Preparation and Mechanical Properties of Magnesium-cemented Straw Composites

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Magnesium-cemented straw composites (MCSC), as an environmentally friendly and energy-conserving material, have an enormous potential to achieve favorable properties, especially for bending strength. In this study, rice straw powder, fly ash, and magnesia cement (MC) were mixed to prepare MCSC. An optimization formula for composites was found to promote the bending strength by 490% from 0.28 MPa (empty sample) to 13.89 MPa (composites). From the variance results, the molar ratio of $MgO/MgCl_2$ (M value) and addition of rice straw (As) noticeably impacted the compressive and bending strengths. The optimum schemes were:10% (weight ratio) for rice straw, 10% for fly ash (Af), 5 for M value, 12 to 15 for H value (the molar ratio of $H_2O/MgCl_2$), 20-mesh of straw powder (Ms), and 28 days for the curing time (T). Considering the different use of MCSC, if the weight vector was 0.7 (compressive strength) and 0.3 (bending strength), the optimized formula was $M_5H_{25}Ms_{20}T_{15days}As_{10\%}Af_{10\%}$. If the weight vector was 0.3 (compressive strength) and 0.7 (bending strength), the optimized formula was $M_5H_{10}Ms_{20}T_{3days}As_{10\%}Af_{10\%}$.

Keywords: Magnesium composites; Mechanical properties; Rice straw; Fly ash

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INTRODUCTION

Magnesium cement straw composites (MCSC) are a new type of bio-inorganic composites that are made of magnesia cement material (MC), straw, and fly ash. Magnesium cement (MC) is known as magnesium oxychloride cement and consists of light burned magnesia powder (MgO), $MgCl_2$, and H_2O. It has a good mechanical strength supported by a crystal structure of $5Mg(OH)_2.MgCl_2.8H_2O$ (5-phase, 5.1.8 phase) and 3 $Mg(OH)_2.MgCl_2.8H_2O$ (3-phase, 3.1.8 phase) (Wang and Yang *et al.* 2015). However, these structures are easily weakened in water (Xiao *et al.* 2018). Therefore, the mechanical strength of MC still needs to be improved. The formulation of raw materials affects the mechanical strength of MC, such as the M value (the molar rate of MgO to $MgCl_2$), H value (the molar rate of H_2O to $MgCl_2$), and curing time (T) *etc.* (Wang and Zhang *et al*. 2015). Meanwhile, the addition of rice straw (As) and fly ash (Af) may effectively enhance the mechanical strength.

Rice straw is a surplus of agricultural production, with an annual output close to 80 million tons in China (Zuo *et al*. 2018). The straw fiber is similar to wood fiber, which effectively enhances the bending strength of composites (Ismail *et al.* 2011, 2012). Fly ash is an industrial waste from flue gas after coal combustion and it mainly contains SiO_2 and Al_2O_3. It has a porous honeycomb structure with large specific surface, high adsorption characteristics, and strong water absorption (Huang and Kong 2018). It can combine with excess H_2O molecules and slow down the destruction of crystal structure caused by hydrolysis reaction to form the stable crystal structure and improve the mechanical properties of materials.

Scholars have conducted a series of related studies aimed to enhance the strength of MC and MCSC. Jiang *et al.* (2013, 2015, 2018) used fiber from leaf material to prepare leaf fiber cement-based material with acrylic emulsion spray to effectively improve the strength. The result showed that pure acrylic polymer emulsion spraying was an optimal treatment method of leaf fibers in comparison to acrylic polymer emulsion and sodium silicate solution. Fauzi *et al.* (2016) studied the effect of Si and Al in fly ash on the composite material to enhance the mechanical strength. The microstructure images presented a correlation between the chemical composition and the bond structure in terms of the high element content (Si and Al) forming the gel and the bond structure in the cementitious process. Tawfik *et al*. (2015) prepared water resistant magnesium oxychloride with rice straw and raw magnesium with a compressive strength of up to 27 MPa. Ruan and Unluer (2017) studied the performance change of magnesium cement with 50% pulverized fuel ash (PFA) and ground granulated blast furnace slag (GGBS). The research showed that samples in 50% PFA indicated the highest strength development, reaching strengths as high as 60 MPa at 28 days, which were 33% higher than those of the corresponding control sample, and the use of both PFA and GGBS decreased the environmental impacts of formulations, which was reflected in lower CO_2 emissions, as well as reduced damage on human health and ecosystem quality. Silva *et al.* (2019) used chemically treated (2% NaOH solution) material at two different temperatures (30 °C and 60 °C). The results showed the compressive strength in 60 °C was better than that in 30 °C, and NaOH pretreatment did not affect the mechanical properties of wheat straw composites. Zuo *et al*. (2018) researched the straw-magnesium cement (SMC) composites that contained silicone-acrylate emulsion (6%) to improve water resistance, fire-retardant performances, and mechanical strength, and found that all the performances increased significantly. Moreover, an organic-inorganic network structure was formed in the novel magnesium cement, which enhanced the integrity of the material and played a role in protecting the crystals against hydrolysis. Nazerian and Sadeghiipanah (2013) investigated the hydration behavior and some physical/mechanical properties of cement-bonded particleboard (CBPB) containing particles of wheat straw and poplar wood at various usage ratios, and bonded with Portland cement with different levels of inorganic additives. The study showed when straw content was 30%, TS (thickness swelling after 24 h immersion in water) was reduced by increasing straw particle usage up to 1.5% and with 5.54% calcium chloride in the mixture. Khandanlou *et al.* (2015) characterized composite materials based on rice straw fiber and polycaprolactone (PCL) using a solution-casting method. With the increase of rice straw, the intensity of FTIR peaks was decreased from 1.0 to 7.0 wt%; it was found that the interaction between rice straw and PCL was a physical interaction. Chen *et al.* (2018) researched the relationship between setting time, compressive strength, cement mortar fluidity, and Portland cement on magnesium oxy sulfate (MOS) cement prepared by light-burned dolomite ores. The results indicated that adding Portland cement in MOS cement will greatly reduce its mechanical properties. Meanwhile, a small amounts of Portland cement in MOS cement can shorten its setting time and maintain most compressive strength. Ma *et al.* (2014) established the microstructure of magnesia-phosphate at the micro-scale, the model was developed to simulate the microstructure of paste. It was found that the simulated pore size distribution curves were consistent with corresponding experimental results. Fang and Chen *et al.* (2018) described an experimental investigation into the compressive strength, flexural strength, and water resistance of magnesium phosphate cement (MPC) mortar would be promoted effectively by prepared using glass fiber.

The above-mentioned research studies mainly focused on the preparation and the optimization formula of the composites. In this study, magnesia cement material, rice straw powder, and fly ash were compounded to improve the mechanical strength of composites. In addition, the optimized formulas were determined in the condition of weight vectors (compressive 0.7, bending 0.3) and (compressive 0.3, bending 0.7).

EXPERIMENTAL

Materials

The primary material selected for the study included magnesium chloride ($MgCl_2$, molecular mass 95.21) (Wuxi Yatai United Chemical Co., Ltd., Zhejiang, China) as Table 1 shows. Additionally, light burnt magnesium oxide (MgO, molecular mass 40.31) (Shi Jiazhuang Tian Yu Magnesium Industry Co., Ltd., Hebei, China), fly ash (Jia Hao Mineral Powder Plant, Ling Shou County, Henan, China), which is mainly composed of SiO_2 (weight ratio 50.8%) and Al_2O_3 (weight ratio 28.1%), as well as rice straw harvested in Shan Dong province (China) and crushed into powder, and screened into 20-, 60-, 100-, and 150-meshes were used.

Table 1. Ingredients List of Raw Materials (%)

Ingredient / Material	$MgCl_2$	MgO	SiO_2	CaO	Al_2O_3	Fe_2O_3	Sulfate	Ca
Magnesium Chloride	98.3	0	0	0	0	0	0.047	0.0048
Light burnt Magnesium Oxide	0	86.26	6.04	1.12	0.48	0.34	0	0
Fly Ash	0	1.2	50.8	3.7	28.1	6.2	0	0

Methods

Preparation of composites

The mass of MgO, $MgCl_2$, and H_2O was weighed using a precision analytical balance (BSA4235; Sartorious, Gottingen, Germany) according to different M values (5, 8, 10, 15, and 20) and H values (8, 12, 15, 18, and 22) (Fig. 1). Then, MgO powder was slowly added to the mixture of $MgCl_2$ and H_2O and stirred with a planetary cement mortar mixer (JJ-5; Wuxi Construction Engineering Test Instrument Equipment Co., Ltd., Wuxi, China) for 3 min. Specifically, the mixture was stirred for 1 min at a slower speed (65 rpm), 1 min at a faster speed (120 rpm), and 1 min at a slower speed (65 rpm) again. Then, fly ash and rice straw powder were added and stirred for 3 min, same as above. The composite material was then placed in the mold ($40 \times 40 \times 160$ mm^3, Chengdu Hongwei Precision Mold Factory, Chengdu, China) that was coated with the release agent in advance, and maintained in the constant temperature and humidity machine (DHS-225; Beijing North Lihui Testing Equipment Co., Ltd., Beijing, China). After 24 h, the materials were demolded, numbered, and placed back in the machine again, with 22 ± 2 °C and 70 ± 5 % relative humidity, maintained for 3, 7, 15, and 28 days. The density of composites was

1.87g/cm^3. Steps for preparation and maintenance were performed according to the Chinese national standard GB/T 17671-1999.

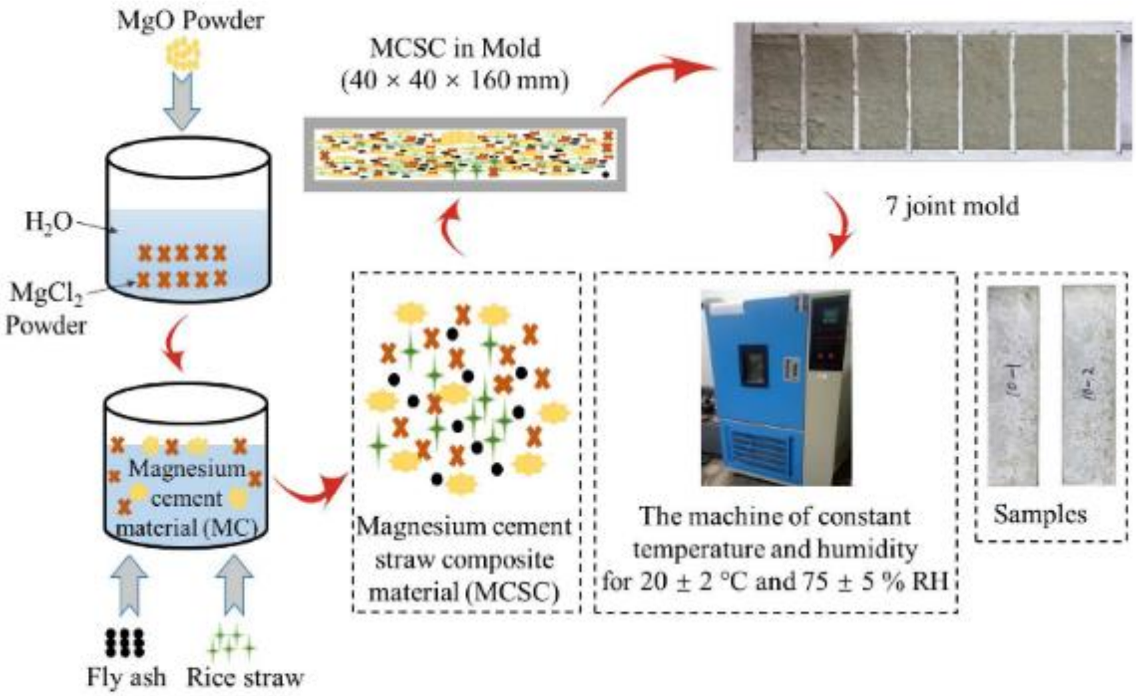

Fig. 1. Schematic of the preparation for the composites

Mechanical property test

The compressive strength and bending strength of MCSC were tested using a universal capability test machine (MMW-50; Jinan Nelson Testing Machine Co., Ltd., Jinan, China), loaded with a displacement velocity of 10 mm/min; the failure strength was recorded. Then, compressive strength and bending strength were calculated according to Eq. 1 and Eq. 2, respectively,

$$\delta = \frac{F}{A} \tag{1}$$

where δ is the pressure per unit area, referring to the compressive strength (MPa), F is the failure force (N), A is the acreage for the area of contact surface (mm^2) between fixture and test-piece,

$$R = \frac{3F \times L}{2b \times h^2} \tag{2}$$

where R is the bending strength (MPa), F is the failure load (N), L is the length for span (mm), b is the width (mm), and h is the thickness (mm); L = 130 mm, b = 40 mm, h = 40 mm in this experiment. The equation according to Chinese national standard GB/T 17671-1999 and GB/T 17657-2013.

As shown in Table 2, an L16 ($4^4 \times 2^3$) orthogonal was selected with six factors. Four levels were set for the first four factors and two levels were set for the latter two. Meanwhile, the range of values for the single factor test are shown in Table 3.

Table 2. Values of Orthogonal Experiment on Mechanical Test

No.	Time (Days)		M Value		H Value		Straw Mesh		Rice Straw (%)		Fly Ash (%)		Compression (MPa)	Bending (MPa)
	L	V	L	V	L	V	L	V	L	V	L	V		
A1	1	3	1	5	1	10	1	20	1	10	1	10	14.51	13.89
A2	1	3	2	10	2	15	2	60	1	10	2	20	2.38	2.58
A3	1	3	3	15	3	20	3	100	2	15	1	10	0.72	0.76
A4	1	3	4	20	4	25	4	150	2	15	2	20	0	0.01
A5	2	7	1	5	2	15	3	100	2	15	2	20	1.05	1.54
A6	2	7	2	10	1	10	4	150	2	15	1	10	0	0.03
A7	2	7	3	15	4	25	1	20	1	10	2	20	0.31	0.71
A8	2	7	4	20	3	20	2	60	1	10	1	10	0.08	0.18
A9	3	15	1	5	3	20	3	100	1	10	2	20	7.3	4.97
A10	3	15	2	10	4	25	4	150	1	10	1	10	14.78	7.19
A11	3	15	3	15	1	10	2	60	2	15	2	20	0.43	0.53
A12	3	15	4	20	2	15	1	20	2	15	1	10	0.1	0.09
A13	4	28	1	5	4	25	2	60	2	15	1	10	2.06	2.50
A14	4	28	2	10	3	20	1	20	2	15	2	20	1.46	2.48
A15	4	28	3	15	2	15	4	150	1	10	1	10	0.72	1.20
A16	4	28	4	20	1	10	3	100	1	10	2	20	0.26	0.26

Notes: L represents level, V represents value, and time represents curing days

Table 3. Values of Single Factor Experiment on Mechanical Property Test

Factor	Reference Value	Range of Value				
Curing time (days)	15	3	4	7	15	28
M value	10	5	8	10	15	20
H value	15	8	12	15	18	22
Straw mesh	60	20	60	100	150	200
Straw proportion (%)	10	5	10	15	20	30
Fly ash proportion (%)	10	5	10	15	25	30

Characterization

Scanning electron microscopy (SEM, Hitachi S-3400N II; Hitachi, Tokyo, Japan) was used to observe the micro-morphology of MCSC. Samples were bonded to the observation tray with conductive adhesive and sprayed with gold (Hitachi E-1010; Hitachi, Tokyo, Japan). A Fourier transform infrared spectrometer (FTIR Thermo Nicolet 6700; Waltham, MA, USA) was used to obtain infrared ray spectra; the samples were crushed, dried, and shattered into 200-mesh powder, prepared by potassium bromide, and pressed. An X-ray diffraction (XRD) analyzer (Bruker D8 ADVANCE; Karlsruhe, Germany) was used to detect and analyze the variation of peak values of the crystal structure in composites.

RESULTS AND DISCUSSION

Mechanical Test Results of Orthogonal Experiments

The raw material formulation for MCSC takes an important role in this experiment. From results of Table 3, the optimum formulation was: M value of 5, H value of 25, the mesh of rice straw powder (Ms) of 20, the curing time (T) of 15 days, the weight rate of rice straw (As) or fly ash (Af) of 10%. The variance analysis of mechanical strength was calculated by Microsoft excel (Microsoft Corporation, Microsoft Office 2016, Redmond, WA, USA). As shown in Table 4, the bigger the F value was, the greater the influence of factor was. The influencing order for compressive strength was As > M Value > T > Af > H Value > Ms, the influencing order for bending strength was As > M Value > T > Af > Ms > H Value. As and M value had the noticeable influence, followed by the T, Af, Ms, and H values.

Table 4. Variance Analysis of Mechanical Strength

Mechanical Testing	Source of Variance	Sum of Squares	Freedom	Sum of Mean Square	F Value
Compression Strength (MPa)	T (day)	77.70	3	25.90	0.87
	M Value	109.99	3	36.66	1.24
	H Value	25.46	3	8.49	0.29
	Ms	21.89	3	7.30	0.25
	As (%)	74.41	1	74.41	2.51
	Af (%)	24.43	1	24.43	0.82
	Error	29.63	1	29.63	
	Sum	363.50	15		
Order of Influence	As > M Value > T > Af > H Value > Ms				
Mechanical Testing	Source of Variance	Sum of Squares	Freedom	Sum of Mean Square	F Value
Bending Strength (MPa)	T (day)	32	3	10.79	0.69
	M Value	77	3	25.59	1.63
	H Value	11	3	3.81	0.24
	Ms	19	3	6.44	0.41
	As (%)	33	1	33.18	2.11
	Af (%)	10	1	10.20	0.65
	Error	16	1	15.73	
	Sum	199	15		
Order of Influence	As > M Value > T > Af > Ms > H Value				

The M value is related to the MgO and $MgCl_2$, it impacts the structure of crystal and the mechanical strength. The crystals are $5Mg(OH)_2.MgCl_2.8H_2O$ (5-phase) and $3Mg(OH)_2.MgCl_2.8H_2O$ (3-phase) as shown by Eq. 3 and Eq. 4. The models for 5-phase and 3-phase are shown in Fig. 3 (Walling and Provis 2016), which arranged neatly to consist the crystal construction like Fig. 2 (a) shows. The SEM results show that the structure with rod-like and needle-like support good strength for composites (Fig. 2). However, the disorderly structure seen as flakey-like is related to the lower strength.

$$5MgO + MgCl_2 + 13H_2O = 5Mg(OH)_2.MgCl_2.8H_2O \quad (3)$$

$$3MgO + MgCl_2 + 11H_2O = 3Mg(OH)_2.MgCl_2.8H_2O \quad (4)$$

Rice straw serves a framework in the composites in a way that can be compared to steel in a concrete building. It becomes incorporated with the 5-phase and 3-phase crystals in MCSC. Functional groups are produced in the composites that could enhance the mechanical strength with composites. The FTIR results in Fig. 4 show hydroxyl functional groups (-OH) and a hydrogen bond (O-H) appeared at 3419 cm^{-1}. The hydrogen bond (O-H) is the kind of stable group with good chemistry and physics performance, and hydroxyl functional groups (-OH) is the composition of $5Mg(OH)_2.MgCl_2.8H_2O$ (5-phase) and $3Mg(OH)_2.MgCl_2.8H_2O$ (3-phase), which increased the strength of the products.

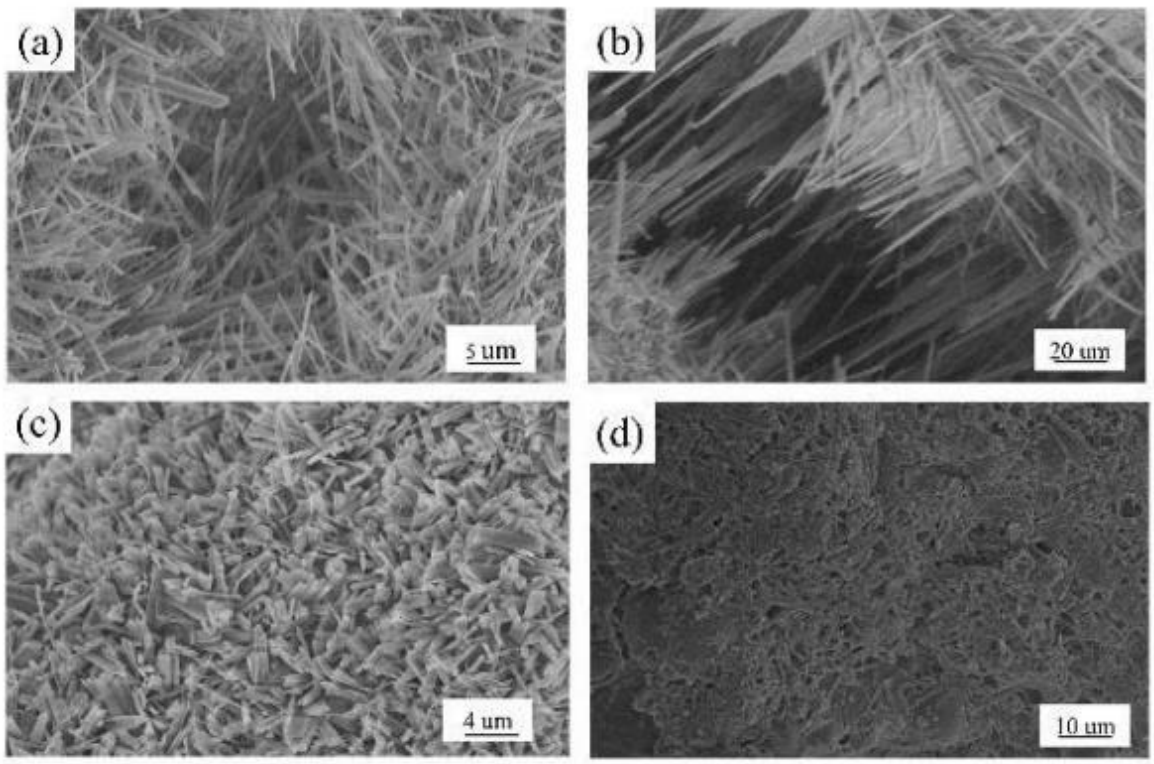

Fig. 2. SEM images of: (a) Rod-like structure, (b) Needle-like structure, (c) Flakey structure, and (d) Flocculent structure

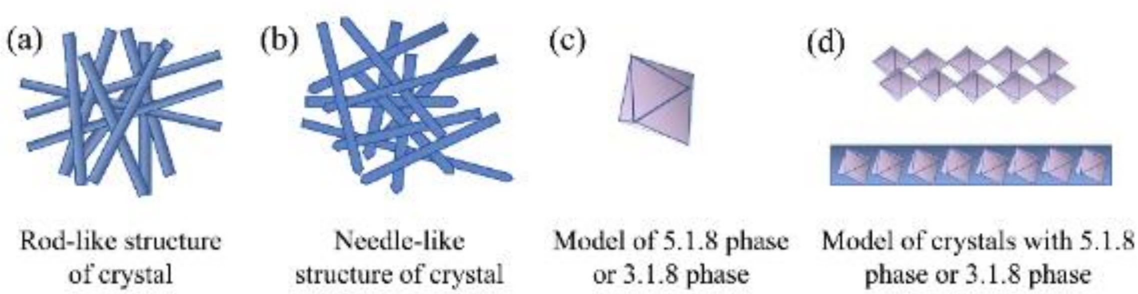

Fig. 3. Schematic of crystal structure

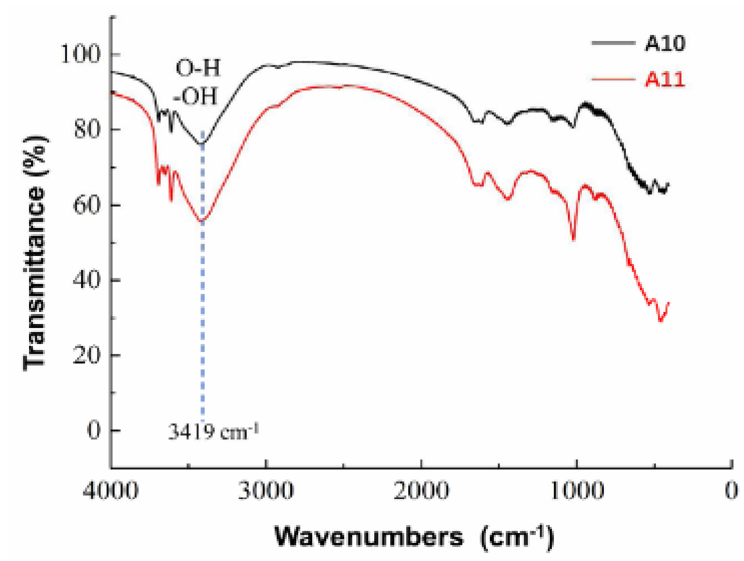

Fig. 4. FTIR analysis for A10 and A11 test group

Mechanical Test Results of Single Factor Experiment

When the M value was 4 to 8, the mechanical properties of composites were higher than others (Fig. 5a). When the M value was less than 4, the crystals and the strength of composites decreased due to the insufficient content of MgO and $Mg(OH)_2$. In contrast, when the M value was greater than 8, the excessive MgO and $Mg(OH)_2$ led to the unstable structure of 5-phase crystal.

When the H value was in the range of 12 to 15, the mechanical strength of MCSC increased (Fig. 5b). However, the mechanical strength decreased accordingly when the H value was lower than 12 or higher than 15. The result of X-ray diffraction is shown in Fig. 7. The black curve represents the D30 test group (H = 12) and the red curve represents the D31 test group (H = 18). The D30 group contained both 3-phase and 5-phase crystals, and the D31 group contained just a few of 3-phase crystals except 5-phase. The compressive and bending strength of D30 group were higher than the D31 group (the bending strength of D30 group was 6.37 MPa and the compressive strength was 6.17 MPa, the bending strength of D31 group was 2.22 MPa and the compressive strength was 3.07 MPa). Although the peak of 5-phase in D31 group was sharper than that in D30 group, the mechanical strength of D31 was still lower than D30. That can be explained by the increase of the peak in the 5-phase group, while the peak of 3-phase was dropped, and even disappeared, in the D31 group. This phenomenon indicated that the mechanical strength of composites was the result of a comprehensive effect of both 5-phase and 3-phase.

As shown in Fig. 5c, the compressive and bending strength of composites were good when Ms was 20 or 60. When it was 100, the mechanical strength decreased as the supports from straw fiber, which act like a skeleton enhancing the mechanical strength, were cut off. A bigger value of Ms resulted in a finer powder and shorter fiber. Therefore, the intersection between the fibers was destroyed and the mechanical strength of composites was weakened.

In Fig. 5d, the strength was highest when the curing time was 28 days, which indicated the MCSC required the fixed period to produce hydrogen bonds and crystalline phases with Si^+, Al^+, OH^-, and Cl^- The stable structures gradually formed after 15 days and finished completely at 28 days. The compressive strength in 15 days (7.21 MPa) reached

93% of that in 28 days (8.42 MPa). The bending strength in 15 days (7.42 MPa) even exceeded that in 28 days (7.35 MPa).

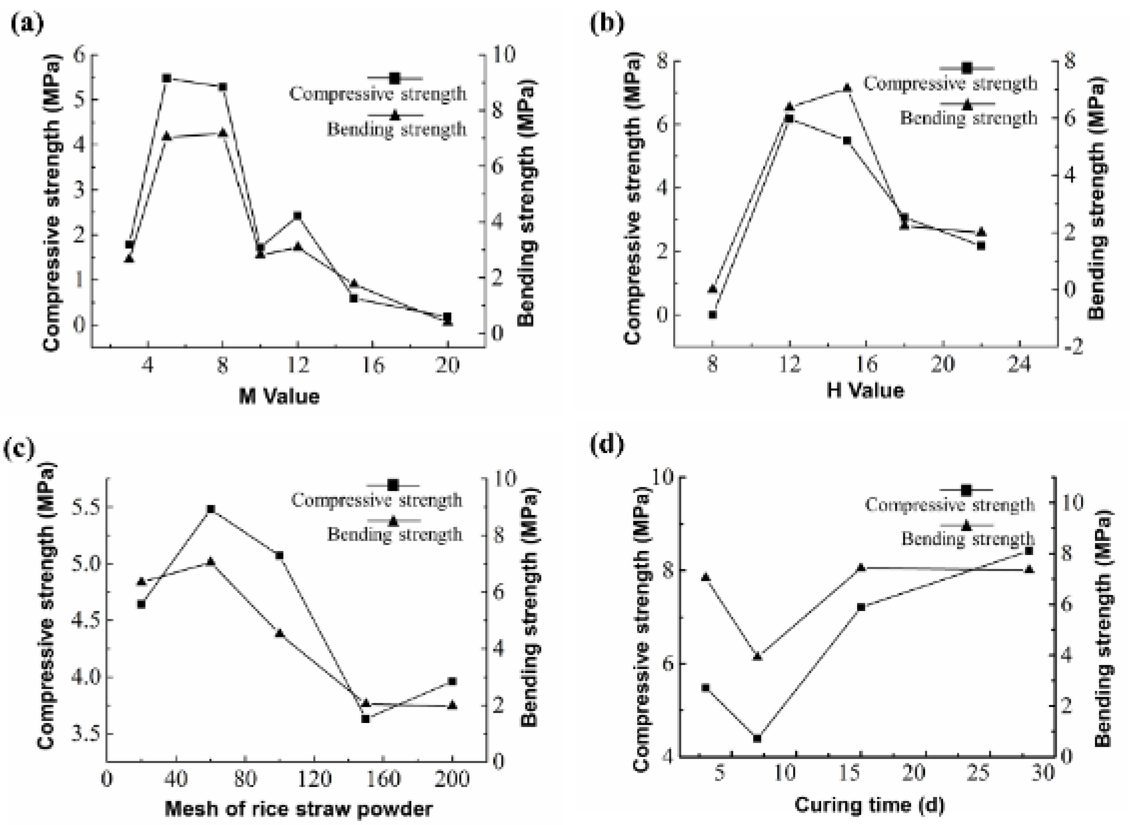

Fig. 5. Compressive and bending strengths for single factor experiment: (a) compression and bending strengths for various M values, (b) compression and bending strengths for various H values, (c) compression and bending strengths for various meshes of straw powder, and (d) compression and bending strengths in curing 3, 7, 15, and 28 days

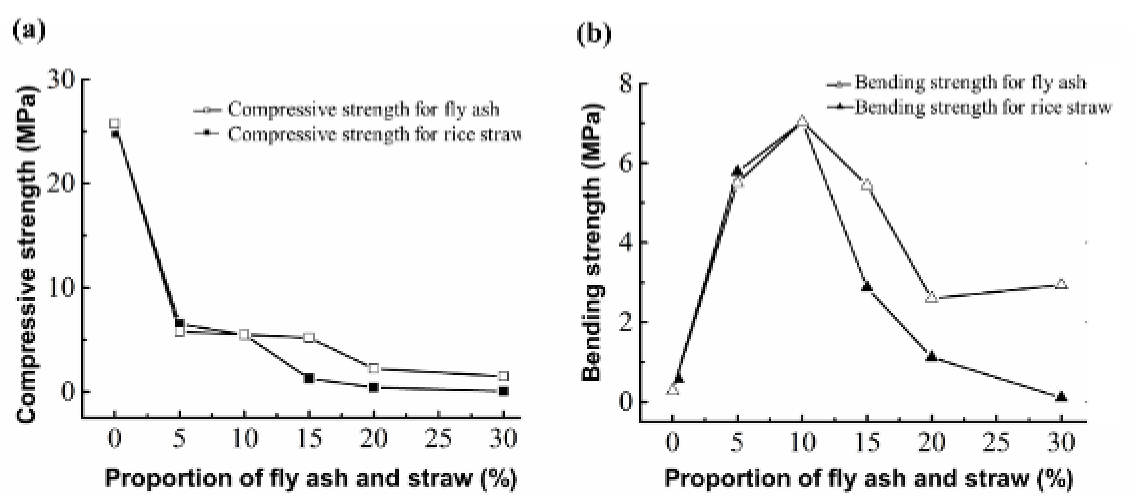

Fig. 6. Compressive and bending strengths of composites with different proportions of fly ash and straw powder: (a) compressive strength with different proportions of fly ash and straw powder; (b) bending strength with different proportions of fly ash and straw powder

The bending strength was increased with As and Af increase in the range of 0% addition to 10% (Fig. 6b). Which increased 25 times from 0.28 MPa to 7.04 MPa. However, the addition ratio exceeded 10%, the bending strength decreased. Because the excessive part of fly ash and straw destroyed or reduced the crystal structure of 5-phase and 3-phase. Moreover, when the proportion was more than 10%, both of the bending strength and compressive strength with fly ash addition were higher than rice straw addition, which indicated SiO_2 and Al_2O_3 in fly ash effectively improved the strength of the product.

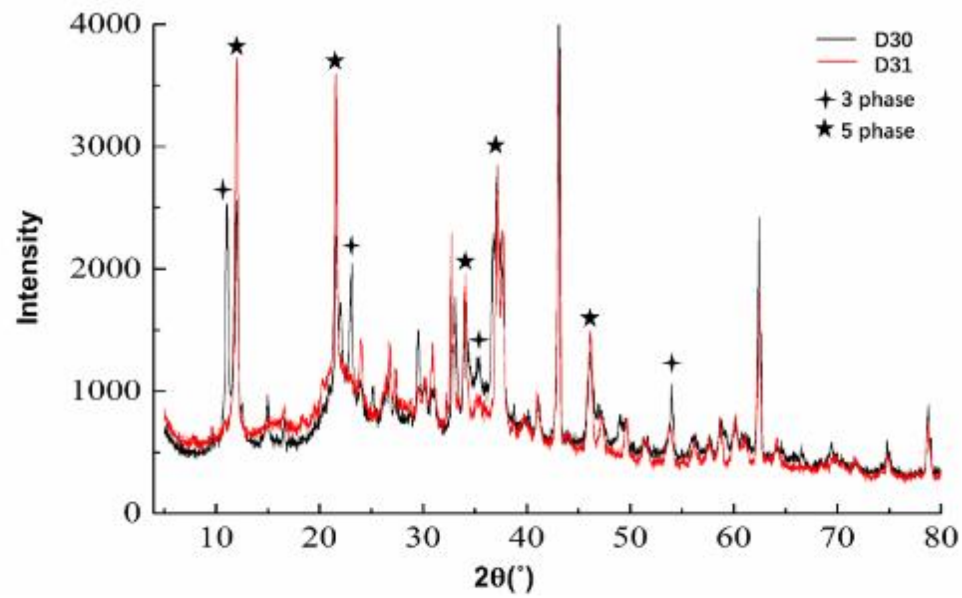

Fig. 7. XRD analysis for D30 and D31 test groups

Formula Optimization for MCSC

In the actual production, the bending strength and the compressive strength must be considered simultaneously. The formula needs to be optimized in the condition by different weight vectors. The fuzzy comprehensive evaluation method is a method of weighted average processing of test data using fuzzy mathematics, mapping the index to the interval of [0 to 1], fuzzifying the average value of each level, listing the evaluation matrix, and then making comprehensive evaluation and level optimization to obtain the comprehensive optimal scheme.

Establishment of evaluation matrix

In the practical use of magnesium cemented straw composites, compressive strength and bending strength are usually considered simultaneously. The authors set the weight ratio of compressive strength and bending strength as 0.7 and 0.3. First, the evaluation matrix was established. Taking the M value as an example. According to the orthogonal test results, the four horizontal mean values of compressive strength corresponding to the M value were: $k_1 = 6.23$, $k_2 = 4.65$, $k_3 = 0.54$, and $k_4 = 0.11$. k_1 was the average value for K_1, which was the sum of compressive strength of level 1, factor "M value". According to Table 2, they were 14.51MPa in A1, 1.05MPa in A5, 7.30MPa in A9, and 2.06MPa in A13. k_2, k_3 and k_4 was the average for level 2, level 3 and level 4.

$$K_1 = 14.51 + 1.05 + 7.30 + 2.06 = 24.92$$

$$K_2 = 2.38 + 0.00 + 14.78 + 1.46 = 18.61$$

$$K_3 = 0.72 + 0.31 + 0.43 + 0.72 = 2.180$$

$$K_4 = 0.00 + 0.08 + 0.10 + 0.26 = 0.440$$

$$k_1 = 24.92 \ / \ 4 = 6.23$$

$$k_2 = 18.61 \ / \ 4 = 4.65$$

$$k_3 = 2.180 \ / \ 4 = 0.54$$

$$k_4 = 0.440 \ / \ 4 = 0.11$$

The weighted average values of k_1, k_2, k_3, and k_4 were represent as r_{11}, r_{12}, r_{13}, r_{14} below:

$$k_1 + k_2 + k_3 + k_4 = 6.23 + 4.65 + 0.54 + 0.11 = 11.54$$

$$r_{11} = k_1 \ / \ 11.54 = 6.23 \ / \ 11.54 = 0.5399$$

$$r_{12} = k_2 \ / \ 11.54 = 4.65 \ / \ 11.54 = 0.4033$$

$$r_{13} = k_3 \ / \ 11.54 = 0.54 \ / \ 11.54 = 0.0471$$

$$r_{14} = k_4 \ / \ 11.54 = 0.11 \ / \ 11.54 = 0.0094$$

If the total evaluation of the six factors in the test formula for strength is expressed by the fuzzy matrix R_1 (M value), R_2 (H value), R_3 (Ms), R_4 (T), R_5 (As), and R_6 (Af), then the fuzzy indexes r_{11}, r_{12}, r_{13}, and r_{14} of compressive strength constitute the first line of the fuzzy matrix R_1. The fuzzification index of bending strength constitutes the second line of the fuzzy matrix R_1. By analogy, a fuzzy matrix of six factors and two indices are as follows:

$$R_1 = \begin{bmatrix} 0.5399 & 0.4033 & 0.0471 & 0.0094 \\ 0.5885 & 0.3155 & 0.0821 & 0.0139 \end{bmatrix}$$

$$R_2 = \begin{bmatrix} 0.3292 & 0.0921 & 0.2069 & 0.3715 \\ 0.3780 & 0.1389 & 0.2156 & 0.2675 \end{bmatrix}$$

$$R_3 = \begin{bmatrix} 0.3550 & 0.1070 & 0.2021 & 0.3357 \\ 0.4411 & 0.1490 & 0.1935 & 0.2165 \end{bmatrix}$$

$$R_4 = \begin{bmatrix} 0.3815 & 0.0312 & 0.4898 & 0.0974 \\ 0.4433 & 0.0631 & 0.3281 & 0.1654 \end{bmatrix}$$

$$R_5 = \begin{bmatrix} 0.8735 & 0.1261 \\ 0.7961 & 0.2039 \end{bmatrix}$$

$$R_6 = \begin{bmatrix} 0.7142 & 0.2857 \\ 0.6642 & 0.3358 \end{bmatrix}$$

Comprehensive evaluation and level optimum selection

The weight vector of compressive strength and bending strength of composites is set as A= (0.7, 0.3). Fuzzy matrix B is the result of comprehensive evaluation, and then，

$$B = A \times R$$

$$B_1 = \{b_1, b_2, b_3, b_4\}$$

$$b_1 = (0.7 \wedge 0.5399) \vee (0.3 \wedge 0.5885) = 0.5399$$

$$b_2 = (0.7 \wedge 0.4033) \vee (0.3 \wedge 0.3155) = 0.4033$$

$$b_3 = (0.7 \wedge 0.0471) \vee (0.3 \wedge 0.0821) = 0.0821$$

$$b_4 = (0.7 \wedge 0.0094) \vee (0.3 \wedge 0.0139) = 0.0139$$

The weighted average processing of b_1, b_2, b_3, and b_4 is refer to B_1, B_2, B_3, B_4, as follows:

$$B_1 = \{0.5196, 0.3881, 0.0790, 0.0134\}$$

By choosing the corresponding level value of 0.5196 in B_1 as the optimal level, the optimal formula under the condition of weight vector (compressive, bending) = (0.7, 0.3) can be obtained. The optimal level of factor 0.5196 corresponded to the first level value (value 5), which was the optimal formula value under this weight vector. According to the same method, it can be concluded that:

$$B_2 = \{0.3120, 0.1316, 0.2043, 0.3521\}$$

$$B_3 = \{0.3408, 0.1430, 0.1940, 0.3222\}$$

$$B_4 = \{0.3469, 0.0574, 0.4453, 0.1504\}$$

$$B_5 = \{0.7744, 0.2256\}$$

$$B_6 = \{0.7, 0.3\}$$

According to the above formula, the optimal formula under the condition of fuzzy evaluation (0.7, 0.3) vector can be obtained when the value of B_2 (H value) is the fourth value (25), B_3 (Ms) is the first value (20-mesh), and B_5 (As) and B_6 (Af) is 10%. In this study, it was assumed that composite materials are used in building materials. Compressive strength was the main factor in 0.7, bending strength was the secondary factor in 0.3, so the vector condition was set as 0.7 and 0.3. The optimal formula under 0.7 and 0.3 was $M_5H_{25}Ms_{20}T_{15days}As_{10\%}Af_{10\%}$. If the vector were changed to 0.3 for compressive, 0.7 for bending, the optimal formula was $M_5H_{10}Ms_{20}T_{3days}As_{10\%}Af_{10\%}$.

In practical use, the vector of compressive strength and bending strength can be adjusted at any time according to the different requirements of the material and environment. When the value of the vector changes, the results of the fuzzy investigation and optimal formula under the comprehensive conditions will also change accordingly.

CONCLUSIONS

1. Magnesium cement straw composites have rod-like, needle-like, flakey, and flocculent-like structures. The crystal was $5Mg(OH)_2.MgCl_2.8H_2O$ (5-phase) and $3Mg(OH)_2.MgCl_2.8H_2O$ (3-phase). The results of FTIR showed hydroxyl (-OH) functional groups and a hydrogen bond (O-H) that appeared at 3419 cm^{-1}.
2. The M value and straw proportion influenced the mechanical strength. The optimum mechanical properties were: M value of 5, H value of 25, Ms of 20, T of 15 days, and As or Af of 10%.
3. The optimization formula, considering the compressive strength and the bending strength as 0.7 and 0.3, was $M_5H_{25}Ms_{20}T_{15days}As_{10\%}Af_{10\%}$. The optimal formula for 0.3 and 0.7 was $M_5H_{10}Ms_{20}T_{3days}As_{10\%}Af_{10\%}$.

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