) ; t_{out} was the outdoor air temperature (°C).

The building envelope involved more types of materials. Thermal conductivity, as an important parameter for evaluating the thermal performance of insulation materials, was affected by a variety of factors such as material type, structural composition, pressure, temperature, density, and humidity. When the same material was in different environments and states, its thermal conductivity would also exhibit large differences. Stagnant air in a closed environment was regarded as a good class of adiabatic materials. For some materials with higher density that contained more internal pores, the material's own coefficient of thermal conductivity would be greatly reduced. At the same time, due to the fact that the thermal conductivity of liquid water is less than that of the material itself, adding wheat straw to concrete would increase the porosity of the concrete, and the material's thermal conductivity would also be significantly affected by its own water content, resulting in greatly reduced thermal insulation performance. Straw concrete facades had large internal porosity and better hygroscopic properties. The humidity buffering effect of the envelope reduced the fluctuation of indoor air humidity (Hong *et al*., 2020, Tang *et al*., 2023), and straw walls stabilized indoor comfort by reducing the fluctuation of temperature and relative humidity (Grove, 1990, Ghaffar & Fan, 2015).

2.2 Compressive strength and thermal conductivity test

The main experimental materials include cement, straw, fly ash, and aggregates. On the basis of calculating the mix proportion, trial mixing was carried out, and the calculated mix proportion is continuously revised to obtain the construction mix proportion. It was calculated that each cubic meter of concrete requires m_{w0}=215 kg、m_{c0}=359 kg、m_{g0}=1144.95 kg、m_{s0}=701.75 kg。In this experiment, two specifications of wheat straw powder (0.5-5mm) and wheat straw strips (10-15mm) were added with 4%, 6%, 8%, and 10% straw at fly ash content of 10%, 20%, and 30%, respectively, to produce cubic compressive strength and thermal conductivity test blocks. The compressive strength of the cube was measured using a microcomputer controlled hydraulic servo press model YAW-2000, and the thermal conductivity test was conducted using a thermal conductivity tester model CD-DR3030B.Other auxiliary experimental equipment includes electronic scales, forced mixers, concrete vibration tables, concrete slump testers, dryers, etc.

2.2.1 Cubic compressive strength test

According to "Standard for test methods of concrete physical and mechanical properties" (GB/T 50081-2019, 2019), the size of cubic specimens is 150mm × 150 mm × 150 mm, a total of 12 groups (Table 1), each group according to wheat straw powder, wheat straw powder to produce two types of test blocks, each type of production of 3 test blocks, a total of 72 test blocks. The standard curing conditions of the specimens were temperature 20℃±3℃ and humidity above 95%, and the concrete strength was measured after 28 days of curing. The test was carried out at a loading rate of 0.3-0.5 MPa/s, the load was applied continuously and uniformly, and the load was recorded when the specimen was destroyed and the press readings no longer increased. The compressive strength of concrete with different proportions of admixtures was obtained.

2.2.2 Thermal conductivity test

In accordance with the "Determination of Steady-State Thermal Resistance and Related Properties of Insulation Materials Protective Thermal Plate Device" (GB/T 50081-2019, 2019), the thermal conductivity for the determination of specimen specifications 300 mm × 300 mm × 25 mm, according to the wheat straw powder, wheat straw strips to produce two types of test blocks, each type of production of 3 test blocks, a total of 72 test blocks. The standard maintenance conditions of the specimens were temperature 20℃±3℃, humidity above 95%, and the thermal conductivity was measured after 7 days of maintenance.

2.2.3 Moisture and Thermal Properties Test

According to "Determination of Moisture and Thermal Properties/Hygroscopic Properties of Building Materials and Products" (GB/T 20312-2006, 2006）, moisture absorption test was carried out in an artificial climate room at 25°C. The test was carried out in an artificial climate chamber at 25°C with four saturated salt solutions, $MgCl_2$, $Mg(NO_3)_2$, NaCl and K_2SO_4, and the equilibrium relative humidity of the upper air was 38.2%, 54.0%, 75.4% and 97.4%, respectively. Powdered WSC was selected as the experimental object, and three similar specimens were prepared for each group, and the three specimens of each group were synchronized during the test. The samples were weighed and recorded every 24h using an electronic scale, and when the change in sample mass was less than 0.1% of the total mass for three consecutive times, it was considered that the samples had reached the state of hygroscopic equilibrium, from which the equilibrium moisture content of the samples at different humidity could be derived, and the thermal conductivity of the WSC was determined at different moisture content rates.

Results and Discussion

3.1 Effect of straw and fly ash admixture on compressive strength

WSC did not have obvious brittle fracture during the compression process, proving that the powdered and striped straw can absorb and consume part of the energy, and did not produce the same brittle damage as ordinary concrete, with the continuous pressure of the pressure tester, WSC around a large number of small cracks, the number and width gradually increased until the material was destroyed, the records were obtained with different proportions of the admixture of concrete cubic compressive strength as shown in Table 1.

At 10% fly ash content, from 4% to 10% straw content, wheat straw powder strength decreased by 23.81%, 43.55% and 70.86%, and wheat straw strip strength decreased by 31.05%, 60.03% and 73.73%, respectively. At 20% fly ash content, wheat straw powder strength decreased by 26.19%, 57.32% and 70.62% and wheat straw strip strength decreased by 22.29%, 48.49% and 61.31%, respectively. At 30% fly ash content, wheat straw powder strength decreased by 31.37%, 44.59% and 55.73%, and wheat straw strip strength decreased by 30.33%, 57.48% and 67.75%, respectively. Fly ash content from 10% to 30% decreased wheat straw powder strength by 11.78% and wheat straw strip strength by 17.12%.

Table 1

Cubic compressive strength of concrete at different content (MPa)

Group	Fly ash content（%）	Straw content（%）	Wheat straw powder		Wheat straw strips	
			Specimen number	Compressive strength (MPa)	Specimen number	Compressive strength (MPa)
A_1	10%	4%	A_{13}	12.31	A_{14}	11.86
A_2	10%	6%	A_{23}	9.32	A_{24}	7.96
A_3	10%	8%	A_{33}	6.84	A_{34}	4.32
A_4	10%	10%	A_{43}	3.41	A_{44}	2.60
B_1	20%	4%	B_{13}	11.33	B_{14}	10.12
B_2	20%	6%	B_{23}	8.04	B_{24}	7.32
B_3	20%	8%	B_{33}	4.13	B_{34}	4.03
B_4	20%	10%	B_{43}	2.46	B_{44}	2.42
C_1	30%	4%	C_{13}	10.86	C_{14}	9.83
C_2	30%	6%	C_{23}	4.53	C_{24}	6.02
C_3	30%	8%	C_{33}	2.80	C_{34}	2.61
C_4	30%	10%	C_{43}	1.16	C_{44}	1.32

X.Y. Lu & Z. Zhao (2022) found that adding rapeseed straw fiber (RSF) to fly ash concrete (FAC) at different volume ratios (0.1-0.4%) and length ranges (20-50 mm) could improve mechanical properties when the RSF content was 0.1%. However, when the content exceeded 0.3% or the fiber length reached 40-50 mm, the compressive strength, splitting tensile strength, and ultrasonic pulse velocity all significantly decreased. Specifically, the compressive strength of the 40-50 mm long fiber specimens decreased by 2.85%, 7.75%, 11.75%, and 16.39% respectively as the RSF content increased from 0.1% to 0.4%. This result was consistent with the conclusion of this study, indicating that the addition of fly ash and straw could increase the porosity of concrete, thereby weakening its strength, and the straw content was the key controlling factor for strength degradation. N. Bheel *et al.* (2022) used 5% and 10% sugarcane bagasse ash/fiber as substitutes for cement to investigate their effects on the mechanical properties of concrete. The results showed that the 28-day compressive and flexural strengths of the benchmark group (0% dosage) were 65.38 MPa and 10.86 MPa, respectively, which were higher than those of the substitute group (5% and 10% dosage). When the substitution rate increased to 10%, the compressive strength of the sugarcane bagasse ash and fiber groups decreased to 53.85 MPa and 48.92 MPa, respectively, while the flexural strength decreased to 6.86 MPa and 5.54 MPa. The trend of concrete strength decreasing with increasing straw content in this study was different from that observed in the present study, which might be due to the fact that the ash-like morphology of sugarcane bagasse was more conducive to optimizing matrix interface bonding, thus exhibiting better strength maintenance ability compared to strip-like or coarse fiber morphologies.

3.2 Effect of straw and fly ash content on thermal conductivity

After the thermal conductivity determination experiment, the experimental data were exported from the instrument, and the data were processed and analysed using the supporting software to obtain the thermal conductivity values of the samples as shown in Table 2.

The analysis of the data in Table 2 showed that the dosage and morphology of fly ash and wheat straw had a significant impact on the thermal conductivity (W/(m-K)) of the composite material. Firstly, under the same fly ash content, as the straw content increased from 4% to 10%, the thermal conductivity of both forms exhibited a decreasing trend. This indicated that an increase in straw content could enhance thermal insulation performance by introducing more porous structures. Secondly, the increase in fly ash content further strengthened this effect: when fly ash was increased from 10% to 30%, under the same straw content, the thermal conductivity of wheat straw powder decreased from 0.5879 in A_4 to 0.5645 in C_4, a reduction of 4.0%; the strip-shaped straw decreased from 0.6086 to 0.5798, a reduction of 4.7%. This suggested that the fine particles of fly ash might optimize matrix density and pore distribution, synergistically enhancing the thermal insulation properties with straw fibers. In addition, the thermal conductivity of wheat straw flour was generally lower than that of strip-shaped straw, which might be attributed to the more uniform dispersion of powdered straw, forming smaller and more closed pores that reduced the heat convection path.

Table 2

Thermal conductivity of WSC with different contents W/(m-K)

Group	Fly ash content (%)	Straw content (%)	Wheat straw powder		Wheat straw strips W/(m-K)	
			Specimen number	Thermal Conductivity(W/(m-K))	Specimen number	Thermal Conductivity(W/(m-K))
A_1	10%	4%	A_{13}	0.6638	A_{14}	0.6738
A_2	10%	6%	A_{23}	0.5979	A_{24}	0.6406
A_3	10%	8%	A_{33}	0.6006	A_{34}	0.6305
A_4	10%	10%	A_{43}	0.5879	A_{44}	0.6086
B_1	20%	4%	B_{13}	0.6514	B_{14}	0.6705
B_2	20%	6%	B_{23}	0.5897	B_{24}	0.6196
B_3	20%	8%	B_{33}	0.5912	B_{34}	0.6046
B_4	20%	10%	B_{43}	0.5746	B_{44}	0.5876
C_1	30%	4%	C_{13}	0.6341	C_{14}	0.6675
C_2	30%	6%	C_{23}	0.5792	C_{24}	0.5857
C_3	30%	8%	C_{33}	0.5756	C_{34}	0.5813
C_4	30%	10%	C_{43}	0.5645	C_{44}	0.5798

B. Niu & B.H. Kim (2022) used corn Straw to prepare cement-based composite materials, studied the strength, thermal conductivity, and hydration characteristics of the composite materials, and explored the proportion of cement-based composite materials treated with 11-20 wt.% corn Straw. The test results showed that the optimal thermal conductivity of corn Straw cement-based composite material (CSCC) was 0.102-0.112 W/(m-K). Consistent with the low thermal conductivity characteristics of straw-fly ash composite materials observed in this study, it was confirmed that increasing biomass content could significantly reduce the material's thermal conductivity. Y. El Moussi *et al*. (2022) studied biobased concrete using straw as aggregate. The influence of the characteristics of straw particles (particle size distribution, bulk density, water absorption capacity, etc.) on the mechanical and thermal properties of biobased concrete was investigated. Specifically, the compressive strength of straw particles was evaluated and discussed in relation to their average particle length. The results indicated that the incorporation of large straw particles with low water absorption capacity produced lightweight concrete with densities ranging from 339 to 505 kg/m³. This concrete exhibited high compressive strength and significant mechanical deformation capacity. Furthermore, an increase in the average length of straw particles appeared to correlate with a decrease in the thermal conductivity of bio-based concrete, which varied between 0.062 and 0.085 W/(m-K). X. Bai *et al*. (2024) aimed to utilize regionally available renewable materials for investigating the ecological application of wheat straw (C-WS) lightweight concrete exterior walls suited for hot summer and cold winter regions. The study examined the effects of incorporating wheat straw on multiple performance indicators, including physical-mechanical properties, thermal-moisture absorption characteristics, as well as non-air-conditioned thermal environments and building energy consumption. Experimental results revealed that adjusting straw content and particle size could reduce the thermal conductivity of C-WS by up to 13.70%. The mechanism is consistent with the conclusion of this study–the introduction of powdered or strip-shaped straw enhanced thermal insulation performance through increased porosity and reduced density. However, the detrimental effects of large-sized straw particles on mechanical properties required careful consideration during material optimization. Collectively, these findings demonstrated that the rational design of straw morphology and dosage represents a critical factor in developing high-performance eco-friendly building materials.

3.3 The effect of air humidity on thermal conductivity

The whole process of the test needs to humidify the test piece 4 times, each time the humidification is completed to wait until the specimen is completely absorbed moisture, the specimen in the humid state of the thermal conductivity coefficient of the test piece is measured and recorded. According to the experimental results of compressive strength and thermal conductivity of straw fly ash concrete in dry state, combined with the characteristics of rural residential buildings, wheat straw powder was selected for the determination of moisture content and thermal conductivity of concrete, and the equilibrium moisture content of A_{13}-C_{43} concrete samples were obtained when the relative humidity of the air was 38.2%, 54.0%, 75.4%, and 97.4%, respectively (at a constant temperature of 25°C) under the thermal conductivity values are shown in Table 3.

Table 3

Moisture content and thermal conductivity for different air humidity

Specimen number	Air humidity 38.2% Moisture content (kg-kg^{-1} /%)	Thermal conductivity W/(m-K)	Air humidity 54% Moisture content (kg-kg^{-1} /%)	Thermal conductivity W/(m-K)	Air humidity 75.4% Moisture content (kg-kg^{-1} /%)	Thermal conductivity W/(m-K)	Air humidity 97.4% Moisture content (kg-kg^{-1} /%)	Thermal conductivity W/(m-K)
A_{13}	1.525	0.7138	1.904	0.7263	2.957	0.761	5.142	0.9294
A_{23}	1.591	0.6437	2.091	0.6581	3.021	0.685	5.651	0.7606
A_{33}	1.658	0.6465	2.174	0.6608	3.218	0.690	6.339	0.7761
A_{43}	1.722	0.6349	2.297	0.6506	3.302	0.678	6.678	0.7702
B_{13}	3.572	0.7686	3.961	0.8209	5.012	0.866	7.23	0.9608
B_{23}	3.613	0.7299	4.142	0.7504	5.034	0.785	7.786	0.8918
B_{33}	3.762	0.7330	4.284	0.7527	5.418	0.795	8.554	0.9136
B_{43}	3.782	0.7157	4.362	0.7373	5.478	0.779	8.779	0.9021
C_{13}	3.742	0.7943	5.158	0.9064	6.132	0.958	8.943	1.1063
C_{23}	4.702	0.8087	5.224	0.8341	6.213	0.882	9.012	1.0190
C_{33}	4.802	0.8046	5.386	0.8325	6.442	0.883	9.483	1.0278
C_{43}	4.895	0.7960	5.464	0.8229	6.3523	0.865	9.3945	1.0089

Using Origin2021, the relationship between thermal conductivity and air humidity of each specimen was plotted. Figure 2 shows the thermal conductivity of straw with a dosage of 4% (A13), 6% (A23), 8% (A33), and 10% (A43) under a 10% fly ash dosage. When the humidity increased from 38.2% to 97.4%, the moisture content of the specimen increased sharply from 1.525-1.722% to 5.142-6.678%, and the thermal conductivity increased synchronously from 0.6349-0.7138 W/(m-K) to 0.7702-0.9294 W/(m-K), with an increase of 21.3-30.2%. This phenomenon is attributed to the high porosity and strong moisture absorption of the material under low fly ash content, which forms a thermal bridge effect after water fills the pores.

Figure 3 shows the thermal conductivity of straw with 4% (B_{13}), 6% (B_{23}), 8% (B_{33}), and 10% (B_{43}) fly ash content at 20% fly ash content. Within the same humidity range, the increase in moisture content is more significant (3.572-3.782% to 7.23-8.779%), but the increase in thermal conductivity is relatively gentle (0.7157-0.7686 to 0.8918-0.9608 W/(m-K), with an increase of about 24.6-29.1%, indicating that the increase in fly ash partially suppresses moisture sensitivity.

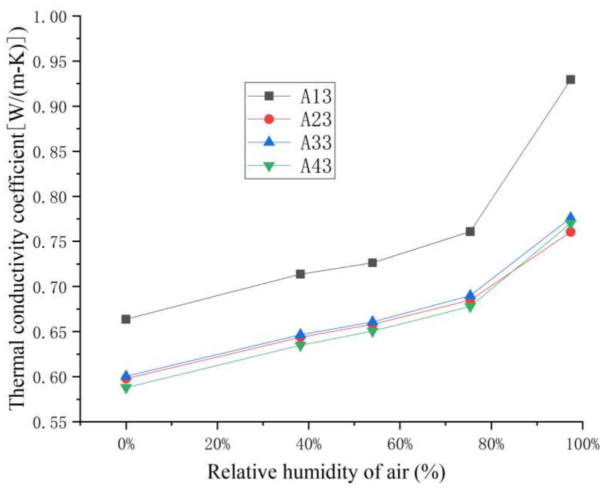

Figure 2. Variation of thermal conductivity with air humidity for test blocks A13-A43
Source: made by the authors

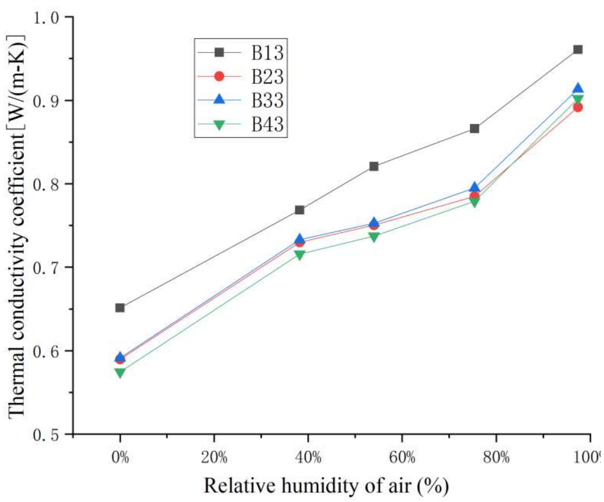

Figure 3. Variation of thermal conductivity with air humidity for test blocks B13-B43
Source: made by the authors

Figure 4 shows the thermal conductivity of straw with 4% (C_{13}), 6% (C_{23}), 8% (C_{33}), and 10% (C_{43}) fly ash content at 30% fly ash content. The thermal conductivity exhibits extreme wet heat response at 97.4% humidity, with the moisture content of the C_{13} sample reaching 8.943% and the thermal conductivity soaring to 1.1063 W/(m-K), an increase of 39.3% compared to 38.2% humidity. This is related to the formation of expansion microcracks in the dense matrix formed by the high fly ash content after moisture absorption.

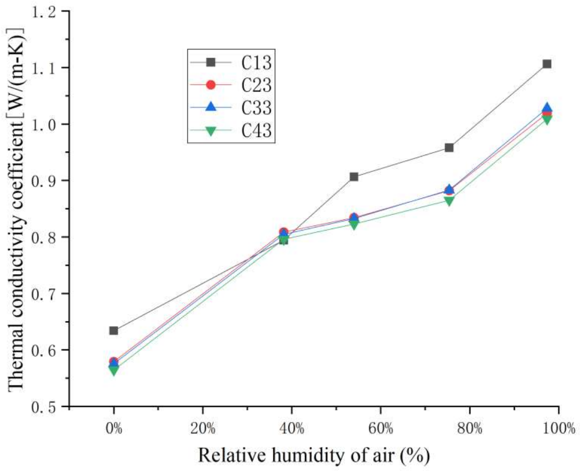

Figure 4. Variation of thermal conductivity with air humidity for test blocks C13-C43
Source: made by the authors

In order to compare and analyse the effect of moisture content on the thermal conductivity of different straw fly ash concrete specimens, and to investigate the variation rule and influencing factors of the thermal conductivity of the specimens. Combined with the moisture content of the specimens derived from the straw fly ash concrete moisture absorption characteristics of the test, using Origin2021 software to fit the test data, fitted out the A_{13}-A_{43} moisture content and thermal conductivity of the function of the relationship is as follows:

$$\lambda_{A13} = 1.08695x^3 - 1.2563x^2 + 0.46448x + 0.66342 \quad R^2 = 0.991; \tag{8}$$
$$\lambda_{A23} = 0.40716x^3 - 0.47951x^2 + 0.2476x + 0.59778 \quad R^2 = 0.997; \tag{9}$$
$$\lambda_{A33} = 0.47115x^3 - 0.54522x^2 + 0.26402x + 0.60047 \quad R^2 = 0.997; \tag{10}$$
$$\lambda_{A43} = 0.521535x^3 - 0.61079x^2 + 0.28694x + 0.58769 \quad R^2 = 0.994, \tag{11}$$

where λ is the thermal conductivity (W/(m-K)), x is the relative humidity of the air (%). The relationship between thermal conductivity and moisture content in Table 3 is plotted as a scatter plot in Fig. 5, and the graphical analysis reveals that the thermal conductivity of WSC increases with the increase of moisture content, which is a very obvious trend. When the adiabatic state or the moisture content is low, the thermal conductivity of straw concrete is mainly determined by the thermal conductivity of solid particles in the specimen; with the gradual increase of the moisture content, the liquid island is formed inside the specimen and the contact thermal resistance between solid particles is reduced, and the evaporation and condensation of the liquid island will increase the internal heat transfer. With the gradual increase of moisture content, liquid island is formed inside the specimen, the contact thermal resistance between the solid particles is reduced, and the evaporation and condensation of the liquid island will increase the internal heat transfer. When the moisture content tends to saturation, then the thermal conductivity increases to the maximum value, and the effect of moisture content on the thermal conductivity will also tend to saturation.

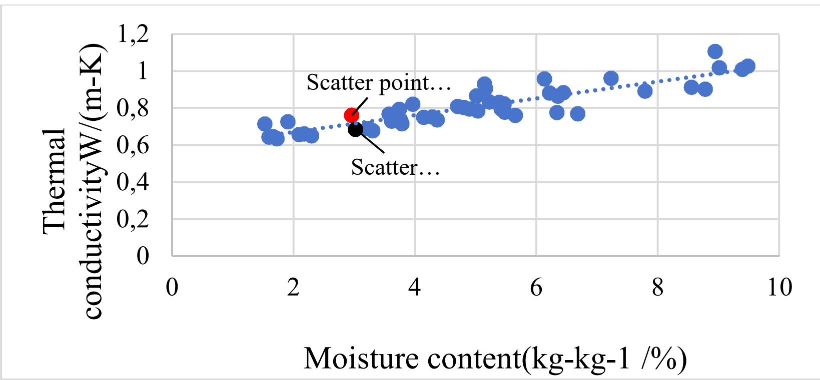

Figure 5. Scatter plot of experimental data of moisture content and thermal conductivity of A13-C43 WSC specimens

Figure 5 shows that the thermal conductivity coefficients of different concrete specimens with similar moisture content have large differences, for example, Scatter 1 (2.957,0.761) is 10% fly ash doping, 4% straw doping, and 75.4% air humidity, and Scatter 2 (3.021,0.685) is 10% fly ash doping, 6% straw doping, and 75.4% air humidity, and the two scatters have similar X-values and large Y-values. The difference in X-values and Y-values between the two scattering points are similar and the difference in Y-values is large, which indicates that the straw content at the same moisture content has an effect on the thermal conductivity, and that in the straw concrete, the content of fly ash and straw causes these differences, and the moisture content is only a factor that causes the change in the thermal conductivity. In order to study the relationship between moisture content and thermal conductivity, it is necessary to analyse and study at the same fly ash and straw content.

The study showed that the thermal conductivity of all the specimens increased with the increase in relative humidity of air. The thermal conductivity of WSC in high humidity (95% relative humidity) environment showed a maximum increase of nearly 44.05% compared to the dry condition. While the increase in thermal conductivity of straw concrete specimens was influenced by the straw content, for every 2% increase in straw content, the thermal conductivity increased by about 1% and for every 10% increase in fly ash content, the thermal conductivity increased by about 10%. When the straw concrete specimens were under low or moderate air relative humidity (<78%), there was no significant difference in the growth rate of thermal conductivity of the specimens with different contents of straw; when the straw concrete specimens were under high air relative humidity (>78%), the growth rate of thermal conductivity of the specimens would be elevated with the increase of straw content. The thermal conductivity of straw fibers is more affected by air humidity. The influence of relative humidity of air cannot be ignored while analysing and studying the thermal conductivity of straw concrete.

K.A. Sabapathy & S. Gedupudi (2019) proposed that straw bales can be used as sustainable insulation materials for building envelope structures, and their application can effectively improve energy efficiency. This study used transient planar source technology to measure the thermal conductivity (0.05-0.09 W/(m-K)) and thermal diffusivity of straw bales under different conditions (25-45 ° C, 40-80% RH, density 50-90 kg/m^3).Research has found that material orientation has significant anisotropy on its thermal properties: fibers arranged vertically/randomly have a thermal conductivity that is 1.7 times lower than those arranged in parallel. In addition, the thermal conductivity of parallel arranged samples increases by 130% and 60% with increasing humidity and density, respectively. These conclusions are consistent with the observed trend of humidity dependence in this study, confirming the crucial regulatory role of microstructure and environmental factors in heat conduction behaviour. G. Tlaiji *et al*. (2023) observed that the thermal conductivity of straw bales increased from 0.047 W/(m-K) to 0.09 W/(m-K) through regulation of their density (80-120 kg/m^3), relative humidity (15-95%), and temperature (15-55 °C).For straw fibers containing 40% cellulose, thermal conductivity rose from 0.05 W/(m·K) to 0.0832 W/(m-K), a finding that was highly consistent with numerical simulation results (root mean square error 0.005 W/(m-K), scattering index 5.5%).The agreement between experimental and modelled data validated the reliability of predicting humidity-driven thermal behaviour, thereby reinforcing the study's conclusions. The hygroscopic nature of straw fiber facilitated moisture adsorption, pore saturation, and thermal bridge formation, which collectively enhanced thermal conductivity. While fly ash exhibited volcanic ash activity, its fine particle distribution intensified moisture retention under high humidity conditions. Although fly ash improved mechanical stability, its humidity sensitivity necessitated integrating hydrophobic surface treatments to optimize thermal performance across variable climatic conditions.

Conclusion

This study systematically explored the effects of wheat straw and fly ash dosage, form, and environmental humidity on the thermal performance of concrete, and revealed its energy-saving potential in rural building envelope structures. The results demonstrated that the synergistic effect of straw and fly ash could significantly reduce the thermal conductivity of the material. Powdered straw exhibited better dispersion uniformity, and its thermal conductivity was generally superior to that of strip-shaped straw. When the straw content was increased from 4% to 10%, the porosity of the material rose and thermal conductivity decreased by 4.0-11.4%, while elevating fly ash content to 30% further enhanced the thermal insulation effect. However, the sensitivity of materials to moisture and heat could not be overlooked: under high humidity environments (>78% RH), the maximum increase in thermal conductivity of straw-fly ash concrete reached 44.05%, a phenomenon associated with the thermal bridge effect induced by water-filled pores and moisture absorption-induced expansion of fly ash particles. Although the incorporation of straw resulted in reduced compressive strength, the substantial improvement in insulation performance indicated the feasibility of applying this material in non-load-bearing walls.

WSC can be produced entirely based on existing technology and equipment, and is a cheap and environmentally friendly concrete with good promotion value in rural residential buildings. In order to further analyse the wet heat coupling mechanism at the three-phase interface of straw fly ash moisture, it is necessary to establish a multi-scale heat transfer model and conduct experiments in the future to study the performance improvement of straw concrete, especially to carry out long-term wet heat cycle and freeze-thaw durability experiments, and evaluate the life and reliability of materials under actual climatic conditions.

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Guo Zhiyong – Postgraduate Student, Vinnytsia National Technical University. Master, Jiuquan Vocational and Technical College. https://orcid.org/0009-0007-2696-0287

Viacheslav Dzhedzhula **–** Doctor of Economic Sciences, Professor, Vinnytsia National Technical University, https://orcid.org/0000-0002-2740-0771

В. В. Джеджула
Чжионг Го

ДОСЛІДЖЕННЯ МЕХАНІЗМУ ТЕПЛОПЕРЕДАЧІ ТА ТЕПЛОТЕХНІЧНИХ ХАРАКТЕРИСТИК ЗОЛЬНОГО БЕТОНУ З ПШЕНИЧНОЇ СОЛОМИ

Вінницький національний технічний університет

Велика кількість сільських житлових будівель у світі не має ефективних заходів теплової ізоляції. Незадовільні теплозахисні властивості огороджувальних конструкцій призводять до низьких температур у приміщеннях узимку та до значного енергоспоживання. Метою даного дослідження було вивчення впливу додавання пшеничної соломи та золовідходів у бетон на його теплотехнічні властивості з метою надання маловартісного та енергоефективного рішення для виготовлення стінових матеріалів сільських будівель. У межах експерименту було підготовлено зразки бетонних блоків із різним дозуванням золи та соломи, створено експериментальну платформу для визначення межі міцності на стиск і теплопровідності, а також змодельовано різні умови вологості за допомогою насичених сольових розчинів з метою аналізу впливу вологості на теплопровідність. Вплив вологості на теплопровідність аналізувався шляхом моделювання середовищ із різними рівнями вологості за допомогою насичених сольових розчинів. На основі апроксимації експериментальних даних та порівняльного аналізу було виявлено механізм впливу домішок соломи, морфологічних характеристик та вологості на властивості матеріалу. Дослідження показало, що теплопровідність бетону з пшеничною соломою та золою поступово зменшувалася зі зростанням вмісту золи та соломи; чим вищий їхній вміст, тим нижчою була теплопровідність. Теплопровідність такого бетону значно зростала зі збільшенням вологості повітря, і взаємозв'язок між вологістю та теплопровідністю виявився тісно пов'язаним зі змістом соломи та золи. Введення золи та соломи до складу бетону ефективно покращує теплозахисні характеристики будівельних матеріалів і є дієвою альтернативою для підвищення енергоефективності будівель та зменшення викидів вуглецю

Ключові слова: *огороджувальні конструкції; домішка соломи; вологість повітря; теплопровідність; гігротермічні властивості; енергоефективність будівель*

Чжионг Го **– а**спірант, Вінницький національний технічний університет. Магістр Цзюцюаньський інститут професійних технологій https://orcid.org/0009-0007-2696-0287

В'ячеслав Джеджула **–** Доктор економічних наук, професор Вінницький національний технічний університет, https://orcid.org/0000-0002-2740-0771